PROCEEDINGS OF THE FIRST INTERNATIONAL SYMPOSIUM ON COSMIC RAY PHYSICS IN TIBET (ISCRP—I)

TIBET UNIVERSITY
AUGUST 12—17, 1994
LHASA, CHINA
The first International Symposium on Cosmic Ray Physics in Tibet (ISCRP—1) have been held in Lhasa, China, on August 12—17, 1994, more than 80 papers from 18 Countries and areas are compiled in the proceedings of Symposium. They cover nearly the whole field of Cosmic Ray Physics, such as VHE and UHE Gamma—ray Sources and Gamma—rays; UHE Cosmic Rays and UHE Interaction; EHE Cosmic Rays; Instrument, Projects and Methods; Theories and Others.

Included in these proceedings are the general reports given by several world famous scientists engaged in this field, such as Prof. L. W. Jones, Prof. A. M. Hillas, Prof. G. B. Yodh, Prof. T. Yuda, Prof. J. Arafune and Prof. Y. H. Tan, etc.

The proceedings reflect the latest achievements and developments of Cosmic Ray Physics. These proceedings may serve also as a reference book for Cosmic Ray Physics scientists and students and other scientists.
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THE FIRST
INTERNATIONAL SYMPOSIUM
ON COSMIC RAY PHYSICS
IN TIBET
August 12—17, 1994 LHASA, CHINA

Organized By
Tibet University
The Science and Technology of Committee of Tibet Autonomous Region of China

Co-Sponsored By
The State of Science and Technology Commission of China
National Natural Science Foundation of China
Chinese Society of Physics
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PREFACE

The experiment success of the International Cooperation—Yangbajing UHE Cosmic Ray Physics in Tibet since 1990 persuaded the steering committee to propose the first international symposium and Tibet University takes the pleasure to organize the first international symposium on Cosmic Ray Physics in Tibet. In fact the ISCRP-I has received strong support in Cosmic Ray Physics community. In addition to the original eight Co—Sponsors: National Natural Science Foundation of China; The State of Science and Technology Commission of China; The International Science Foundation of USA; The Institute for Cosmic Ray Physics, Tokyo University, Japan; Chinese Society of Physics; Chinese Society of High Energy Physics; The Science and Technology Commission of Tibet, China; The Institute of High Energy Physics of Academic Sinca.

The Symposium aims at the exchange of the recent achievements in both fundamental research and experiment project among Scientists in Cosmic Ray Physics Community. 118 Scientists from 18 countries and areas attended this symposium, more than 80 oral reports have been presented. The representatives and accompanying persons visited Yangbajing Cosmic Ray Observatory with great interest at Aug. 15, and sightseeing Potala Palace, Jokhang Monastery as well as other famous sights of Lhasa during the Symposium. The Symposium also provided an opportunity to promote mutual understanding and friendship among these scientists who participate the Symposium. The aim have been met by the contributions of the eminent invited speeks and other distinguished scientists from various parts of the world. On behalf of the organizing committee and also the editorial board it is our great honour to express sincere thanks to the sponsoring societies for their support and cooperation.

I should also thank the invited speekers, all contributors who present their papers at the symposium. Many thanks to those who have helped in the collection, review and edition of the papers for their excellent work. Especially many thanks to Prof. L. K. Ding, Prof. Y. H. Tan and Prof. T. Yuda for their comments support and cooperation.

Finally I would like to express our great thanks to the Tibet Autonomous region Government, the State of Science and Technology Commission of China and the National Natural Science Foundation of China as well as International Science Foundation of USA for their financial support.

Mei Dongming
December, 1994, Lhasa, China
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Strong Interaction Physics from Cosmic Ray and Accelerator Studies

Lawrence W. Jones*
University of Michigan

Abstract

At the Fermilab Tevatron a small, semiparasitic experiment is in progress to seek evidence for “disordered chiral condensates”, suggested by J.D. Bjorken as a possible cause of the Centauro phenomenon. Another recent experiment relevant to cosmic ray physicists was a test at SLAC of the Landau-Pomeranchuk-Migdal effect. These experiments are discussed together with other accelerator experiments of interest to the cosmic ray community.

I. INTRODUCTION

Cosmic ray studies of elementary particle interactions were originally very closely coupled to the studies with particle accelerators during the 1940’s and 1950’s when the first machines with energies capable of producing mesons were constructed. It is significant that the first synchrotron in the United States of over a GeV energy was called the “Cosmotron”. However this close liaison seemed to lapse, so that the first observation of charmed hadrons by Niu about 1970 was not noticed by the accelerator community, and all credit for the discovery of charm was given to the discoverers of the \( J/\psi \) particle several years later; this is only the most conspicuous example. Currently it appears that there is again a closer linkage between these two communities. One goal of my report at this symposium is to strengthen further this communication.

I shall discuss below several experiments, past, present, and future, at particle accelerators which should be of interest to the cosmic ray community, beginning with a search at the Tevatron Collider for evidence for the Centauro phenomenon, and continuing with a discussion of the LPM effect, and the search for antiproton decay. I will discuss more briefly studies of jet production and will close by summarizing generic results on cross sections and other processes of general interest.

*Supported in part by the U.S. National Science Foundation
Many of the remarkable phenomena reported from cosmic ray experiments appear at energies in the range between $10^{14}$ and $10^{16}$ eV. The antiproton-proton colliders at CERN and at Fermilab have produced center-of-mass energies of about 600 GeV and 1.8 TeV, equivalent to about $2 \times 10^{14}$ and $2 \times 10^{15}$ eV, so that observations with these colliders are very relevant to the cosmic ray studies. However there is a major difference; cosmic ray experiments are primarily sensitive to energy flow, whereas the accelerator studies have focused on the central region of phase space in the c.m. system. 

In terms of pseudorapidity, $\eta$, where

$$\eta = -\ln \tan \frac{\theta}{2},$$

the large collider detectors are sensitive only in the central half of $\eta$-space (in the center-of-mass), $-4 < \eta < +4$. Cosmic ray experiments, on the other hand, are sensitive to the particle distribution in pseudorapidity space weighted by energy. It may be recalled that $\eta$ is approximately equal to the rapidity $y$, where $y$ is given by

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \tan^{-1} \left( \frac{p_z}{E} \right).$$

In the case of the Fermilab Tevatron, the full range of $y$ is from +7.5 to -7.5, equivalent to a nucleon of 2 PeV colliding with a stationary nucleon (where $y$ ranges between 0 and 15). Since

$$E \approx \frac{m_+}{2} e^y \quad \text{for} \quad y >> 1,$$

the energy-weighted distribution to which cosmic ray experiments are sensitive is proportional to

$$e^y dN/dy.$$

This comparison, first pointed out by Gaisser[1], is illustrated in Figure 1.

I should note that there have been two other meetings of Cosmic Ray physicists this summer; the Vulcano (Italy) "Workshop on Fundamental Objects in Particle Physics and Astrophysics"; and the Tokyo "VIII International Symposium on Very High Energy Cosmic Ray Interactions". Much of the material in this report is also included in my reports to those other meetings.
II. THE CENTAURO AND ANTICENTAURO PHENOMENON

“Centauro” events are events observed in emulsion chambers at high mountain elevation characterized by a small number of electromagnetic cascades in the topmost lead-emulsion layers and a large number of hadron-initiated cascades in the lower chamber. “Centauro I”, the first candidate event of this type, was recorded by the Brazil-Japan collaboration in 1971.[2] This event is sketched in Figure 2. The signature is consistent with a proton-air nucleus interaction in the atmosphere above the chamber array resulting in a large number of charged hadrons (probably mostly charged pions) and either no neutral pions (no gamma rays) or very few. Table I presents a summary of properties of five Centauro candidate events reported by the Brazil-Japan Emulsion Collaboration. A related variable is the fraction of the final-state energy carried by charged hadrons. This is plotted for a large sample of events from both the Chacaltaya and the Pamir emulsion chamber groups[3] in Figure 3.

Table I. Summary of Properties of Five Centauro Candidates from the Brazil-Japan MT. Chacaltaya Emulsion Chambers

<table>
<thead>
<tr>
<th>Centauro interaction</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>event number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>height of interaction in meters</td>
<td>50</td>
<td>80</td>
<td>230</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>estimated number of A-jets</td>
<td>3</td>
<td>5</td>
<td>13</td>
<td>32</td>
<td>18</td>
</tr>
<tr>
<td>hadrons estimated at the interaction number</td>
<td>74</td>
<td>71</td>
<td>76</td>
<td>90</td>
<td>63</td>
</tr>
<tr>
<td>total energy in TeV</td>
<td>330</td>
<td>370</td>
<td>350</td>
<td>340</td>
<td>350</td>
</tr>
<tr>
<td>(e, γ) estimated at the interaction</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Another rather different emulsion chamber program has been carried out by the Japanese-American Cooperative Emulsion Experiment (JACEE) research program. This group has flown emulsion chambers with balloons to study both primary composition and the nature of interactions at primary energies in the range of 100 TeV. A section of one of their emulsion stacks is shown in Figure 4. As with the mountain-top emulsion chambers, many more conventional events have been recorded and studied. Here charged hadrons
are observed as minimum ionizing tracks from the collision vertex which do not generate EM cascades in the lead-and-emulsion layers, and gammas are seen as neutral secondaries that do initiate such cascades. One interesting event is shown in Figure 5, where the distribution of charged secondaries and of gammas from one event of about 100 TeV is presented in $\eta - \phi$ space\[4]. In this event, there is a region of $\eta - \phi$ space of radius of about one unit where there are almost no charged particles but a large number of gammas. For obvious reasons, this type of event is referred to as an "Anti-Centauro".

It would be interesting to hear a discussion of the sensitivity of the mountain-top emulsion chambers to Anti-Centauro events. It is probable that they would be difficult to identify except in unusual events where the interaction vertex is close to and clearly resolved in the chambers, as EM cascades so dominate the observed products of almost all interactions.

III. DISORDERED CHIRAL CONDENSATES

J.D. Bjorken and Cyrus Taylor\[5] have discussed "Disordered Chiral Condensates" (DCC) as a mechanism which might explain the otherwise-puzzling Centauro (and Anti-Centauro) phenomenon. Briefly, their idea is that, following a hard quark-quark collision, the expanding volume of the excited vacuum may have the isotopic spin vector frozen in isospin space, such that, when the vacuum "materializes" to pions, etc., there is a high probability that the resulting pions will be all neutral or all charged. Quantitatively, the prediction is that the distribution in the region of $\eta - \phi$ space occupied by the resulting pions will behave according to the following:

$$dN/df \propto f^{-\frac{1}{2}}, \text{ where } f = \frac{N(\pi^0)}{N(\pi^0) + N(\pi^\pm)}.$$ 

Otherwise, one would expect just a binomial distribution in $f$ peaked at $f=1/3$, based upon charge independence and simple statistics. This is illustrated in Figure 6.

As I am not a theorist, let me use Bjorken’s words to better describe this idea\[6]. "The basic notion is that in the interior of the expanding shell of debris produced in a proton-antiproton collision there is created not the usual vacuum of the strong interactions, but one of its near-degenerate alternatives, characterized by a different order parameter. So if in the fireball interior the vacuum orientation is tilted toward one of the pion directions, then when the
fireball shell hadronizes, the interior vacuum will relax to the true vacuum by emission of a coherent semiclassical pulse of pions with the same (cartesian) isospin as had the vacuum disorientation. That is, if the order parameter is knocked toward the $\pi^0$ direction, then all the emitted DCC pions will be $\pi^0$'s. This leads to anomalously large fluctuations in the charged-to-neutral ratios and the motivation for the experiment.

One can argue that such effects are easily masked in the central region of a high energy interaction due to the large number of processes contributing to the large pion flux, and that it is particularly relevant to look in the less-populated regions of the final state; e.g. at extreme values of rapidity. Of course the energies at which the Centauro phenomena are reported are altogether comparable to the energy of the Fermilab Tevatron collider. However, the Tevatron experiments have focused largely on the central regions of pseudo-rapidity, whereas the cosmic ray observations are strongly weighted toward forward production. In this context, then, it may not be surprising that DCC have not been observed at the Tevatron and still have been seen in the much poorer statistical sample of cosmic ray events.

IV. MINIMAX

In order to study this concept and to seek evidence for DCC in accelerator data, a small test experiment has been set up in a colliding beam area at the Tevatron. This experiment, called "Minimax", is basically a proportional wire chamber telescope of 16 chambers "looking" at the $\bar{p}-p$ collision region at an angle of about 45 milliradians ($\eta \cong 3.8$) together with appropriate trigger scintillators, a lead converter, and an array of lead-scintillator EM calorimeters. The region of phase space subtended is about one-half unit in radius in $\eta-\phi$ variables. The objective is to study, on an event-by-event basis, the numbers of gammas and of charged hadrons (pions) in this solid angle. The experiment[7] is sketched in Figure 7. The participating physicists are listed in Table II.

J.D. Bjorken had initiated a study group and a letter of intent for the SSC centered around a "Full Acceptance Detector". In discussions with M.J. Longo, the smaller-scale version of F.A.D., adapted to the Tevatron, was developed. The present Minimax test experiment grew out of that concept, as something which could be done on a short time scale and which has the potential to explore this very interesting DCC concept.
Table II. Participants in Fermilab Test/Experiment T864

<table>
<thead>
<tr>
<th>Case Western Reserve University</th>
<th>Fermilab</th>
<th>University of Michigan</th>
</tr>
</thead>
<tbody>
<tr>
<td>K. del Signore</td>
<td>P. Colestock</td>
<td>R. Ball</td>
</tr>
<tr>
<td>W. Fickinger</td>
<td>B. Hanna</td>
<td>H.R. Gustafson</td>
</tr>
<tr>
<td>T. Jenkins</td>
<td>M. Martens</td>
<td>L. Jones</td>
</tr>
<tr>
<td>E. Kangas</td>
<td></td>
<td>M. Longo</td>
</tr>
<tr>
<td>M. Knepley</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K. Kowalski</td>
<td>SLAC</td>
<td></td>
</tr>
<tr>
<td>C. Taylor*</td>
<td>J. Bjorken*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Duke University</th>
<th>University of Tennessee</th>
<th>Virgin Polytechnic Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Oh</td>
<td>A. Weidemann</td>
<td>A. Abashian</td>
</tr>
<tr>
<td>W. Walker</td>
<td></td>
<td>D. Haim</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N. Morgan</td>
</tr>
</tbody>
</table>

*Spokesman

Although the chambers, counters, electronics, and data collection are all assembled and operating successfully, no definitive data have yet been taken, in part due to background from the accelerator beam pipe. A new vacuum tank is being fabricated and will be installed later this year.

V. THE LANDAU-POMERANCHUK-MIGDAL EFFECT

The Landau-Pomeranchuk-Migdal (LPM) effect was calculated many years ago by these Russian authors; it predicts a departure from the classical Bethe-Heitler Bremsstrahlung expressions (as well as those for pair production) due to multiple Coulomb scattering in a short-radiation-length radiator for high energy electrons[8]. This basically quantum mechanical effect considers the uncertain energy and momentum of a final state system following exchange of a virtual photon between an energetic electron and a nucleus. If, in the context of the Heisenberg Uncertainty Principle, the electron experiences another photon exchange (e.g., Coulomb scatter) before the Bremsstrahlung photon has been radiated, the effect is to suppress the radiation. The effect is most important for soft photons radiated by high energy electrons in
radiators of short radiation length. Specifically, the effect is important for photons of energy below a threshold $E_\gamma$ given by:

$$E_\gamma = E(c)^2 / E_{LPM}, \text{ where } E_{LPM} = 7.6 \times X_0 \text{ (TeV)},$$

$E_c$ is the incident electron energy in TeV, and $X_0$ is the radiation length in cm. (1)

This effect is clearly important for cosmic ray photons of energies of 100 TeV and higher, and it is not readily apparent at accelerator energies where most of the quantitative tests of QED have been carried out. There have been qualitative verifications of the effect from cosmic ray emulsion exposures[9] and from an early experiment with 40 GeV electrons at Serpukhov[10].

At the Dublin International Cosmic Ray Conference, we proposed undertaking a quantitative study of the effect with a 350 GeV electron beam at Fermilab, and we subsequently made a formal proposal to Fermilab[11]. This proposal is still under discussion, and we are optimistic that we will undertake this measurement during the next fixed-target running period.

However, in the meantime, a young and energetic group at Stanford has carried out a very clean measurement at the Stanford Linear Accelerator Center with a 25 GeV electron beam. Although the effect is only apparent at very low energies there, they none-the-less have very nice data[12], some of which is displayed in Figure 8.

VI. TEVATRON COLLIDER RESULTS

The most recent news-worthy result from the Tevatron has been the reported evidence for the Top Quark. Recently the Collider Detector at Fermilab (CDF) group announced the observation of 12 events from 19 $pb^{-1}$ of collider data which are consistent with the decay mode of the top quark into a bottom quark and a W intermediate vector boson, with either or both of these decay products in turn decaying leptonically (the W) or semileptonically (the b quark). The top quark mass quoted is $174 \pm 17$ GeV (where the error includes both statistical and systematic uncertainties)[13]. The group asserts that this identification is "99.75% certain".

Other Tevatron results recently reported by the CDF group include new determinations of several inclusive pbar-p cross sections, measured at 1800
GeV and 546 GeV c.m.[14]. These include the total, elastic, single diffractive, inelastic, and non-single diffractive cross sections. These values are summarized in Table III and plotted in Figure 9.

Table III. Elastic, Total, and Single Diffraction $\bar{p}p$ Cross Sections (CDF)

<table>
<thead>
<tr>
<th>$E_{cm}$</th>
<th>1800 GeV</th>
<th>546 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{total}^{(mb)}$</td>
<td>80.03 ± 2.24</td>
<td>61.26 ± 0.93</td>
</tr>
<tr>
<td>$\sigma_{elastic}^{(mb)}$</td>
<td>19.70 ± 0.85</td>
<td>12.87 ± 0.30</td>
</tr>
<tr>
<td>$2\sigma_{single , diff}^{(mb)}$</td>
<td>9.46 ± 0.44</td>
<td>7.89 ± 0.33</td>
</tr>
<tr>
<td>$\sigma_{inelastic}^{(mb)}$</td>
<td>60.33 ± 1.40</td>
<td>48.39 ± 0.66</td>
</tr>
<tr>
<td>$\sigma_{non , s. , d.}^{(mb)}$</td>
<td>50.87 ± 1.84</td>
<td>40.41 ± 0.89</td>
</tr>
</tbody>
</table>

Another result of interest to cosmic ray physicists is the measurement of the inclusive jet production cross section as a function of transverse energy in the central region of rapidity[15]. Cross sections from both TeV detectors are presented in Figure 10. Note that the ordinate scales are different for the two graphs.

The D0 group has also studied the question of "rapidity gaps"[16]. When two quarks scatter through the exchange of a gluon, the final state contains the exchanged gluon stretched as the excited quarks separate, and mesons are created and radiated along this stretching gluon. The result is that the region in rapidity space between the two final-state jets is populated by smaller meson-initiated jets. However, if the exchanged quantum is "colorless", e.g. is a meson or a "Pomeron" (of diffraction scattering fame), there is no final state radiation along this exchange, and the two jets are cleanly separated. A measure of this may be obtained by studying events where there is a gap in rapidity space between two energetic final-state jets. This is illustrated in Figure 11. The results of the D0 search for rapidity gaps is shown in Figure 12, where the fraction of events with no tagged particles between the two leading jets is plotted as a function of the gap between jets as measured in units of pseudo-rapidity, $\eta$.

It is very tempting to identify parton-parton scattering, as studied at the Fermilab and CERN colliders, with the binocular events reported by the emulsion chamber groups[17]. As the two jets would generally scatter forward and backward in the c.m. system, it is natural that the emulsion
chambers would see only the forward-scattered jet and the ongoing projectile nucleon jet; the target nucleon fragments and the backward-scattered jet would probably not produce gamma cascades above threshold visible in the chambers. As noted above, a gluon exchange would often lead to a string of energetic mesons produced along the exchange. Such a process could logically then lead to the observed “linear” events reported by the emulsion chamber groups. Examples of such events are seen in Figure 13 (from ref. 3).

VII. A SEARCH FOR ANTIPROTON DECAY

A Fermilab group has made a proposal to search for evidence of antiproton decays, and has recently published a preliminary lifetime limit orders of magnitude longer than older established data[17]. The obvious astrophysical and cosmological interest in this measurement is to explain the apparent matter-antimatter asymmetry of the Universe. Although there may well be other explanations (through CP-violating interactions in the early Universe), and although a decay lifetime of the antiproton different from that of the proton would violate CPT, never-the-less an antiproton lifetime of even $10^8$ years would comfortably explain the particle-antiparticle asymmetry observed. If such a measurement is possible and straight forward, it seems well worth doing.

The experiment, known as APEX (AntiProton Experiment) looks at a high-vacuum section of the 8 GeV antiproton accumulator ring at Fermilab, and, with an array of track chambers, scintillators, and lead-glass calorimeters, seeks evidence for decays in flight leading to $e^-\pi^0$ and other final states (Figure 14). Their preliminary data already set a lower limit of about 1000 years to the antiproton lifetime,[18] and they expect to push below ten million years with a new, specially engineered vacuum tank and detector improvements.[19]

VIII. LEP PHYSICS

The CERN electron-positron collider has completed 5 years of data collection with the four LEP detectors operating on and near the Z Intermediate Vector Boson mass (about 91 GeV). Recently a report has appeared with a summary of important parameters of the Z derived from a statistical averaging of results from the four independent experiments.[20] Table IV below
is a summary of these results. All of the results are in good agreement with predictions of the Standard Model, where these predictions exist. A point worth following is the small (about 2 standard deviations) disagreement [21] between the CERN and Stanford determinations of $\sin^2 \theta_w$.

Table IV. LEP $e^+e^-(M_z)$ Summary ALEPH · DELPHI · L3 · OPAL

<table>
<thead>
<tr>
<th>$M_z$</th>
<th>$91.183 \pm 0.007$ GeV</th>
<th>$\Gamma_{inv}$ = $497.6 \pm 4.3$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_z$</td>
<td>$2.489 \pm 0.007$ GeV</td>
<td>$g_{\nu} = 0.0359 \pm 0.0018$</td>
</tr>
<tr>
<td>$N_{\nu}$</td>
<td>$2.980 \pm 0.027$</td>
<td>$g_A = -0.50093 \pm 0.00082$</td>
</tr>
<tr>
<td>$\Gamma_{\ell}$</td>
<td>$83.82 \pm 0.27$ MeV</td>
<td>$\alpha_s = 0.123 \pm 0.006$</td>
</tr>
<tr>
<td>$\Gamma_h$</td>
<td>$1740.3 \pm 5.9$ MeV</td>
<td>$\sin^2 \theta_{\nu}^{eff} = 0.2321 \pm 0.0007$</td>
</tr>
</tbody>
</table>

SLD: $\sin^2 \theta_{\nu}^{eff} = 0.2292 \pm 0.0009$ (Stat) $\pm 0.0004$ (Syst.)

Beyond these confirmations of the Standard Model, LEP has reported no evidence for a host of other postulated objects. Searches have been made and negative results reported for the following: the (neutral) Higgs boson of $m<60$ GeV, heavy (excited) leptons, super-symmetric particles, and other objects. An interesting set of 4 events was reported last year by the L3 group where these events appeared to include a pair of gammas with an invariant mass of about 60 GeV.[22] As more data has been collected, including more high mass gamma pairs, the statistical significance of these events has declined.

IX. CONCLUSIONS

There is a beginning of a firmer dialogue between accelerator physicists and the cosmic ray community; let us all work to strengthen this mutually constructive interaction. One class of data from accelerators which is very much lacking is comprehensive differential production spectra in the forward direction of various particles; production as functions of energy (momentum) and angle. Such data would not be too difficult to collect and would be very useful in resolving many of the continuing arguments over scaling and the energy dependence of inelasticity; however no experiment has been proposed
to seriously make such studies. This situation was summarized nicely by L. Voyvodic.[23]

In spite of all that can be learned from accelerators, I must close by quoting Professor Fujimoto, who has said “There is evidence that there is a fundamental change in the character of strong interactions above $10^{16}$ eV.” Alas, this remains above any energies we will reach before the end of this century in the laboratory.

References


Figure 1. The kinematic range of rapidity, $y$, for the Tevatron collider (1.8 TeV) and for the equivalent cosmic ray nucleon-nucleon energy ($1.7 \times 10^{15}$ eV). The particle density vs. rapidity is shown (approximately) in (a) for the Tevatron collider, with the range of sensitivity of the Fermilab Collider Detector noted. In (b) the same rapidity space for cosmic ray experiments is shown with energy flow, $d(NE)/dy$, vs. rapidity plotted. The curves are from T.K. Gaisser.
Figure 2. Centauro I, as reported by the Brazil-Japan Emulsion Chamber Collaboration[2].
Figure 3. Correlation plot—number of hadrons $N_h$ versus portion of hadrons energy $Q_h = \Sigma E_h^\gamma/\Sigma E_{tot}$. Selection rule: $\Sigma E_{tot} = \Sigma E_\gamma + \Sigma E_h^\gamma > 100$ TeV, $N_h \geq 0, N_\gamma \geq 0, \Sigma E_\gamma \leq 400$ TeV.

- = experimental points (about 200 hadron families);
$\times$ = QGS-model points (without procedure of registration);
$\bigcirc$ = two Pamir Centauro type events (recording during another run of exposure);
$\blacksquare$ = Chacaltaya Centauro type events
Figure 4. A schematic diagram of the JACEE balloon-borne emulsion chamber.
Figure 5. An event from the JACEE collaboration [4]. The region of \( \eta - \phi \) space within the dotted circle contains an anomalously high ratio of gammas to charged secondaries.
Figure 6. Expected distribution for the neutral fraction $f$ for various total pion multiplicities according to $5 \times 10^5$ Pythia Monte Carlo events. Also shown is the dcc inverse square root distribution, which is essentially independent of pion multiplicity.
Figure 7. Layout of the MiniMax detector now installed at the C0 interaction region at Fermilab.
Figure 8. Bremsstrahlung spectra from 25 GeV electrons on 5% radiation length U and 6% radiation length C illustrating the LPM effect. The dotted lines are the Bethe-Heitler predictions, the dashed lines are the LPM prediction, and the pluses are the data.
Figure 9 (a). Total $\bar{p}p$ cross section vs. energy from various experiments, including the most recent Fermilab measurement [14].

(b). The ratio of $\sigma$(elastic)/$\sigma$(total) from various experiments.
Figure 10 (a). Cross-section for inclusive jet production in $0.1 < |\eta| < 0.7$ from $14.3 \text{ pb}^{-1}$ at CDF, compared to NLO predictions.

(b). D0 inclusive jet cross-section from $4 \text{ pb}^{-1}$. Open circles are data, closed circles NLO QCD prediction with HMRSB0 structure function at a scale $\mu = E_T/2$. Solid lines show the uncertainty from energy scale.
Figure 11. Structure of an event containing a rapidity gap and jets. No particles are found in the central region.

Figure 12. D0 observed fraction of events containing a rapidity gap as a function of gap width $\Delta \eta$. Statistical errors only.
Figure 13. Isodensity contours from X-ray film for 6 Pamir multicore halo events.
YANGBAJING COSMIC RAY OBSERVATORY AND ITS EXPERIMENT RESULTS

Y.H. Tan
(The China-Japan Tibet AS\gamma Collaboration)

In the late part of last decade, a world wide effort for searching for ultra-high energy (UHE) Gamma-ray point sources have been made, many new air shower (AS) arrays such as HEGRA, CYGNUS, CASA-MIA and EAS-TOP were founded. They are complex detector arrays and are sensitive for a source in the galaxy with a flux dozens times lower than that claimed by Kiel group in 1983[1]. By same motivation and towards lower energy, Yangbajing was selected as the observatory site and China-Japan AS\gamma Collaboration was founded in 1988. The installation of the current AS array was carried out in the winter of 1989, and the formal running have began since June of 1990. Up to now, more than 1.5 billion of AS events have been recorded. Gamma-ray emission from 70 concerned objects in the northern sky have been checked in the 10 Tev region, and more comprehensive investigations including the solar activity effect, the Gamma-rays from Active Galactic Nuclei (AGN) and cosmic Gamma-ray Burst (GRB) are carried on. Though no any UHE point sources have been found, the Tibet experiment together with the common efforts of other groups in the world have greatly improved our knowledge on cosmic ray origin. I'll give a brief summary on the first phase Tibet Experiment below.

1. The Feature of Tibet AS\gamma Experiment

YBJ observatory located at the cross point of Qinhai-Tibet and China-Nepal highways, 90Km north-west from the Lahsa city, 4300m above the sea level. Yangbajing basin is a vast pasture and a famous geothermal energy power base in China. Except two, severnal Tibetan villiges, there are two electric power plants and many green houses there. It's average temperature over a year is -5.1° and 10.8° for daily low and high respectively, and the deepest snowfall so far recorded is only 7 cm. The existed facilities, the mild climate and the unobstructed traffic there enable us running a high technical system continuously at such high land with good maintenance.

As shown in Fig.1, the current YBJ Array essentially consist of 49 scintillation detectors with 0.5$M^2$ area. Taking the advantages of high elevation, it have high event rate (20Hz), and lowest effective observation energy ($\geq7$Tev) among all AS arrays in the world. Its main features[2] can be outlined as the following.

* Location: 90.53°E, 30.11°N.
* Atmosphere Depth: 606 g/cm².
* Trigger Rate: ≈20Hz under Any-4 fold coincidence.
* Energy Response: (Fig.2)
The acceptance of array begins from 3Tev;
mode energy in primary proton case: 7Tev for "all Events", 35Tev for the events with $\sum \rho_{FT} \geq 100$. Here $\sum \rho_{FT}$ is the sum of particle density of all fired detectors in a AS event.
Median energy in primary proton case: 35Tev for "All Events", 56Tev for the events with $\sum \rho_{FT} \geq 100$.
* Detection Efficiency at 10Tev: 18% for proton induced AS; 31% for Gamma ray induced AS.
* Angular Resolution: Given by simulation for proton induced AS is $1.15^\circ$ and $0.49^\circ$ for "All Events" and those with $\sum \rho_{FT} \geq 100$ respectively. Given by the moon shadow observation is $0.87^{+0.13}_{-0.10}^\circ$ and $0.54^{+0.11}_{-0.08}^\circ$ for "All Events" and the events with $\sum \rho_{FT} \geq 100$ respectively.

Besides, with its distinctive 7-40Tev ASγ observation window, Tibet Array fills the energy gap between the traditional VHE and UHE ranges. The Gamma rays in this energy range is almost transparent for cosmic microwave photon field, and the cosmic rays around 10Tev is just in the right energy to observe the effect of the interplanetary magnetic field (IMF) on the displacement of the sun shadow of cosmic rays.

Note that, the array performances mentioned above are based on the "Contained Events", they are selected by imposing the following conditions on the recorded events. They are:

1. Each of the four FT detectors contributed the Any-4 coincidence should give a signal more than the 1.25 particle per 0.5 m².
2. Two or more of the four detectors recording highest particle density should be inside the inner 5×5 detector matrix.
3. (In case of Gamma-ray observation) The mean lateral spread of shower $\langle r \rangle$ should be less than 25m, where $\langle r \rangle = \sum r_i \rho_i / \sum \rho_i$ and $r_i$ is the distance of ith detector from the estimated core and $\rho_i$ its particle density.

About 1/4 of the total recorded events satisfied these 3 conditions and be used for the further analysis. By this way to make our dataset free from the triggering bias and have higher detection efficiency, higher measuring accuracy and signal-background ratio in the Gamma-ray observation.

In the case of point source investigation, the event number of on-source $N_o$ is picked up from the ASs coming within a circle of apparent radius 1.0° centered at the position of source object; and the off-source event number $N_b$ is calculated from the AS event coming from 8 adjacent windows of same size along the declination of source. This window size
is choose to maximum the ratio $N_e/N_0^{0.5}$, it contains about 50% of signal from the source.

2. Results of Yangbajing Experiment (first phase)

Based on the observation during the period of June 18 of 1990 to the September 29 of 1992, following results have been yielded.

2.1 Interplanetary Magnetic Field (IMF) Effect on the Sun Shadow of Cosmic Ray

Detecting the cosmic ray shadow by using the Moon as a collimator have became a common means to check the direction determination (point error and angular resolution) of a high resolution AS array[3][4][5][6]. Because of the effective detection energy of all AS arrays except YBJ Array are higher than 40Tev, the bend of the tracks of charged cosmic rays under the influence of IMF are unmeasurable under the current angular resolution, the detection of the Sun shadow just function as the Moon shadow does. The YBJ Array is effective for cosmic rays with energy as lower as 7Tev and have a trigger rate as higher as 20Hz, it should be possible to manifest the influence of solar MF and IMF on the charged composition of cosmic ray by means of Sun shadow figure.

In the moon shadow case, only geomagnetic field (GMF) effect is important. From the Moon shadow measurement of YBJ Array[6][7], the maximum cosmic ray deficit position was found by $7.1\sigma$ singnificance level at $0.16^{+0.115}_{-0.096}$ to the west and $0.02^{+0.075}_{-0.069}$ to the south away from the Moon for "All Events" (Fig.3). This displacement is mainly due to the GMF effect on the positively charged cosmic rays. For the events with $\rho_{FT} \geq 100$, the shadow center falls almost on the position of Moon. The overall pointing error of the YBJ Array was therefore be estimated to be less than 0.1°, and the angular resolution of the array is $0.87^{+0.135}_{-0.106}$ for "All Events" and $0.54^{+0.115}_{-0.096}$ for those with $\sum \rho_{rm,FT} \geq 100$.

The contour map of Sun shadow for "All Events" (Fig.4a), when comparing with that for the Moon, is slightly disordered and is shifted to the south-west of the Sun evidently. The shadow center is located at $0.70^{+0.106}_{-0.106}$ to the west and $0.40^{+0.095}_{-0.105}$ to the south of the Sun. The probability of a chance occurence of this displacement is $6.3 \times 10^{-8}$ and the significance of the maximum event deficit is $4.6\sigma$. For the events with $\rho_{FT} \geq 100$, the Sun shadow was also clearly observed by significance of $4.3\sigma$ and a smaller displacement (Fig.4b). Its center position is at $0.25^{+0.156}_{-0.155}$ W and $0.10^{+0.155}_{-0.155}$ S, the displacement is about $1/3$ of that for "All Events", just about the same ratio between the median energies of these two groups of AS event. After substracted the displacement due to the GMF ($0.16^\circ W, 0.02^\circ S$), the net displacement of the Sun shadow ($0.54^\circ W, 0.38^\circ S$) is resulted from the influence of the solar and interplanetary MF on cosmic rays. The complexity and big variation of this large scale magnetic field during the data taking period (near the
maximum of solar activity) somewhat disordered the shadow map and the mixed charge composition of cosmic rays added some additional complexity on furthermore.

The effect of the IMF have been directly examined connecting with its sector structure[7]. Cosmic rays arriving through the "Away" and the "Toward" sector were selected for Sun shadow study separately, to check that if their tracks are bent in opposite direction to each other with respect to the shadow center. As shown in Fig.6, the observed position relation between the most probable positions of the shadow center for each sector case and the shadow center of all events as well as the apparent center of Sun, just demonstrated the expected feature. After removing the geomagnetic displacement, the most probable position of the shadows are found to be (0.41°W,0.66°S) and (0.70°W,0.27°S) respectively for the cosmic rays coming through Towards Sector and Away Sector, their angle distance is about 0.34°.

This is the first direct observation of the IMF effect on the Sun shadow of cosmic rays. It is very interesting and important to monitor the monthly variation of the Sun shadow over a whole solar activity cycle, and investigate the variation of solar MF and IMF related to the solar activity.

2.2 Search for Gamma-Ray Sources in Our Galaxy

2.2.1 Continuous Emission of 10-Tev Gamma-Rays from Point Sources

Taking the advantages of high altitude and appropriate latitude of YBJ, the array have more than 4 hours effective observation time each day for all objects within the -10°–70° declination band. Steady emission of ≈10Tev Gamma-rays have been surveied for more than 50 potential sources. So far, no any statistically singnificant excess was found from these directions, but their flux upper limit are obtained. Among them, the emission from Crab Nebula, Cygnus X-3 and Hercules X-1 have been reported previously[8][9]. In case of Crab Nebula, the energy of our data are just located in the sensitive range for models and the flux upper limits are laid on the extrapolated line from the Wipple spectrum. Tibet data is in favour of Compton-Synchrotron model of De Jager and Harding[10] (Fig.7). It’s $F(\geq 10TeV) \leq 9.1 \times 10^{-13} cm^{-2}s^{-1}$, is in good coincidence with the model prediction and slightly lower than the respective values of THEMISTOCLE[11] which was reported as a positive detection at $\approx 6\sigma$ level.

For Cyg X-3, our flux limits are dozens below the extrapolated level from the Kiel flux[1] using an integral spectrum of $E^{-1}$ and are consistent with the CYGNUS[12] and CASA-MIA[13] data in a combined energy spectrum (Fig.8). Situation is similar in case of HerX-1 (Fig.9), it seems the flux upper limit given by Muon poor data of CYGNUS and CASA-MIA are lower than the level extrapolated from Tibet data (though the EAS-TOP's upper limit[14] is much higher). It’s too early to say anything about the break of Gamma-ray spectrum based on this combined data, but all their negatic detections
and lower flux limits clearly established that the CygX-3 and Her X-1 are no longer the continuous emitters of \( \geq 10 \) TeV Gamma-rays at the sensitivity level of these AS arrays.

For binary radio pulsar PSR1957+20, PTCHEFSTROOM group\[15\]|16\] claimed a positive detection of orbitally modulated Gamma-ray DC emission at 2.7 TeV. No event excess was found from our dataset even by orbital modulation analysis, and the obtained flux upper limit are much below the extrapolated level from the PTCHEFSTROOM flux at 2.7 TeV or flux limit at 5.5 TeV (Fig.10). It's not contradicting with their model prediction\[16\] on the Gamma spectra cutoff at \( \approx 6 \) TeV. A similar check have been done for PSR1855+09 and similar situation was resulted.

2.2.2 Sporadic Pulsed Emission of 10-TeV Gamma-rays from Pulsar

Three Gamma-ray sporadic emission events from Her X-1 pulsar were observed. Fig.11a shows the two order Rayleigh Power distribution of the daily AS event number. The data of May 23 and June 20,1991 are evidently isolated from the total distribution with a chance probability of \( 10^{-7.1} \) and \( 10^{-5.7} \) respectively (a trial factor of \( \approx 400 \) have not been multiplied). Their phase analysis with the pulsed emission period of 1.235637 sec. clearly exhibited the pulsed emission at the phases of \( \approx 0.2 \) and 0.6 (Fig.11b and 11c). This pulse period shows a slight blue shift comparing with the measurements of other groups made in last decade (Fig.11d). The fact of all the 3 sporadic events have exactly a same period of pulsed emission, gives an additional confirmation on these events.

A similar survey have been carried out for pulsar PSR0540+23. The Rayleigh Power of the data on Feb.18,1991 reaches maximum (-logP=6.7) when a pulse period of about 10^{-7} second smaller than its radio pulse period was used. Besides, there is an indication of DC excess on this event: contrasting with the \( \approx 90 \) AS events per day in general, there are 138 AS events come from the PSR0540+23 direction that day.

2.3 10 TeV Gamma-Ray Emission from Active Galactic Nuclei (AGN) and Gamma-Ray Burst (GRB) Like Events

25 extragalactic objects have been detected as powerful Gamma-ray emitters above 100 Mev by EGRET\[17\] on board of Compton GRO satellite. They are very bright and some of them with a flat energy spectrum, some of them are variable on Gamma-ray intensity in few days or few months time scale. One of these EGRET source, Markarian 421, was also observed at energy above 500 Gev by the WIPPLE Observatory\[18\] and shows that there is no spectra bend up to a few Tev energy region.

Motivated by the interest on the apparent energy break of Gamma-ray spectrum of AGNs and the better estimation of the intergalactic infrared photon density, we've examined the 10 TeV Gamma emission for 15 EGRET sources in the northern sky using Tibet dataset. No evidence was found on steady emission from any of them and on time
variation of concerned time scale. Their upper limits of flux at 95% confidence level are obtained[19].

Among them, Mrk 421 is the closest (redshift Z=0.031) therefore the most promising one for the 10Tev Gamma-ray detection, though it's the weakest EGRET's AGN Gamma-ray emitter. Its flux upper limits of ours together with the limits given by CYGNUS[20] and CASA-MIA[21] as well as the flux measured by EGRET and WIPPLE are shown in Fig.12. They are almost fall on the extended line through the EGRET and WIPPLE's data corresponding to an integral spectrum with a power index of -1.06. It seems that, the energy density of the cosmic infrared photon is not as dense as the expect[22] and we may have chance to have a positive detection in the future.

To search for the possible time variation of Gamma-ray flux from these AGNs, the daily DC excess was examined by the Li & Ma Sigma. No statistically significant excess was observed at 10Tev energy region. To make YBJ Array to be effective for the extragalactic Gamma-ray detection and the time variation monitor to reveal the size of source region, enlarge the current array and further reduce its energy threshold are indispensable.

To search for 10Tev GRBs, Both full survey and detail search a narrow direction and time range indicated by BATSE GRBs are used, to find if there is any high significance AS event cluster (i.e, showers arriving closely in time and direction scale). In the search by the first method, among those found burst-like clusters in a time duration less than 1.7 sec., 4 events with AS number more than 4 (while the average is about 0.2) are found to be coincidence with the BATSE GRB event within the direction measurement error of BATSE, and arriving time difference of ≤ a few hours. Apart from that the chance probabilities are not small enough and the direction constraint are rather loose followed the worse angular resolution of BATSE, a feature is interesting: All these 10 Tev coincidence events delay from its corresponding (20Kev-2Mev) BATSE GRB event. In the search by the second method, about 10 clusters are found at chance probability 10^-2 to 10^-4. The triggering time difference between each cluster and its corresponding BATSE burst is less than 200 sec, and showers arrive in a ≤ 2° narrow direction range very near the BATSE event direction (the angular distance between the cluster center and the BATSE event location is less than the angle resolution of BATSE). One cluster of them even have a similar characteristic time profile with its coincident BATSE burst 1B911208. It seems, one can think that it's the high energy part of the same Gamma-ray burst.

3. The Prospects

Right after this symposium, the current YBJ Array will be enlarged 4 times in cover area and 8 times in effective area (Fig.13). Based on its high trigger rate (about 200Hz)
and significant improved statistics, the following prospects can be expected.

(1) A Sun shadow map can be obtained per two months, and the continuously monitor on the monthly variation of interplanetary magnetic field related to the solar activity can be done over a full solar cycle.

(2) A possible positive detection on Crab Nebula may be achieved at $\approx 10$ TeV energy region by 2–4 years observation, otherwise, a further constraint on the model assumption of Nebula magnetic field can be put. Meanwhile, there is some probability to see $\approx 10$ TeV Gamma-rays from Mrk 421, if not, with a 3–4 times reduced flux upper limit the estimation of upper limit of the cosmic near-infrared photon density can be improved.

(3) More sporatic pulsed Gamm-ray emission events for Her x-1 and other objects will be found. The increase of event statistics is indispensible for the understanding of what happened sporaticly on some pulsars and objects.

(4) Probably, dozens of $\approx 10$ TeV GRB-like events will be seen by the enlarged array in future. Among them, a cluster consist of dozens of AS events may be found, so that we can have much higher singnificance and get its fine time profile, its relative open angle distribution etc., to steadily establish it and make sure if it's the high energy part of a corresponding CGRO Gamma-ray burst. If so, that will be very attractive for its high energy and therefore its unlikely cosmic origin.

(5) After the $80m^2$ emulsion chambers be combined with the array in 1996, the element composition of cosmic ray can be studied by the combination of both Gamma-family paramenters and the paramenters of its parent air shower. With the dynamic range of the density channels of the array be improved correspondingly, the precision character of high altitude experiment will manifest itself in the fine measurement of the cosmic ray primary energy spectrum around the "knee" region.

(6) The experience from the common effort of last decade and the success of WIPPLE and EGRET tips us that, while enlarge the array to raise the observation sensitivity, find a effective way (better than Muon-cut) to greatly increase the signal-noise ratio and decrease the energy threshold of detection, is the key matter to break the quiet status on the ground based source search and effectively avoid the fatal absorption of Gamma-ray from AGNs by cosmic photon field. Water Cherenkov pool and/or compact detector array may become a choise. A suitable and well tested device be used in YBJ level, its effectiveness will be greatly enhanced and we can expect the combination of advanced technique and the advantages of YBJ site will enable us to approach that goal.

References


[22] F.W.Stecker et al., APJ., 214(1977)L51
Fig. 1. Schematic layout of the scintillation detectors in the Tibet air shower array. Closed squares stand for the FT-detectors. Big squares stand for 0.5m² detectors, small squares stand for 0.25m² detectors.

Fig. 2. The energy response of Yangbajing Array. N is the counts of AS event; $\Sigma \rho_{FT}$ is the Sum of particle density measured by all FT detectors.
Fig. 1. — Contour map of the weights of deficit event densities around the Moon in the area of 4° × 4° centered on the Moon (dotted circle). The contour lines are drawn from a level of no deficit, 0 e, with a step of 1 e.

Fig. 2. — Most probable positions of the shadow center for each case of the toward and away sectors in the IMF, respectively. The center of the shadow for all events is shown by "P" and "O" denotes the apparent center of the Sun.

Fig. 3. — (a) Contour map of the weights of the event densities around the Sun, as shown in Fig. 1, for all showers. (b) Same as (a), but for showers with $\sum \rho_{\nu} > 100$.
Fig. 7. Experimental results for the Crab Nebula. Marks in figure are follows: (D) DURHAM, (W) Whipple, (T) Tibet AS7, (C) CYGNUS, (H) HEGRA, (F) Fly's Eye II, (U) UMC, (U*) UMC's muon-poor data, (E) EAS-TOP. Dotted and Dashed lines show spectra calculated by Cheng et al. [4] and De Jager and Harding [5], respectively.

Fig. 8. Experimental results of gamma-ray flux for Cygnus X-3. Marks in figure are follows: (T) Tibet AS7, (C) CYGNUS, (H) HEGRA, (F) Fly's Eye II, (U) UMC, (U*) UMC's muon-poor data, (E) EAS-TOP, (K) Kiel. Dotted line shows spectrum calculated by Hillas assuming luminosity of $10^{39}$ erg s$^{-1}$ for $10^{17}$ eV monoenergetic proton accelerator [63].
Experimental results for Hercules X-1. Marks in figure are follows: (T) Tibet ASγ, (C) CYGNUS, (II) HEGRA, (F) Fly's Eye II, (U) UMC, (U*) UMC's muon-poor data, (E) EAS-TOP. Dashed line is only eye guide of $E^{-1}$.

Fig. 9. Observed $\gamma$-ray fluxes for PSR 1957+20 by Ptchefstroom and flux upper limits given by Air Shower experiments (T: Tibet; H: HEGRA; C: CYGNUS; KGF: Kolar Gold Field)

Fig. 10.
Fig. 11a. The Rayleigh Power distribution for daily event number arriving from Her X-1 direction.

Fig. 11b. The Light curve for May 23, 1991 sporadic emission of Her X-1 pulsar, when the period \( p=1.235637 \) sec. be used.

Fig. 11c. The light curve for June 20, 1991 sporadic emission of Her X-1 pulsar, when the period \( p=1.235637 \) sec. be used.

Fig. 11d. Comparison of the UHE \( \gamma \)-ray emission periods of Her X-1 pulsar, measured by several groups over last 10 years.
Fig. 12. Observed γ-ray fluxes for Markarian 421 and flux upper limits obtained from this experiment (T), CYGNUS and CASA-MIA. The flux extrapolation is based on a simple power-law assumption with the index -1.06 in the integral form.

Fig. 13. Tibet II-c Array (36,900 m²)
THE MILAGRO GAMMA RAY OBSERVATORY:

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Representing The MILAGRO Collaboration


Abstract

Milagro will be the first water-Cherenkov detector specifically built to study extensive air showers. It is being built in an existing man-made pond 60m x 80m by 8m, located in the Jemez mountains near Los Alamos, NM. Unlike conventional air shower detectors, which sample less than 1% of the particles which reach detector level, MILAGRO will be totally sensitive to the electrons, photons, hadrons, and muons in the air shower. The threshold of the MILAGRO detector is comparable to atmospheric Cherenkov detectors, however it has several advantages over these optical detectors. MILAGRO is operational 24 hours a day in all weather conditions and it has an open aperture which allows it to view the entire northern sky every day. These capabilities allow for a systematic all-sky survey to be done for the first time at these energies. MILAGRO will measure the Crab spectrum with high significance. In addition, it will detect and measure the spectra from AGN's such as MRK 421. MILAGRO will be the first VHE detector capable of recording Gamma Ray Bursts at energies above 250 GeV. MILAGRO will search for point sources of VHE gamma radiation, both steady and episodic. The physics merits of this detector together with its design and current status are discussed.

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1 Introduction

Non-thermal high energy gamma ray emission can originate from acceleration or nuclear collisions of cosmic rays of high energy. They can come from synchrotron or curvature radiation in very strong magnetic fields ($B \sim 10^{12}$ gauss), inverse Compton scattering of electrons on ambient photon fields, electron bremsstrahlung, electron-positron annihilation or pi-zero production in nuclear collisions. The power law spectra of progenitors give rise to power law spectra for emitted gamma rays. The problem of origin, acceleration and propagation of cosmic rays which give rise to gamma rays at high energies is still an unsolved problem. There are many possible sources of cosmic rays, including supernova(SN) explosions, shock acceleration in ISM from SN shocks, stellar wind shocks, Active Galactic Nuclei(AGN) and Fanaroff-Riley class II radio galaxies. Non-thermal gamma rays can also arise from evaporation of Primordial Black Holes(PBH) in their last gasp producing a burst of 1 to 100 TeV gamma rays in a span of few seconds.

Although gamma rays are undeflected by magnetic fields, they do suffer attenuation due to pair-production processes in collisions with photons either in the source or in their transit from source to the earth. The attenuation length for gamma rays in transit as a function of their energy is shown in Figure 1, which shows that only at energies below 100 TeV one can observe sources beyond 10 Mpc.

Observation of gamma ray sources in the TeV and PeV energy ranges is, therefore, important for understanding the origin of cosmic rays and the nature of the accelerators of cosmic rays. They may shed light on whether Gamma Ray Bursters(GRB) are galactic or cosmological and on the rate of evaporating PBHs. If gamma rays are produced in nuclear collisions they should also give rise to high energy neutrinos for which currently large telescopes are being built, such as AMANDA and DUMAND.

In this paper, I shall give a brief account of current status of TeV and PeV observations and then discuss the prospects of the future with special reference to the capabilities of a new water Cherenkov detector, MILAGRO, currently being built at 8700 feet in New Mexico.

2 Features of High Energy Gamma ray emission

The Compton Gamma Ray Observatory(CGRO) has observed gamma ray emission from various sources from Mevs to 10s of GeV, including that from the Crab, from Geminga, from GRBs and from AGNs. Two general features of gamma ray emission can be discerned from their data: (1) Many of the observed spectra are non-thermal and hard, with differential spectral indices near -2 and (2) the intensity is variable over periods from hours to days. This indicates existence of particle acceleration
mechanisms that are efficient and emission regions which are small. Some of the observed spectra by the EGRET instrument extend up to 10 GeV and for GRBs the burst duration for high energy emission is longer than that for lower energies. The sensitivity range of CGRO makes it difficult to answer whether these spectra continue to higher energies. It is of great interest to find out if emission extends to higher energies. If it does then one can put constraints on models of production of gamma rays, understand better the nature of particle acceleration and even estimate the distance to sources based upon attenuation consideration implied by Figure 1.

UHE gamma ray astronomy started with a bang starting with reports of observation of signals from:

- Cygnus X-3, covering a period from late 70s to middle 80s [1,2,3,4,5,6,7,8,9].
- Vela X-1 and LMC X-4 in the southern hemisphere, in the early 80s[10].

This was followed by the observations of:

- Episodic emission from Hercules X-1 in 1986[11,12,13]
- Episodic emission from the Crab in 1989 [17,18,19] and pulsed emission in the 1984-88 period by Ooty[20]
Figure 2: The current results for steady emission from the Crab in the TeV/PeV energy range. The differences between the spectra measured by different techniques indicate the need of independent determination of the spectrum by new techniques such as the water cherenkov telescope Milagro.

- Steady emission from the Crab was observed by the Whipple and the Themistocle experiments\[15,16\] A summary of results for steady emission from the Crab are shown in Figure 2, which indicates the spread in flux values determined by different air-Cherenkov experiments.

Typical intensity observed by the Kiel, Haverrah Park and the Ooty experiments above $10^{15}$ eV were as large as $\sim 10^{-14} cm^{-2}s^{-1}$ to $\sim 10^{-13} cm^{-2}s^{-1}$. These signals were not compelling like the $18\sigma$ observation of the steady Crab by the Whipple group, although the UHE signals appeared to show correlations with source periods. The observed fluxes implied high intrinsic luminosities for the parent particle beams of the order of $10^{38}$ ergs/sec, sufficient to provide for the flux of high energy cosmic rays.

These UHE data offered no conclusive evidence that the primaries of the observed showers were conventional gamma rays. The showers observed by Samorsky and Stamm from Cyg X-3[1] had a muon content comparable to that of ordinary cosmic ray showers. The Hercules X-1 burst events, observed by CYGNUS[13], also have a muon content that is anomalously large compared to that expected for gamma ray showers.

After six years of observations with more sensitive telescopes these questions
have not been answered as no steady source of UHE radiation, conventional gamma rays or otherwise, has been observed with compelling statistical significance.

3 MILAGRO

Multi Institution Los Alamos, Gamma-Ray Detector

The field of gamma ray astronomy has been revolutionized by the CGRO and in particular by the EGRET instrument. EGRET has detected high energy gamma rays from about 2 dozen Active Galactic Nuclei (AGN) and from several Gamma Ray Bursters (GRBS). EGRET energy sensitivity extends to about 10 GeV. Many of the observed spectra are hard extending into the GeV range. It is, therefore, of the utmost importance to extend the observation range beyond 10 GeV. Aperture limitations make this difficult for space based instruments. The MILAGRO instrument has been designed to explore the energy range above 100 GeV extending into the UHE range. The MILAGRO telescope will have the capability to observe over 1 sr of the sky, continuously and be sensitive to a wide range of time scales.

3.1 Characteristics of MILAGRO telescope:

3.1.1 Layout

The telescope is based on the technique of using water cherenkov detector of large area, fully sensitive to all components (except neutrinos) of the air shower. Located at high altitude it can detect air showers with energy down to 100 GeV with good efficiency. The detector measures energy flow and samples a large number of particles in the shower front to minimize timing fluctuations. The detector is to use an already existing large covered pond, 60 m by 80 m and 8 m deep, located at Fenton Hill at an altitude of 8600 ft near Los Alamos. It will be instrumented with three layers of fast 8 inch phototubes. The Cherenkov light emitted by electrons and positrons, by pairs produced by photons in water, by muons traversing the detector and by hadrons making cascades will be detected by the layer of phototubes under 1.5 meters of water. A plan view of the Milagro water Cherenkov pond and associated air shower array is shown in Figure 3, also shown is a schematic of the cross section showing the placement of PMTs in the three layers.

3.1.2 Energy sensitivity and Trigger Efficiency

The energy sensitivity of MILAGRO detector is best illustrated by a plot of the effective area as a function of primary energy for three different trigger requirements for two different species of primary particles: protons and gammas. This is shown
Figure 3: MILAGRO experiment at Fenton Hill. The dots are CYGNUS scintillators deployed around the Pond shown in the center.

in Figure 4. With a trigger requirement of 15 tubes the trigger rate is expected to be about 3 KHz. These curves also show a very important feature of MILAGRO at lower energies: The trigger efficiency for low energy protons is at least an order of magnitude smaller than that for gamma rays at energies below 300 GeV.

3.1.3 Angular resolution

The arrival direction is determined by timing. Because of the large number of particles detected per shower, the angular resolution will be $\leq 0.4^\circ$ at 10 TeV, a considerable improvement over present values. Expected angular resolution based upon measurements made with the five pools in CYGNUS array is shown in Figure 5. For large showers (large number of PMT hits) the angular resolution improves to 0.25$^\circ$.

3.1.4 Muon and Hadron detection:

A second layer of phototubes, looking upwards, will be sensitive to not only tails of electromagnetic showers but also to hadrons of high energy near the cores of air showers produced by cosmic ray nuclear primaries. A third layer of PMTs, near the bottom of the reservoir, will count muons in the shower. These tubes are shielded
Figure 4: Effective area of MILAGRO as a function of primary energy. Dashed curves correspond to proton primaries and solid curves to gamma primaries. Three sets are for three different conditions. Lowest for greater or equal to 50 PMT, next for 25 PMT and topmost for 15 PMTs, respectively.

Figure 5: Expected angular resolution a function of illuminated photomultiplier tubes.
from downward coming Cherenkov light by opaque barrier and each tube will have its own 3mx3mx1m diffusing muon cell. The muon layer will provide excellent rejection of hadronic showers at energies above few TeV.

### 3.2 Sensitivity and Physics Capabilities

#### 3.2.1 Point Source Sensitivity:

The ability of MILAGRO to detect a point source depends on both the intensity and the spectrum of the source. The significance of a signal from a source is given by

\[
S = \frac{0.72 \int A_\gamma(E)I(E)dE}{\sqrt{B}} = \frac{\left(\Omega T \int A_p(E)0.1(E_{TeV})^{-2.87}dE\right)^{0.5}}{(\int \int \int)}/B
\]

where we have explicitly inserted the measured proton flux \(5.1 \times 10^{-2} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\) in the denominator. In the above equation \(A_\gamma(E)\) and \(A_p(E)\) are the effective areas of the detectors for gamma rays and protons as a function of primary energy, \(\Omega\) is the solid angle of the source bin, and \(I(E)\) is the source spectrum. The factor 0.72 is the fraction of source events that fall within the optimal angular bin and \(T\) is the observation time on the source. Background rejection of cosmic ray showers by muon detection can be included in the effective areas.

There are two classes of constant sources of interest. The first is a source with a simple power law spectrum and the other class of sources are those with a cutoff in their spectra. The cutoff may be due to the source itself or due to the absorption of gamma rays as they propagate to the earth. Crab can be taken as a representative of the first class and AGNs for the second class, respectively. We discuss, next, MILAGRO sensitivity to the two classes of sources.

#### 3.2.2 The Crab

MILAGRO can distinguish between the different spectra reported by the Air Cherenkov telescope groups, Whipple and Themistocle, shown in Figure 2. If the emission is steady, and if the spectra continue unchanged up to several TeV, then in one year of operation and using a 25 tube trigger condition we should observe 25 \(\sigma\) for the Themistocle spectrum, 11 \(\sigma\) for the Old Whipple spectrum and 7 \(\sigma\) for the New Whipple spectrum. These numbers do not include any rejection of hadronic showers based upon muons or other techniques. If we see the signal without muon rejection and if the signal disappears when we cut on events with muons then it would indicate onset of some significant new physics.
3.2.3 Active Galactic Nuclei

From Figure 1 it is clear that low energy threshold is needed to detect distance sources. In Figure 6 is shown the expected statistical significance of a signal from an AGN in MILAGRO after 1 year of observation versus distance to the AGN. The three curves correspond to the three different trigger requirements of Figure 4. The dot-dash curve is for a 15 PMT trigger, the dashed curve for a 25 PMT trigger and the solid curve for a 50 PMT trigger. The source flux used was $3.6 \times 10^{-11}/E \text{ cm}^{-2}, \text{s}^{-1}, \text{TeV}^{-1}$ where $E$ is in TeV. This roughly five times the flux of Mrk 421 and more typical of the observed AGNs by EGRET. A model for the extra-galactic IR field is used. The effect of a lower trigger threshold trigger is dramatic, MILAGRO with 15 tube trigger can see nearly twice as far as with a 50 PMT trigger.

3.2.4 Sensitivity to Gamma Ray Transients

MILAGRO has very good sensitivity for transients such as those from GRBs or evaporation Primordial Black Holes(PBHs) over a range of time scales from 100 ms to 100 seconds. Assuming a differential spectral index of -2.5 (i.e. $A_0(E(\text{TeV}))^{-2.5}$), Figure 8 shows the sensitivity of MILAGRO as a function of duration of the burst. The y-axis is the differential burst flux ($A_0$ above), that yields a pre-trial probability of $10^{-8}$. This guarantees a significant detection after any trial penalties are assessed.
Figure 7: Sensitivity of MILAGRO as a function of burst duration

(because of poorly determined burst location, the examination of a number of bursts, etc.) For PBHs we present the sensitivity in another way in Figure 9 which shows the maximum distance to an observable evaporating black hole as a function of the zenith angle of the hole. The improvement over the sensitivity of the CYGNUS experiment is also shown.

3.3 Concluding remarks:

We expect the MILAGRO telescope to become operational by end of 1997. With the operation of the MILAGRO instrument we will enter a new era in the study of high energy gamma sources such as AGNs, GRBs and other point sources, opening up a new energy range and providing continuous coverage of the overhead sky.

4 Acknowledgements

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Figure 8: Distance to an observable evaporating PBH as a function of zenith angle of the PBH for MILAGRO as compared to that for CYGNUS

References


Extremely High-Energy Cosmic Rays

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Abstract

The background to recent work on the highest energy cosmic rays is outlined. The likelihood that supernovae accelerate particles to somewhere around $10^{17}$ eV is the starting point for considering the particles of even higher energy. Recently (a) the energy spectra obtained from different experiments in the range $10^{17}$ to $3 \times 10^{19}$ eV have come quite closely into line, showing a "dip" just below $10^{19}$ eV, but (b) most experiments have now reported particles in the energy range 1 to 3 x $10^{20}$ eV , well beyond the cut-off expected for particles from cosmic sources, and (c) the Fly's Eye group has offered a specific data interpretation showing a (presumed extragalactic) proton flux above 3x$10^{18}$ eV taking over from a galactic heavy-nucleus flux below this. The spectral features exist: their interpretation is not yet established, though. The great uncertainty remaining in the source of these energetic particles is underlined. The upsurge of interest in this area is illustrated by the fact that most of the references are to 1993 papers. The proposed 5000 km$^2$ array has several very specific questions to address.

The Energy Spectrum: Background

The most remarkable feature of cosmic rays is the very high energy of the individual particles. The most energetic particle reported to date was probably a proton or light nucleus, of $3 \times 10^{20}$ eV (Bird et al., 1993). This radiation does not arise from a trivial process on a galactic scale, as the energy carried by cosmic rays in interstellar space is comparable to the local density of thermal energy from stars and to the density of kinetic energy of mass motions, but it is extremely difficult for us to see where it originates. Because of the difficulty in observing cosmic-ray sources and of deducing the nature and location of the particle accelerator, particles of extremely high energy have been of especial interest: firstly, their direction of motion should be much less disturbed by interstellar magnetic fields, so that the approximate direction of the sources might become visible; and secondly, the conditions required to accelerate particles to such energies become so extreme that many suggested sites can apparently be ruled out, so that we may be left with very few possibilities to investigate further. But if we are to draw such conclusions from our studies of these extreme particles, we should ask whether they are representative of cosmic rays as a whole.

Figure 1 shows the energy spectrum of cosmic ray particles reaching the Earth. $J(E) dE$ is the number of particles with kinetic energy between $E$ and $E+dE$ arriving on unit area, per unit solid angle of direction, per second. From $10^9$ eV to around $10^{13}$ eV, the radiation has been subdivided into fluxes of individual atomic nuclei (and a small proportion of electrons), and over this range, the spectrum of many of the major nuclei has the form $J(E) \propto E^{-2.6}$, although the protons fall off a little more rapidly, as $E^{-2.75}$. This power-law form of the spectrum dominates the whole energy range, and the most widely believed explanation is that particles gain energy stochastically. If at each time step of an acceleration process, a particle gains on average a fixed
fractional increase in energy, and also a fixed fraction of the particles are lost from the accelerator, such a power-law spectrum results. The simplest model of this was introduced in 1977-8 (e.g. Bell, 1978) and applies to the situation of a shock front advancing supersonically into an ionized interstellar gas, such as at the boundary of a supernova explosion.

![Figure 1.](from Hayashida et al., 1994)

At first sight, the spectrum in Figure 1 appears so smooth and continuous that it is hard to imagine that particles of different energy come from accelerators of different kinds, and hence particles of any energy carry information about the same source. However, the presence of different spectral components, from different sources, might be masked by the highly compressed intensity scale, if all operated by stochastic processes yielding necessarily rather similar spectral forms. Detail is more likely to be seen if the intensity scale is magnified, by plotting the ratio \( J(E) / J_{\text{ref}}(E) \), where \( J_{\text{ref}} \) is a reference spectrum of the simple form \( J_{\text{ref}}(E) = k \cdot E^{-\alpha} \). In Figure 2 (also from Hayashida et al., 1994), \( \alpha \) is taken as 2.75, to match the spectra of protons over...
energies $10^9$ to $10^{13}$ eV. The quantity plotted is thus $E^{2.75} I(E)$. The famous “knee” of the spectrum is here seen clearly, near $5 \times 10^{13}$ eV, where the flux suddenly begins to fall off more rapidly.

From the continuity of the spectrum, it seems that the particles of $10^{17}$ eV and $10^{19}$ eV belong to the same population, probably from the same sources, probably supernovae; but above $10^{19}$ eV we may be observing a separate flux which does not link with that at $10^{17}$ eV, but becomes visible when the “supernova” flux falls off too far to be detectable.

So lessons learned from the most extreme particles may have no relevance to the bulk of the observed cosmic rays. Nevertheless, the observations will strongly constrain this “new” source.

Before concentrating on the extreme energies, let us scan through the rest of the spectrum, as even here the very high energy particles are important.

At the lowest energies the most fully worked-out model for acceleration is that of diffusive acceleration at the shock front where supernova material ploughs through the surrounding gas. If the Mach number is very high, a spectral exponent of 2 (or slightly more) should be generated. A source spectrum of $E^{2.18}$ and a residence time of cosmic rays in the Galaxy of $T_{\text{res}} \propto E^{-0.3}$, as deduced by nuclear spallation, seen by HEAO-3, for example, would result in a suitable spectrum. But the residence time in the Galaxy can hardly continue falling as rapidly as $E^{\frac{3}{2}}$, or the residence time of 20 million years at 1 GeV would have fallen to 20,000 years at $10^{15}$ eV, and 2000 years at $10^{17}$ eV, resulting in a very large flow rate and large anisotropy at these high energies which is not seen. (Even if we suppose that we are specially placed in the galactic disc, near a point of reversal in the direction of leakage, surely a second harmonic, or two-way flow, would be seen.) Biermann (1993a) suggests instead that the residence time varies as $E^{0.18}$, in accordance with scattering by a Kolmogorov spectrum of plasma waves, and that two-stage trapping processes are involved in steepening the spectrum.

In the original model, cosmic rays were to be accelerated where expanding supernova gas collides with the interstellar medium, but this model would have difficulty in accelerating particles to $10^{14}$ eV-per-nucleon or beyond, because of the short lifetime of the shock. (Lagage and Cesarsky, 1983). But the spectrum continues to at least $5 \times 10^{17}$ eV, though with a somewhat larger spectral exponent beyond the knee — and this could result from a re-acceleration process, as pointed out by Axford (1991). But to accelerate particles to this energy in supernova remnants requires a larger magnetic field, to confine the particles well within the remnant, and if shock acceleration is involved, a shock with a lower Mach number would be welcome, to give a steeper spectrum. This may be possible: deduced magnetic fields in supernova remnants are $\sim 400 \mu$gauss, much higher than expected from sweeping up the interstellar medium, and of the magnitude required; and where two gas masses collide, shocks come in pairs if the gas is not too hot, on the inside and outside of the shocked zone. The “reverse” shock is in much hotter material and will indeed have a lower Mach number, so this is an attractive site for the acceleration to above $10^{17}$ eV, if particles accelerated at the outer shock can be made to reach the nearby inner-facing shock. This may involve some stirring-up by fast-moving fragments such as are seen inside Cas-A, for example.

An alternative way to extend the spectrum has again been proposed by Biermann; noting as have several authors that type II supernova explosions will be sweeping into a sphere filled with a wind from the pre-supernova hot star, and suggesting that in many cases this would contain a tightly-wound spiral magnetic field, as in the solar wind, but of several hundred $\mu$gauss. This wind region thus also offers possibilities for acceleration beyond the “knee”. Hence, considering different supernova environments, there may well be two related sources with somewhat different limiting energies and picking up gas of different nuclear composition may be involved. (Stanef, Biermann and Gaisser, 1993, have examined a possible detailed spectrum resulting from some of these processes.)
The next best alternative to supernova shocks as the main accelerators of cosmic rays are the termination shocks of these very powerful stellar winds from very hot stars or groups of stars.

The most puzzling observational feature is the sharpness of the "knee". With nuclei of different charges (and hence different magnetic rigidities at $5 \times 10^{15}$ eV), from a number of explosions into media of different densities, it is hard to see why the knee occurs at such a well-defined energy. The latter point (about densities) may be illusory, if pre-existing winds dominate the scene, but this is a warning that we may have things wrong.

However, we have a very plausible galactic source of particles to somewhere above $10^{17}$ eV. The highly-charged nuclei would be the most energetic ones, being more readily deflected, for a given energy.

What has been learned in recent years about the spectrum above $10^{17}$ eV?

Above $10^{15}$ eV, particles are recorded by means of the extensive air showers that they generate, and although different techniques have been used, the results are in rather good agreement. More recent detector arrays have had larger overall exposure than the pioneering Volcano Ranch array, and have had better energy resolution than the large Sydney array (SUGAR), so the fluxes to compare are those obtained by Haverah Park, Yakutsk, Akeno (arrays of detectors of charged particles reaching the ground) and by the Fly's Eye (which forms optical images of the glowing column of ionization in the air). In the scintillator arrays, the experimenters usually determine the particle density, $\rho_{600}$, at 600 m from the shower axis, from the data, and then have to derive a relationship between $\rho_{600}$ and $E$ (for each zenith angle). The Fly's Eye images can be used to determine the number of charged particles at several points along the shower trajectory, usually encompassing the shower maximum. The area under this curve gives the primary energy. Figure 3 illustrates a shower curve obtained by a single "eye": this is the most energetic particle ever detected.

![Figure 3](image_url)

Watson (1991) compared the spectra obtained in these experiments and discussed possible causes of error. Using a reference spectrum $J_{\text{ref}} = E^{-3.8} \text{ m}^2 \text{sr}^{-1} \text{s}^{-1} \text{eV}^{-1}$, the upper part of the spectrum
Figure 4. Energy spectra: $J(E) / B^3$; A: Akeno/AGASA (quoted by Sommers, 1993); H: Haverah Park, Y: Yakutsk (both as replotted by Bird et al., 1993); F: Fly's Eye stereo data (Bird et al., 1993)
from these 4 experiments has been updated and is shown in Figure 4. The data are taken from plots by Bird et al. (1993: H, Y and F) and Sommers (1993: A). Since this is effectively a plot of $E^3 J(E)$, a 20% error in the determination of $E$ from the data, with no other errors, would displace all points vertically by 40% (in addition to a small shift on the $E$ axis). It can be seen that the different methods of energy calibration are in agreement to better than 20%.

The Fly's Eye spectrum, shown here (from Bird et al., 1993) has recently come into line with the others: all agree that the flux begins to fall off more steeply before $10^{18}$ eV, with a distinct "dip" before $10^{19}$ eV, before a recovery.

The Fly's Eye group has supported a very explicit interpretation of this dip, which they correlate with changes in the composition of the radiation, to suggest that the upper end of the main cosmic-ray spectrum, dominated here by heavy nuclei, ends around this energy, and a less steeply-falling spectrum of protons from another, presumably extra-galactic, source is left as the dominant radiation above 3 EeV (see figures 4F and 7).

Note on nature of the particles at the highest energies:
There is only indirect evidence. The main indicators used so far are...

Depth in the atmosphere at which the shower reaches its maximum. This depends on the number of steps of cascading before the shower particles have their average energies degraded to the critical energy, below which absorption dominates. A primary particle made up of $A$ nucleons generates $A$ subshowers of energy $E/A$: the particles do not have to reduce their energy as much (by a factor $A$) to reach the critical energy as does a proton: fewer steps are required, and the shower maximum is reached earlier. One has to distinguish shower profiles such as those shown in Figure 5 (Stanev, Biermann & Gaisser, 1993). This may be compared with the information available from the experiment, as illustrated in Figure 3.

Figure 5. Showers of same energy due to different primary particles (calculation).

Muon content of the shower. Again, the fewer steps needed for a heavy-nucleus shower to reach critical energy in its hadron cascade (when pions can decay), means that by the time that charged pions have low enough energy to decay to muons and stop cascading, they have not lost so much of the cascade energy to the $\pi^0$ secondaries, and hence to the electron-photon component. For this reason —and also because their electrons have died away more at ground level, from a shower maximum higher up — heavy-nucleus showers have a larger proportion of muons relative to electrons.

Fluctuations in depth of maximum. The depth at which a proton injects most of its energy into secondary particles can fluctuate greatly, by 1-2 mean free paths,
whereas a large primary particle will start the process sooner and then the energy is rarely concentrated in very few particles, so that large fluctuations are unlikely.

**Gamma-ray primaries.** At energies well above $10^{19}$ eV, the Landau-Pomeranchuk-Migdal effect delays the development of their showers. Figure 6 shows examples of individual gamma-ray showers of $10^{21}$ eV, simulated by Mizumoto, 1993. The starting points are artificially zero here, but it is found that at above $10^{20}$ eV the ratio of peak height to area is much reduced.

![Figure 6: gamma-ray showers ($10^{21}$ eV)](image)

Thus the $3 \times 10^{20}$ eV shower observed by the Fly's Eye appears unlikely to be due to a gamma-ray (except of far more extreme energy): it does not have a probable development curve. It is quite consistent with a proton or light nucleus.

Figure 7 shows the depth of maximum, $X_{\text{max}}$, found by the Yakutsk experiment (Dyakonov et al., 1993, using the lateral distribution of Cerenkov light, which is very sensitive to distance from shower maximum), and by the Fly's Eye (Bird et al., 1993, Gaisser et al., 1993), from their optical images of showers. The full lines "p" and "Fe"

![Figure 7:](image)

show the depth of maximum predicted by the detailed KNP-model Monte-Carlo simulation of very high energy hadronic interactions described by Gaisser and co-workers. The simulated shower profiles have been analyzed by the normal experimental
analysis algorithms, so as to be directly comparable with the data. Bird et al. have seen
this as evidence that the cosmic rays are predominantly very heavy nuclei near $10^{17}$ eV,
but that they have become mainly protons above $10^{19}$ eV. They note that this is entirely
consistent with a the flux of a heavy-nucleus galactic component dominating below
$4 \times 10^{17}$ eV but then falling off rapidly at higher energies, and a proton component
becoming dominant above $3 \times 10^{18}$ eV (see Figure 4F). Figure 6 also shows (dotted
lines) the predicted depth of maximum for protons ("p-qgs") and iron nuclei ("Fe-qgs")
quoted by Dyakanov et al. (1993), using a quark-gluon-string model of interactions.
According to this there is less evidence of a change in composition. The "elongation
rate" of the shower — the increase in depth of maximum per decade of energy — is
most important in this interpretation: the lower elongation rate of $\sim 52$ g cm$^{-2}$ in the
newer Bartol models (which is lower than the observed elongation rate of $\sim 70$ g cm$^{-2}$
and hence implies an increase in primary mass) appears to the present author to be
possibly related to the effect of nuclear targets on hadronic, and especially pion,
collisions. Gaisser et al. considered a few different models of ultra high energy
collisions, but did not favour one which gave a large elongation rate. (Sokolsky (1993),
incidentally, warns against too close a comparison of the Fly's Eye and Yakutsk data,
as the experiments have event selection criteria which can bias the distributions of $X_{\text{max}}$
though any such bias is also inserted into the lines "p" and "Fe". However, any such
systematic displacement of these lines does not appear to be large.)

More work is required to test this significant proposal — of a change in
composition of the radiation beginning at about $4 \times 10^{17}$ eV — as the data from other
experiments had not suggested any change in elongation rate at $4 \times 10^{17}$ eV. (The
Yakutsk data are consistent with the old Chacaltaya experiment near $10^{16}$ eV: this
would not allow a deeper $X_{\text{max}}$.)

Another approach to composition of the radiation is through fluctuations in the
depth of maximum (again deduced indirectly). Watson developed some of these
methods at Haverah Park, and has summarised the position (1991). The rms deviation
of $X_{\text{max}}$ appeared to decrease with increasing energy over the range $10^{17}$ to $10^{19}$ eV
(from about 75 to 50 g cm$^{-2}$). The values were large compared with the expectation for
heavy nuclei (about 30 g cm$^{-2}$ for a mixture of oxygen up to iron), but not what would
be expected if the nuclear mass is decreasing over this range. Perhaps there are still
unrecognized factors increasing the apparent scatter at lower energies.

This remains an area where better information is required. The evidence for a transition to
protons at the highest energies is still inadequate and will act as a stimulus to further studies.

Above $10^{19}$ eV: (a) expectations

The shape of the spectrum here is related to the distribution of the sources of ultra-high-
energy cosmic rays for the following reason. If our galaxy generates as many high-energy cosmic
rays as the average galaxy, its contribution should dominate the local flux, because of its
proximity, just as in the optical domain (and perhaps rather more than in that domain, because
cosmic rays remain within the galaxy for a longer time, because they do not follow straight
paths). In this case the particles should be seen to come largely from the direction of the galaxy,
if magnetic gyroradii are tens of kiloparsecs, and this is not evident at the highest energies (more
on this later). On the other hand, if our galaxy is a negligible source of such cosmic rays, and
these are instead generated by special sources spread uniformly through the cosmos, then distant
sources should dominate — or at least, cosmic rays with long travel times, of many Gyr, should
dominate. But in the latter case, the reactions of protons or nuclei with the primeval radiation \((py \rightarrow N\pi, \text{ or } [\text{nucleus A}]\gamma \rightarrow [\text{nucleus A-1}]\pi)\) should occur when the cosmic ray protons or nuclei exceed threshold energies \(\approx 5 \times 10^{19} \text{ eV}\) for protons, or a little higher for iron nuclei, and lower for light nuclei. The time scale for energy loss becomes \(\approx 10^8 \text{ years}\) at a little above \(10^{20} \text{ eV}\), so the bulk of the radiation, from distant sources should be cut out. One further possibility is that the sources are not spread uniformly in space, but are highly clumped, and that the closest source is much nearer than any others, though outside our own galaxy. This might mean a source in our local supercluster of galaxies, at \(\approx 30 \text{ Mpc}\). Figure 8 shows the expected fall-off in the flux of protons from sources at specific distances, due to photopion interactions (from Sommers 1994).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure8.png}
\caption{Evolved Integral Spectra}
\end{figure}

\textbf{(b) observations}

\textit{The upper end of this spectrum has recently been transformed.}

Until a few years ago, the emphasis in several of these experiments had been in seeking the rapid fall-off in flux above \(5 \times 10^{19} \text{ eV}\) predicted by Greisen and by Zatsepin and Kuzmin, and the Yakutsk and Fly's Eye groups in particular had no indication of any particles beyond this point. Particles above \(10^{20} \text{ eV}\) had previously been reported at Volcano Ranch and Haverah Park: very recently, they have also been reported at Yakutsk, AGASA (an extension of Akeno) \((2 \times 10^{20} \text{ eV})\), and Fly's Eye \((3 \times 10^{20} \text{ eV})\). Greisen's question "An end to the cosmic ray spectrum?" (1965) has been clearly answered "No!".

Thus there are now several more energetic particles not shown in the spectra of Figure 4.

Energies above \(10^{20} \text{ eV}\) reported:

<table>
<thead>
<tr>
<th>Arrival direction</th>
<th>R.A.</th>
<th>Dec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcano Ranch: (1.4 \times 10^{20} \text{ eV})</td>
<td>307°</td>
<td>+47°</td>
</tr>
<tr>
<td>Haverah Park: up to (1.6 \times 10^{20} \text{ eV})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yakutsk: (1.5 - 2 \times 10^{20} \text{ eV})</td>
<td>75°</td>
<td>+45°</td>
</tr>
<tr>
<td>AGASA*: (2 \times 10^{20} \text{ eV})</td>
<td>19°</td>
<td>+21°</td>
</tr>
<tr>
<td>Fly's Eye: (3 \times 10^{20} \text{ eV})</td>
<td>86°</td>
<td>+44°</td>
</tr>
</tbody>
</table>

[* Preliminary report at Snowmass meeting, 1994].

If the spectrum extends to \(3 \times 10^{20} \text{ eV}\), it is surprising that there have not been numerous showers observed in the range \(1 - 2 \times 10^{20} \text{ eV}\) on the Yakutsk and Fly's Eye detectors, although the
collecting area is not independent of energy. Hence it is possible that (a) there might be a new component above \(10^{20}\) eV, distinct from that seen in the range \(3 \times 10^{18}\) eV to \(10^{20}\) eV, or (b) if the particles are indeed not trapped and isotropized, the flux from individual sources and at different Larmor radii might be very patchy.

**Constraints on a possible accelerator at extreme energies**

Almost all proposed processes involve energy gain from an electric field due to a changing magnetic field. While gaining energy, the charged particle gyrates in the magnetic field, and the size of the region where the energy gain takes place must be large enough to contain these gyrations. It turns out that the size \(L\) of this region must exceed the diameter of the gyro-orbit by at least a factor \((c/v)\), where \(v\) is the velocity of the plasma giving rise to the induced fields and hence the acceleration (Hillas, 1984). In a field \(B_{\muG}\) microgauss, a particle of charge \(Ze\) and energy \(E_{14}\) EeV has a gyro-radius of \(r_2 = 1.08 \times E_{14}/ZB_{\muG}\) kpc, so the size requirement may be written \(B_{\muG}L_{kpc} > 2E_{14}(c/v)/Z\).

As an example, consider the "hot-spots" in an active radio galaxy, considered as one of the few conceivable sites where particles might attain the most extreme energies. The most rapid acceleration might occur if the beam of matter flowing from the galactic nucleus loses much of its kinetic energy at a shock, and if the magnetic field carried by the beam is at a large angle to the shock normal. The most effective energy gain occurs if the point of intersection of a magnetic field line with the shock front travels along the field line at nearly the speed of light. This might correspond to a bulk speed of the inflowing plasma of \(v \approx 0.1c\), which is quite reasonable for such a jet. A particle gyrating around the field line, and approaching the shock, may be reflected back from the shock (on encountering the increased magnetic field behind the shock) with much increased energy (perhaps by a factor \(-4\)). The particle may then be scattered back towards the front, where it may again be reflected or transmitted. A power-law spectrum of particles is built up. In the process of reflection, the particle makes many loops through the shock front, drifting sideways and backwards, whilst gaining energy and being eventually reflected or transmitted, and to gain energy \(\Delta E\) it is displaced by a distance \(D = \Delta E / ZvB\), where \(v\) is the plasma velocity and \(B\) is the (upstream) magnetic field strength. \(vB\) is the strength of the electric field seen in the "laboratory" frame as the electric field is zero in the plasma frame. Rewriting in terms of the astrophysical units used earlier, one finds that the field must extend over a region \(L\) as quoted before, in order to accommodate this drift. (There can be an even larger motion in a direction parallel to \(B\).) This is an ideal situation: if the field does not remain at the optimum angle to the shock all the way across the region, a smaller energy gain is achieved in a given space. Thus with a field strength of 100 \(\muG\) upstream (and 4-5 times this downstream, to agree with typical fields deduced from synchrotron radiation), to reach \(2 \times 10^{20}\) eV with \(Z=1\) (proton), with \(v \approx 0.1c\), one requires a space \(L > 2 \times 200 \times 10/100 = 40\) kpc even before allowing for space needed to scatter the particle back to the front. This is about 20 times the size of the larger hot-spots. For an iron nucleus (\(Z = 26\)), the lower limit would be 1.5 kpc, which seems unlikely to fit but might not be obviously impossible. If one were to consider diffusive shock acceleration in a relativistic flow with fields parallel to the shock normal (cf Rachen & Biermann, 1993), the lateral displacement may be somewhat less, but one requires a long working distance parallel to the flow. The fields are large, though, and evidently carried out by the plasma, so a parallel field seems unlikely. That radio hot-spots are relevant to such acceleration is cast into doubt by a recent paper from Harris, Carilli and Perley (1994), who cite evidence from X-ray emission from Cygnus A that the hot-spots accelerate electrons but not protons. Again this evidence is not yet conclusive, though.

Since it is so hard to find a place to site an accelerator, one should mention two different mechanisms that have been proposed. A remote possibility but a very intriguing one, is the decay of topological defects in space (massive strings) into super-massive particles which then decay into very energetic hadrons. In this case, we do not expect to find complex nuclei at the highest
energies: protons and gamma-rays would dominate. The gravitational glitch in space, which one might hope to have seen, would have disappeared before the particles were observed. And Colgate had an old suggestion that a dense shell of relativistically moving plasma, ejected from a supernova, may gain a bulk speed corresponding to particle energies up to $10^{21} \text{ eV}$ through internal pressure! This would offer the whole cosmic ray spectrum from one source (but it is hard to see how the inter-particle forces act successfully up to these energies).

Directions of arrival

This line of investigation has been disappointing. There is no really clear evidence of anisotropy where the showers are numerous. Some evidence of a larger flux from directions at low galactic latitudes exists within half a decade either side of $10^{19} \text{ eV}$ (see Watson, 1991), as had been suggested by Wdowczyk and Wolfendale (1984). This is a rather late onset of the effect to fit in with the Fly's Eye interpretation of figures 4F and 6.

At the highest energies, if the particles are indeed protons, magnetic deflections over tens of kiloparsecs should be rather small, and there is some sense in looking for specific sources. Chi and Wolfendale (e.g. 1991) have made the interesting suggestion that the most energetic particles will point very nearly to sources, and that their directions tend to be surrounded by a cluster of somewhat less energetic (and hence more deflected) particles. These clusters are not statistically very convincing according to Watson et al., so we need more data to decide on this. However, the three most energetic particles (Fly's Eye, AGASA, Yakutsk) tabulated above have been reported since the study of Chi et al., they are seen to arrive from directions very close to two pairs of these "clusters". See Figure 9, where these three directions have been added (points marked A, F, Y) to the sky map showing clusters of Chi et al. (1991):

![Sky map showing clusters of Chi et al.](image)

This may perhaps indicate that magnetic deflections in galactic/intergalactic space are small. But Elbert and Sommers have remarked on the absence of plausible active objects anywhere near the direction of the $3 \times 10^{20} \text{ eV}$ event. But does the concentration of the above clusters near the galactic plane mean that the sources are very close by, in our own galaxy—peculiar pulsars?

So we still have a puzzle at the highest energy—an invisible source. Is it now extinct?—a decayed massive string perhaps, or a radio galaxy that has shut off remarkably soon—or are the particles after all galactic once again?
Prospects for the future

Cronin has actively stimulated design studies for 5000 km² arrays capable of surveying the whole sky with high statistics on particles above $10^{19}$ eV. This could show whether there is a cosmic Greisen-Zetsepin-Kuzmin drop followed by another more local component. The directions of arrival could also be very well charted. The fluctuations in the depth-of-maximum could also be studied at these extreme energies, with the right instrumentation, as a further check on the nuclear mass of the particles.

We still have no widely accepted source for a large part of the cosmic-ray energy domain, but there are very specific interpretations to test, and the stage is set for the operation of a very big array.

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STUDIES OF HIGH ENRGY COSMIC RAYS AT HIGH ALTITUDE

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We have continued high energy cosmic ray experiments in Tibet with Chinese scientists since 1980. Tibet is an excellent experimental site for studying high energy cosmic rays because the atmospheric depth of Tibet altitude is close to the maximum development of air showers with energies around $10^{14}$-$10^{17}$ eV. This enables us to observe high energy families of energies more than 100 TeV with high quality using emulsion chamber (EC), and to detect air showers with energies around 10 TeV with no serious bias as well. Based on such situation, the first collaboration experiment between Japan and China has started from 1980 by exposing a joint emulsion chamber of area $15 \text{ m}^2$ at Mt. Kanbala (5500 m above sea level) and continued its exposure until 1989 with a great success [1,2,3,4]. The main objective at that time was to understand hadronic interactions at ultra-high energy region over $10^{15}$ eV, inaccessible with big accelerators. A series of emulsion chamber exposures reached more than 1000 m$^2$·year in total, and we have detected more than 100 families with energies higher than 200 TeV. From this experiment, a lot of interesting results have been derived on the hadronic interactions as well as primary cosmic ray composition at energies around $10^{15}$ eV.

New collaboration experiment has also started in 1990 at Yangbajing (4300 m a.s.l.) to search for 10 TeV gamma-ray emission from point sources such as the Crab Nebula, Cygnus X-3, and so on [5,6,7,8]. This experiment has been successfully continued until now with fruitful results, and its scale will be further extended from this year. I will briefly review these experiments here.

A. EMULSION CHAMBER EXPERIMENT AT MT. KANBALA

A-1. Emulsion Chamber and Families

In the early 1980s, there were many discussions and suggestions on the change of hadronic interactions at energies around $10^{15}$ eV, so the aim of large-scale emulsion chamber experiment at Mt. Kanbala was naturally focused on these studies through the observation of ultra-high energy cosmic ray phenomena. Among cosmic ray experiments done at ultra high energies, only emulsion chamber experiment will provide us a direct information on the hadronic interactions.

Emulsion chamber essentially consists of absorber (lead or iron) plates and photosensitive layers, which are piled up alternatively. Each photosensitive layer contains
high sensitive X-ray films or both of X-ray films and nuclear emulsion plate. In some cases, carbon blocks are inserted between absorber materials to detect hadronic components efficiently. These chambers with an effective area of the order of $100 \text{ m}^2$ are usually exposed for more than 1 year.

These experiments enable us to observe many instances of events called a "family" which is a bundle of high-energy particles originated by a high energy cosmic ray in the atmosphere. High energy particles such as gamma-rays (abbreviation of electromagnetic components) and hadrons, which constitute a family, can be detected with emulsion chamber in the form of cascade showers. When the energy of showers exceeds about 1 TeV, cascade development is recorded as a series of black spots on the X-ray films ranging over several layers in the emulsion chamber. The energy of each shower is easily estimated by measuring the change of optical density of shower spots and by comparing it with a calculation based on the cascade theory. The overall accuracy of energy determination is estimated to be about 20% around several TeV of shower energy.

A family is easily identified by confirming that the showers of family members are parallel to each other. Cascade showers in each family are statistically classified into two groups: gamma-rays and hadrons. In general gamma-rays are defined as showers with starting depth less than 6 cu, but with no accompanying successive interactions in the chamber, and others are treated as hadrons. Then, families are also divided into two classes, i.e., "gamma-families" and "hadron families". The former is composed of only gamma-rays and the latter of both gamma-rays and hadrons.

As an example we show a density map of showers, at the depth of 12 cu in EC, in the family with $\Sigma E = 2200 \text{ TeV}$, observed at Mt. Kanbala, in Fig.1.
The study of these families is the key subject of emulsion chamber experiment at mountain altitude.

Shown in Fig. 2, for example, is the distribution of primary particle energies responsible for generating gamma families with $\Sigma E > 500$ TeV at Mt. Kanbala. For protons, its mean value almost corresponds to $10^{16}$ eV, so the study of families in this energy region would bring us information on hadronic interactions at energies around $10^{16}$ eV.

![Fig. 2 Energy distribution of primaries responsible for generating families with $\Sigma E \geq 500$ TeV at Mt. Kanbala.](image)

**A-2. Gross Features of Families**

We have observed a number of high-energy families from the Mt. Kanbala experiment, and these results have also been compared with the data obtained at Mt. Fuji (3700 m), where almost same experiment has been carried out by Japanese scientists [9,10]. Since both the chamber structure and procedure of experiment are very similar to each other, its comparison is very important to get reliable results.

Using the data obtained from both experiments, the behavior of families has been carefully examined in the energy region over 100 TeV, and extensive efforts have been devoted to get new information on hadronic interactions and primary cosmic ray composition around $10^{15}$-$10^{17}$ eV. Therefore, when one interprets their behavior based on some hadronic interaction model, at least following gross characteristics of families must be explained systematically [2,3,4,11].

1. Rapid attenuation of families in the atmosphere, that is, attenuation length $\Lambda_{att} \sim 100-110$ g/cm$^2$.

2. About 10% or more frequency of multi-core families with large lateral spreads in the energy region of $\Sigma E > 100$ TeV.

3. Large fluctuations of the number or energy flow of shower particles and also on lateral spreads.
4. Sizable number and/or fluctuation of hadronic components in the families.

Among those, the intensity of families in the atmosphere is the most sensitive to a change of hadronic interactions or primary composition. The data shows that primary cosmic ray particles dissipate energy very rapidly in the atmosphere. For example, Feynman scaling in the fragmentation region and proton-rich primary are incompatible with 1) and 4). Softening of energy spectrum of produced particles at high energies causes a rapid attenuation of primary particles, but this does not meet with 2) or 3). Until now, several models on hadronic interactions as well as primary composition have been proposed in order to explain these behavior as discussed below.

A-3. Hadronic Interactions and Models

The primary energy region covered in emulsion chamber experiments is higher than several times $10^{14}$ eV, where neither hadronic interactions nor primary cosmic ray composition are definitely known. Of course, although QCD is most favorite theory to describe hadronic interactions at high energy, multiple particle production is too complicated to calculate or formulate its process correctly. Hence, phenomenological models are adopted to interpret experimental data and some free parameters or quantities inherently involved in it are adjusted so as to agree with the data. In particular inelastic cross sections, particle production spectrum in collisions (for example, validity of Feynman scaling in the fragmentation region) and also inelasticity coefficient of projectile particles, all of which are rather difficult to evaluate in terms of conventional theoretical model, are most sensitive to interpret the family phenomena.

Adding to this, since statistical fluctuations in the interaction processes, together with experimental bias, deform the family phenomena observed considerably, a Monte Carlo simulation is indispensable to get reliable conclusions from experimental data.

The Fuji and Kanbala collaborations have done extensive Monte Carlo simulations to get reliable information on the hadronic interactions as well as the primary cosmic ray composition at energies higher than $10^{15}$ eV, comparing with the experimental data. These results have already been published elsewhere [2,3,4], so the following is a brief summary.

A-4. Result and Implication

The main results on the hadronic interactions obtained from our experiments are as follows,

1. Feynman scaling in the fragmentation region is approximately valid at least up to the energies around $10^{16}$ ev or more.

2. Inelastic cross sections continue to increase with energy as $\sigma_{in}(p\text{-}air) = 290 (E_0/1TeV)^{0.5} \text{ mb}$, where $\delta$ is estimated to be 0.05-0.06.

3. Particle production with high transverse momentum is within the scope of QCD prediction.
4. No Centauro-type event and other exotic event have been observed in our experiments. This will contradict with other experiments at Mts. Chacaltaya and Pamir [12].

That is, gross features of family events observed with this experiment are wholly compatible with those expected by ordinary interaction model which is smoothly extrapolated from the accelerator region in energy, based on QCD.

On the basis of these results, it is possible to estimate the primary proton spectrum in the energy region around the knee.

![Energy spectrum of protons estimated from the emulsion chamber experiments.](image)

This is due to the fact that the observed flux of high energy families is very sensitive to the protons in the primary cosmic rays. For example, even if we assume a heavy-enriched primary, more than 70% of families are shown to be generated by the collisions of protons. That is, the ambiguity due to the contribution from the nuclei with $Z \geq 2$ can be kept below 30% at the maximum estimate. With the aid of detailed Monte Carlo simulations, it is possible to estimate the primary proton spectrum in the energy region around the knee.
Carlo simulation, we have estimated the energy spectrum of protons around the energy region. The result obtained is shown in Figs. 3 and 4 [13].

A remarkable point is that the energy spectrum estimated indicates a break at energies around 100 TeV, resulting in a heavy enriched primary composition around the knee energy region. The total cosmic ray spectrum recently obtained by the Tibet air shower array [14] is also shown in Fig. 5. Our total spectrum seems to connect smoothly to the direct observations at lower energies [15,16].

![Figure 5](image_url)

**Fig. 5** Energy spectrum of total cosmic rays estimated from the Tibet air shower experiment is compared with other experiments.

In comparison with these results, the fraction of protons to the total is estimated to be 15-20% at energies around $10^{15}$ eV. It is also stressed that neither a flattering of the proton spectrum around $10^{14}$ eV nor a hump around $10^{15}$ eV is inferred from this result. The recent JACEE data [16] seem to support our estimation, and also the new Fly's Eye result [17] suggests a deficit of protons at the knee energy region.

One of the most promising acceleration models of UHE cosmic rays is a shock acceleration at SNRs, but such accelerations have some difficulty to accelerate particles up to more than $10^{14}$ [18], so other acceleration mechanism will be at work at much higher energies. No scenario, however, to accelerate protons to more than $10^{15}$ eV is yet close to being reliable. Thus, the present result on the proton spectrum will give a constraint to particle acceleration models at UHE region.

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**B. AIR SHOWER EXPERIMENT AT YANGBAJING**

**B-1. Air Shower Experiment to Search for Gamma-Ray Point Sources**

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After finishing the emulsion chamber experiment at Mt. Kanbala, we have started new collaboration experiment at Yangbajing in Tibet (The Tibet AS-γ Collaboration) in 1990. The main objective of this experiment is to search for gamma-ray point sources at 10 TeV energy region, still not explored by any other experiment. The first phase experiment has been successively continued until now, and for the first time obtained important results on the search for gamma-ray point sources at 10 TeV region [5,8], as well as on the shadowing of cosmic rays by the Sun and Moon [6,7]. Furthermore, the observation of air showers at 10 TeV with sufficient accuracy is very important to be able to fill the unexplored energy gap between the TeV region by Cerenkov observations and the PeV region by air shower observations in high-energy gamma-ray astrophysics.

Fig. 6 Gamma-ray fluxes from the Crab Nebula.

Fig. 7 Gamma-ray fluxes from Mrk 421. T: Tibet, C: CYGNUS, CM: CASA-MIA.
At present, unfortunately, no evidence on the emission of gamma rays is found from any source of the Crab Nebula, Cyg X-3, Mrk 421, etc., but our results give the most stringent flux limits on these sources at energies around 10 TeV, as shown in Fig.6 and Fig.7. For example, observation of Mrk 421, the nearest AGN observed at GeV region by EGRET [19], as well as at TeV region by the Whipple Cerenkov telescope [20], is of keen interest to provide an estimate of intergalactic infrared photon density which is much better than direct measurements [21].

Fig. 8 Contour map of the Sun shadow observed with the Tibet air shower array.

The observation of the deflection of the Sun shadow, as shown in Fig.8, is expected to bring us new information on the large-scale structure of the interplanetary and solar magnetic fields and their time variation. The Sun is now in quiet phase, but after several years it becomes active. A time variation of the deflection of the Sun shadow could give us a clue for studying a three-dimensional structure of the solar magnetic field, which has not been achieved by any other method yet.

The present array will be enlarged by a factor of about 4 within this year as shown in Fig.9. The effective detection area of about $10^4$ m$^2$ will be about 8 times larger than the present one. Then, the trigger rate is estimated to be about 200 Hz to detect air showers with energies around 5 TeV. The data taking will be made by use of a FASTBUS-CAMAC system controlled by IBM-PC. The data will be stored in 8mm video tape of a 10 GB capacity.

If the Whipple data are correct and can be extrapolated up to high energies, then the new array can detect a positive signal from this source for several years observation (see Fig.6). Such situation is also same for Mrk 421, which will be more interesting for us as discussed before. Anyway, the new Tibet array has the highest sensitivity among air shower arrays in the world, and will play an important role in the search of
**VHE/UHE gamma-ray point sources.**

![Diagram of Tibet II Array](image)

**Fig. 9** Layout of the new Tibet array.

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**B-2. Hybrid-Experiment of EC and AS Array**

A hybrid experiment of emulsion chamber and air shower array is planned to be carried out at Yangbajing from 1996. In such an experiment, usually emulsion chambers are set up in the central part of air shower array, and burst detectors are put just under the emulsion chambers to get information on the position, size and arrival time of cascade showers induced by high energy gamma-rays or hadrons which are associated with an air shower. Then, the experiments provide simultaneous observation of families and its accompanying air showers. That is, air shower array works to get information on the primary energy as well as the stage of air shower development at the observation level, while emulsion chamber gives information about hadronic interactions and primary composition.

The aim of experiments is almost same as those of emulsion chamber experiments. However, behavior of families is expected to be more refined by adding information on accompanying air showers. For example, air shower information is very helpful when one observes some peculiar event in emulsion chamber. One of the advantages in doing this experiment is that the primary energy generating both of air showers and families can be uniquely estimated by measuring air shower sizes, as shown in Fig.10.

This approximate linear dependence of primary energy $E_0$ on air shower size $N_e$ is examined to be almost independent upon interaction models as well as primary composition at $10^{15} - 10^{16}$ eV, but weakly depends on the observation level. A conversion factor from $N_e$ to $E_0$ is estimated to be about 2 GeV, taking slightly larger value at
high altitude.

![Graph](image)

Fig. 10 Correlation of the air shower size $N_e$, accompanying a family with $\sum E \geq 30$ TeV, and the primary energy $E_0$ at Yangbajing altitude.

This means that air showers accompanied by families are almost all equal in the stage of shower development at the observation level. Actually the age parameters, when we fit the lateral distribution by a NKG function, distribute in the narrow region between 0.6 and 0.7. A small-scale experiment was done at Mt. Norikura in 1980s [13,22] and the energy spectrum of protons was for the first time obtained in the knee energy region, as shown in Fig.4. Of course, its statistics is still not enough, but the result is very promising.

In 1996, we will set up a hybrid detector of emulsion chamber and burst detector with about 100 m$^2$ in the center of the new Tibet array. The thickness of emulsion chamber is 14 c.u. to detect gamma families with energy higher than about 30 TeV. Two years exposure of this detector will provide the energy spectrum of protons in the energy region between $10^{15}$ and $10^{16}$ eV with the accuracy better than 30 %. Direct measurement of protons in the knee energy region will not be achieved in the very near future because of its extremely low flux, so our result is of considerable importance to understand the origin of the knee.

References

EXTENSIVE AIR SHOWERS AND HIGH ENERGY INTERACTIONS

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Abstract

The most actual problem for the nuclear aspect of cosmic ray physics is now in what field could cosmic rays contribute to our knowledge of high energy interactions. In the study of the primary mass composition at high energies there are some problems, which could be referred to properties of AA-interactions. In this light the probability to find some additional electromagnetic energy losses in high energy AA-collisions is discussed. The other highlight problem is the behaviour of the inelasticity at high energies. The need to incorporate the study of the EAS longitudinal development complementary to the multivariate analysis of EAS on the observation level is emphasized.

There is a wide spread opinion that the nuclear aspect of cosmic ray physics is now dead due to the successful offensive of accelerators. I am not going to disprove it, since regard myself as its supporter. Nevertheless, there are some questions in my mind, which don’t let me to become the complete, 100% supporter. As for me I prefer instead of the word "dead" to use another word "the death-bed", which gives the sick person a chance to recover.

In this point I think that the Organizing Committee was completely right inviting me to give the talk on "Extensive Air Showers and High Energy Interactions". Doubts of the potential opponent are usually more valuable, than claims of the passionate supporter. Besides that if the Organizing Committee didn’t suggest me to give this invited talk, I never had an opportunity to see such an original and beautiful region of the world like Tibet. I thank all the members of the Organizing Committee with all my heart.

Now I’ll tell you about these doubts. First of all, I should like to draw your attention to the observation, which seems to me relates to the subject of this talk. My favourite problem during a few latest years is the mass composition of cosmic rays, because it
has the straightforward relevance to the cosmic ray origin. I spent some efforts to study it, especially in the "knee" region. Because direct measurements of the mass composition didn't reach this energy domain, we study it by means of EAS. The methods applied are based on the difference in the development of atmospheric cascades, induced by different primary nuclei. At the fixed primary energy $E_0$ heavier nuclei of the mass $A$ have less value of the energy per nucleon $E_0/A$. At the same rate of the energy loss they produce pions and kaons of lesser energies. Their electromagnetic cascades develop and attenuate faster, than similar cascades of proton induced showers. Similarly, lower energy pions and kaons decay more often and give more muons. If the showers are observed beyond the maximum of their development, then nuclei induced showers of the same energy have more muons and less electrons, than the average shower. On the contrary, proton induced showers have less muons and more electrons. So if we select showers by their total electron number $N_e$, we select preferentially proton induced showers. The selection of EAS by their total muon number $N_\mu$ gives an advantage to nuclei induced showers.

The mass composition of cosmic rays is usually studied by the analysis of EAS $N_e$ and $N_\mu$ distributions. The shape of experimental $N_\mu(e)$ distribution of showers, selected in the fixed interval of $N_e(\mu)$, is compared with the theoretical one, obtained by simulations for the superposition of showers induced by different primary nuclei. The best fit partial fractions of such showers give the so called "observed" mass composition. It is the mass composition of particles, which induce EAS, observed at the fixed atmospheric depth and selected by one of their classification parameters. The "observed" mass composition is: a) different from the primary mass composition and b) different for different classification parameters. For example, observed mass composition for $N_e$ - selected showers in the knee region has to be lighter than that for $N_\mu$ - selected showers. After the necessary correction they both should coincide and give the same primary mass composition.
However from the very beginning, when such an cross-check analysis has been made /1/, it was noticed, that the observed mass composition of $N_{\mu}$ - selected showers was not heavier than that of $N_e$ - selected ones. Within the errors they gave the same result. Unfortunately errors of fitting integrated one-dimensional $N_e(\mu)$ histograms by theoretical 5 nuclei group distributions were large. Neither in /1/, nor in our later re-analysis /2/ of the same experimental data we could say anything definite. We preferred just to keep this observation in our minds.

This summer we completed the analysis of the new experimental material, obtained at our Tien-Shan "Hadron" array. Now it was not the analysis of separate one-dimensional histograms, but of the two-dimensional distributions within so called triangle diagrams /3/. This technique is applicable to arrays with the large calorimeter area. By means of this area we measured directly the energy of the electromagnetic $E_{e\gamma}$ and hadron $E_h$ component of the shower. Our underground muon array permitted us to measure the energy $E_\mu$ of the muon component. If we sum up these three energies we obtain the energy of the shower at the observation level $E_{690}$ ( 690 g/cm$^2$ is the depth of our observation level at Tien-Shan ) :

$$E_{e\gamma} + E_\mu + E_h = E_{690}$$  \hspace{1cm} (1)

The energy of neutrinos is not measured and not included into the definition of $E_{690}$. If we divide both parts of the expression (1) by $E_{690}$, we obtain:

$$\delta_{e\gamma} + \delta_\mu + \delta_h = 1$$  \hspace{1cm} (2),

where $\delta_i = E_i/E_{690}$ is the energy fraction, carried by i - component at the observation level. The idea is that each individual shower is indicated as a point inside the equilateral triangle with the height equal to 1. The distances of this point from three sides of the triangle should be equal to energy fractions carried by electromagnetic $\delta_{e\gamma}$, muon $\delta_\mu$ and hadron $\delta_h$ components of the shower at the observation level. We know that in this case sum of $\delta_i$ must be equal to 1.
Observed showers were selected by their electron size $N_e$ and their energy at the observation level $E_{690}$. Because $E_{690}$ is the considerable part of the primary energy $E_0$, we expected that the mass composition derived from this subset of EAS, had to be close to the primary mass composition. It means that it would be heavier than for showers selected by $N_e$.

The result nevertheless was similar to the case when showers were selected by $N_\mu$. Observed mass composition for $E_{690}$ selected showers was not heavier, but close to that for $N_e$ selected showers (Fig.1). I am sure that this similarity is due to the muon component because $E_\mu$ is the essential part of $E_{690}$ ($\delta_\mu = 0.25-0.35$). Hadron component has less influence due to its less magnitude of $\delta_H = 0.16-0.18$.

This surprising observation looks as if nuclei induced showers have less muons than expected from our theoretical models. The deficit of muon-rich showers transforms into a lighter mass composition especially for $N_\mu$ or $E_{690}$ selected showers.

Our observation is confirmed by another set of experiments. Here I mention the analysis of the cosmic ray mass composition, based on high energy electromagnetic and muon components of the
shower. I mean so called gamma-families and underground muon groups. The latest analysis of X-ray emulsion chamber data, obtained at Mt's. Norikura and Fuji in Japan and here in China at Mt. Canbala, favours the heavy primary mass composition /4,5,6/. It follows mostly from the low absolute intensity of gamma-families. Pamir results don't contradict to japan-china conclusions. Their intensities are also low, although they prefer to explain them by the high inelasticity /7,8/. Their upper limit of iron nuclei fraction is relatively high: \( \Delta Fe < (0.24 - 0.32) \) at \( E_0 > 10 \text{ PeV} /9/.

On the contrary, results of the high energy muon data support the so called "light" or normal mass composition. Multiplicity spectra for muon groups, detected at Baksan /10/, NUSEX /11/, KGF /12/, Frejus /13/, MACRO /14/, Homestake /15/, Soudan /16/ arrays agree with a normal primary mass composition at energies of 1 - 10 PeV. As an example, Fig.2 demonstrates the muon multiplicity spectrum of the largest MACRO detector in Gran Sasso, Italy, compared with simulated expectations for the "light" and "heavy" compositions respectively. It is seen, that the conclusion about the "light" composition comes again from the deficit of muon-rich showers.

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Fig.2. High energy muon multiplicity spectrum, obtained in MACRO experiment (full circles), compared with spectra, simulated for light primary mass composition (open squares) and heavy composition (open circles) /14/.
Here I can just suggest some qualitative explanation. It is highly speculative, but could have a relevance to the subject of my talk - high energy interactions in EAS. Suppose, that the iron nucleus $Z_1$ with the energy in the vicinity of the knee encounters the air nucleus $Z_2$. In all our simulation models we examine just the strong interaction of these nuclei. However, it should be mentioned that the electromagnetic interaction during this encounter is also strong: $Z_1 Z_2 \propto 1$, where $\propto$ is the electromagnetic constant. The electric field of the projectile nucleus with $Z_1 = 26$ and the lorentz-factor $\gamma > 10^5$ has the dense virtual photon field, which could be the source of additional bremsstrahlung and electron-positron pairs during its reformation in the head-on collision. So I suppose that high energy nuclei lose their energy not only due to multiple pion and kaon production, but also due to electromagnetic processes (Fig.3). Their partial inelasticity $K_\gamma$ is higher than we usually adopt. This energy loss is highly fluctuating, because the strength of the electromagnetic interaction depends on the impact parameter. Finally, this electromagnetic energy loss has to be via the production of pretty soft bremsstrahlung photons and electron-positron pairs.

What are the consequences of this idea?

* $<K_\gamma>_{AA}$ for high energy AA interactions has to grow with the primary energy, even if $<K_\gamma>_{pA}$ doesn't essentially grow;

* due to the additional electromagnetic energy loss and the soft spectrum of produced electron-positron pairs and bremsstrahlung gamma-quanta, the intensity of EAS in the stratosphere has to increase (Fig.4);
Fig. 4. Longitudinal development of electromagnetic and muon components of the nucleus induced cascade in the ordinary (dotted lines) and proposed model with the increased electromagnetic energy loss (full lines).

* at the same time due to the soft spectrum of the electromagnetic component and less energy, preserved for the development of the nuclear cascade, the attenuation of the EAS in the lower part of the atmosphere has to increase. The number of electrons beyond the shower maximum must decrease;

* due to the less energy of the nuclear cascade the number of muons in the shower of the fixed primary energy $E_0$ has to decrease. Respectively, the intensity of muon groups of the fixed multiplicity must also decrease. As regards the composition problem, it would imitate the lighter composition, if analysed by the ordinary models.

* it is difficult to predict, how $N_\mu(N_e)$ - dependence will be modified. It is because in the lower atmosphere both $N_e$ and $N_\mu$ would decrease. However, because the attenuation of $N_e$ is exponential, its decrease is expected to be stronger, than the decrease of $N_\mu$. So $N_\mu(N_e)$ - dependence can become steeper;

* because the entire development of EAS shifts to the upper atmosphere, the $Q/N_e$ - ratio of the amount of Cherenkov light, normalized to the EAS size, should increase for the large showers.
It looks usually well in our institute, if the author of the speculative idea indicates himself the possible experiment, which might kill this idea. Of course, the most direct experiment is the observation of interactions of PeV nuclei with the high Z in the emulsions. There is a hope that the GOAL program of LDBF - long duration balloon flights will be able to look into this energy region /17/. Also RHIC - relativistic heavy ion collider will give an opportunity to check the energy balance among secondaries produced in high energy AA - collisions /18/ It is desirable to select for this purpose central collisions with the small impact parameter. I should like to mention that JACEE - collaboration which studied the interactions of TeV - nuclei with emulsions noticed the surprisingly large amount of electron-positron pairs, produced by soft photons in the close proximity of the vertex /19/ ( Fig.5 ).

![Fig.5. Number of electron-positron pairs as the function of distance from the interaction vertex in high energy JACEE events /19/.](image)

Usually the defence of the nuclear aspect of cosmic rays is based on the statement that they are complementary to accelerator studies. They can study the so called fragmentation region of the secondaries inclusive spectra ( Fig.6 ). In contrast, for example, at the future LHC secondaries with \( x > 0.1 \) won't escape the vacuum tube of the collider and cannot be studied nearer than hundreds of
m from the interaction point. FAD - the project of the full acceptance detector for the former SSC is an example of such a hard attempt /20/. Colliders are mostly adjusted for the study of the central region of inclusive spectra.

![Inclusive rapidity spectrum of secondaries. Central and fragmentation regions studied at colliders and in cosmic rays, are marked by light and dense hatching respectively.](image)

This statement is true, though the cosmic ray study of the fragmentation region at high energies is also extremely difficult. All the variations of the spectra at high energies are masked by multiple production processes at lower energies. As a proof of this difficulty I can remind that even such a general and fundamental characteristic of the high energy interaction, as the inelasticity, which is dominated by fragmentation particles, is still discussed /21/. As for myself, I prefer the large and slowly rising inelasticity. However I am not sure, that if the Minijet model is indeed correct, that there is no gluon spectators and the scattered constituent quark as a dressed quark doesn't preserve its former gluon environment after the collision. In this case the inelasticity, being large at moderate energies, could begin decreasing. It is due to that the projectile hadron interacts with progressively lower x - partons and can preserve the larger part of its initial energy. It will carry this energy down the atmosphere and release it closer to the observation level.

In this connection I should like to mention the recent result obtained at Tien-Shan /22/. It relates to the flattening of the EAS
size spectrum at $N_e > 10^8$ (Fig. 7).

![Graph showing size spectrum of EAS at Tien-Shan](image)

Fig. 7. The size spectrum of EAS, observed at Tien-Shan /22/. The effect is too strong to be explained by increasing fluctuations of the EAS development before the maximum. An increasing contribution of extragalactic protons wouldn't give such a strong increase of the intensity too, because the difference between iron and proton induced showers shouldn't be very big at this energies in the framework of conventional models. Besides that the increasing contribution of protons in the primary flux should be seen as the similar flattening at other altitudes in the atmosphere: for larger EAS at higher and for smaller EAS - at lower altitudes. In fact, observations indicate just the opposite picture: high intensity and the flat size spectrum of EAS at $N_e > 10^6$ in the stratosphere and the flattening at $N_e > 10^9$ at the sea level. Most of the showers in the excess observed at Tien-Shan are very young. It means that the bulk of the energy is indeed released close to the observation level. Could it be due to the decreasing inelasticity or it is the indication of the increasing role of charmed particles with the high $x$ in the fragmentation region, which carry their energy down the atmosphere and release it there by the decay? In both explanations we refer to the fragmentation region of secondaries spectra.
I mentioned here some effects, which could have the relation to the nuclear aspect of cosmic ray physics, but it is not easy to prove this relation. It seems to me that, following R. Kolb terminology, "to take the smell" of high energy interactions in the conditions of the large background of "lower energy pollution", we must find the way out from the two-dimensional picture of the shower. Complementary to the multivariate analysis of the individual shower at the observation level, we have to study its longitudinal development. Cherenkov and fluorescent light give us such an opportunity, but it is not enough. With their help we can study the longitudinal development of only the electromagnetic part, but unfortunately with a low efficiency due to the short duty cycle. I think we must try to develop so called TTC (track and time complementarity) - methods to study the longitudinal development of the muon component /23,24/. They are based on the same idea as the well known Fly's Eye experiment. However they use not optical photons, but another penetrating particles - muons as carriers of the information on the shower history. Using tracking and timing of muons it is principally possible to reconstruct their birth points in the atmosphere. Thus the development of the nuclear cascade could be "smelled" with no mediation of electromagnetic cascades with their intrinsic fluctuations. GeV muons are produced in average in the higher atmosphere than Cherenkov photons. Therefore, they are more sensitive to upper parts of atmospheric cascades, to the rate of the energy loss there and so, to the properties of high energy interactions. It is clear, that with TTC detectors you can work all along the day, so your duty cycle is not restricted by the night time and the good weather.

To conclude my talk I should say that we have to work a lot of, in order not to let our sick person die, but on the opposite, in terms of R. Moudi, to give him "life beyond the life".
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3. Conclusion

   The IHEP (Institute of High Energy Physics) of CAS (Chinese Academy of Sciences), founded in 1973, is a comprehensive research institute. Among its various scientific research fields, IHEP mainly devotes to high energy experimental physics on BEPC/BES.

   1). The BEPC

   BEPC (Beijing Electron Positron Collider), the first HEP experimental base in China, was constructed during the years from 1984 to 1988. It mainly consists of a linac and a storage ring. Around the ring, there are synchrotron radiation facilities. BES (Beijing Spectrometer) is the single detector on the interaction point of the collider.

   BEPC Parameters:
$E_{cm} = 3 - 5.6$ GeV
Peak Luminosity = $6 \times 10^{30}/cm^2/s$ (at $E_{cm}=4$GeV)

The BEPC runs about 5000 hours per year. Among them, about 2500 hours are used for BES physics experiments, and about 1000 hours for the synchrotron radiation facility running in the dedicated mode. Other hours are for the machine study and linac injection.

The following data have been collected on BEPC/BES:
- $9 \times 10^6 J/\psi$ events,
- $1.4 \times 10^6 \psi'$ events, and
- $22.3 \text{ pb}^{-1}$ (at $E_{cm}=4.03$GeV) $D_s \tau$ data.

The team on BES experimental physics:

There are more than 200 Chinese scientists working on BES. About 150 of them are from IHEP. Others are from about 13 Chinese universities and institutes.

Since the Spring of 1991, about 40 American scientists from 10 institutes and universities of USA have participated the BES collaboration.

From 1994 to early 1996, BEPC is undergoing its upgrade, after which the luminosity will be 3 times as it is now.

2). The Synchrotron Radiation Facility

The BSRF (Beijing Synchrotron Radiation Facility) is around the storage ring of BEPC. It has altogether 7 beam lines and 10 experimental stations. They are topography station, EXAFS (Extensive X-ray Absorb Fine Structure) station, small angle x-ray scaterring station & diffraction station, photoelectron spectrometer station, lithography station, fluorescence analysis station, diffuse scattering station, and others.

BSRF users distributed all of China. There are hundreds of scientists from 56 institutions doing various experiments and interesting results have been obtained.

The research and application subjects are in the field of condensed solid physics, electronics, super-conduct & laser materials, medicine, resource & environment sciences.

3). FEL (Free Electron Laser) Project

Based on a 30 MeV electron linac accelerator, the FEL project in IHEP, a Compton infra-red mode FEL facility made big progress in the past two years. And the stimulated emission was firstly observed in April 1993.

4). The Proton Linac

Another accelerator in IHEP is the BPL (Beijing Proton Linac). Its performance parameters, and the experiment & application on it are as following:
Energy: 35MeV, Current: 60mA, frequency: 12.5MHz and running 4000 hours/year

Experiments and applications:
   a) Low energy nuclear physics experiments (new nuclide 19 Na)
   b) Neutron therapy for cancer
   c) Radio isotope production for hospitals

5). Cosmic Ray Physics and Astrophysics

In China, the research on cosmic ray physics started in 1950’s. Now there are about 70 scientists of IHEP working in the field. In 1960’s, a large cloud chamber was built on the mountain in YunNan Province, the south west China, where a charged, stable particle with its mass > 20 GeV was found in the experiments. After that, an emulsion chamber was built on the Kanbala mountain in Tibet, China. And an EAS (Extensive Air Shower) array and a VHE (Very High Energy) gamma ray astronomy observation station were built in 1980’s, both of them were in the suburb of Beijing. The space high energy astronomy observation loaded on balloon flights and the high energy astrophysics data analysis on computer are also features of IHEP in the field.

What is more, the China-Japan cooperative project on the Yanbajing EAS array, Tibet, has been successfully working for years.

6). Theoretical Physics

About 20 physicists in IHEP devote to the theoretical particle physics. There are also about 20 physicists in IHEP working on the intermediate and high energy nuclear theory.

There are other divisions in IHEP, such as the Nuclear Tech. & Application Division, Computer Center etc. It’s too much to introduce all of them here in detail.

7). International Collaboration

In 1950’s and 60’s, Chinese physicists participated the high energy physics collaboration in Dubna, former Soviet Union. Since 1970’s hundreds of Chinese physicists, as the visiting scholar, were sent to Japan, USA and European countries to work and study. The experience they gained from abroad is very useful and helpful to the construction and running of BEPC & BES. Now IHEP keeps good cooperative relationships with KEK, CERN, SLAC and many other labs and univ in the world.

8). The Future Plan of TCF (Tau-Charm Factory):

The possible construction of TCF in Beijing is now under consideration. The first stage of the project is R & D, which would estimate the challenge from B-Factory to Tau-Charm physics, and research the key technology for
the collider and detector.

The preliminary design of parameters:
Energy : 3 - 5 GeV
Luminosity : \(1 \times 10^{33}/cm^2/s\)
Research field : Tau, Charm and Charmonium physics, the precise research and test of the standard model.

The cost for TCF construction is estimated to be 100 million USDs, which is too much money, if paid only by China. Now some sort of international cooperative project on it is under discussion. The concern and support from world scientific community are welcomed.

Other large scientific projects, such as the third generation of synchrotron radiation light source, are also discussed in China.

2. BES Physics

BES is mainly composed of MDC (Main Drift Chamber), TOF (Time Of Flight), BSC & ESC (Barrel & End-cap Shower Counter), and MUC (Muon Counter).

Its performance parameters are as follows:
MDC momentum resolution: \(\sigma p/p = 1.7\% \sqrt{1 + p^2}\)
MDC dE/dx resolution: 8.5%
TOF time resolution: \(\sigma t = 330\text{ps}\)
BSC energy resolution: \(\sigma E/E = 22\% \sqrt{E}/(GeV)\)
BSC spatial resolution: \(\sigma Z = 3\text{cm}\)
ESC energy resolution: \(\sigma E/E = 2.1\% \sqrt{E}/(GeV)\)
ESC spatial resolution: \(\sigma x = 1.5\text{cm} \ \sigma y = 1.7\text{cm}\)
MUC spatial resolution: \(\sigma \phi = 3\text{cm} \ \sigma Z = 5\text{cm}\)

1). Tau Mass Measurement

There were four experiments measuring \(\tau\) mass from 1978 to 1980. And the PDG (Particle Data Group) book of 1990 gave
\[m_\tau = 1784.1^{+2.7}_{-3.6}\text{ MeV}.
\]

Since precise measurements of \(\tau\) lifetime and its decay branch ratio were available in early 1990’s, the \(\tau\) mass became more important in checking the lepton universality.

Mainly it refers a leptonic coupling constant \(G_\tau\)
\[G_\tau^2 = 192\pi^3 \times Br(\tau \rightarrow e\nu\nu)/(\text{Lifetime}_\tau \times m_\tau^3).
\]

If the leptonic universality is correct, \(G_\tau^2 / G_\mu^2\) should be 1, which however couldn’t be approved by old data.

In late 1991, the \(\tau\) mass was precisely re-measured on BEPC/BES. The procedure of the experiment was a data-driven scan around the energy region
of \( e^+e^- \rightarrow \tau^+\tau^- \) threshold.

The experiment gave a preliminary result of

\[ M_\tau = 1776.9^{+0.3}_{-0.5} \pm 0.2 \text{MeV}, \]

which was based on 14 \( e\mu \) events.

The final result, based on 64 events from more channels, was given as

\[ M_\tau = 1776.96^{+0.18+0.20}_{-0.19-0.16} \text{MeV}, \]

which, along with the corrected \( \tau \) life time from LEP, solved the consistency problem of lepton universality, and gave:

\[ (G_\tau/G_\mu)^2 = 0.9997 \pm 0.0122 \] (comparing the previous value of 0.935).

2). Branch Ratio of \( \psi' \rightarrow \tau^+\tau^- \)

It's again a check of lepton universality. \( \psi' \), with its energy above all of three leptons' pair production, provides unique chance to do the comparison. And the last branch ratio of \( \psi' \rightarrow \tau^+\tau^- \) was firstly measured by BES.

Since the following value calculated from the branch ratio \( B \), lepton mass \( m \) and \( \psi' \) mass \( M \) should be a constant,

\[ B_{h\ell}/(1+4m_\ell^2/M^2)(1-4m_\ell^2/M^2)^{0.5} \]

the branch ratios from \( \psi' \) to \( ee, \mu\mu, \) and \( \tau\tau \) should follow the equation:

\[ B_{\tau\tau}/0.3885 = B_{\mu\mu} = B_{ee} \]

The branch ratio is given by the tau pair event number, subtracting the QED process contribution, then over the \( \psi' \) event number,

\[ B_{\tau\tau} = (N_{\tau\tau} - \sigma_{QED} L)/N_{\psi'} \]

where, the QED cross section of \( ee \rightarrow \tau\tau \) was calculated by theorists, the luminosity was measured by large angle dimuon events, the \( \psi' \) number was collected at its resonance, and the \( \tau\tau \) number was collected on 4 channels, combined with acceptance, efficiency etc. and the weighed average value was above 9000 events.

Finally the branch ratio was given as

\[ Br(\psi' \rightarrow \tau\tau) = (3.69 \pm 0.71 \pm 0.66) \times 10^{-3}. \]

This result is consistent with the above equation.

3). J/\( \psi \) Decay

Motivation

The \( J/\psi \) decay width and branch ratio fractions were mostly measured by fitting the cross section at its resonance region with \( ee, \mu\mu, \) and hadron products. The typical results reflected in PDG 90 values. However MARKIII re-did the work through another channel of \( \psi' \) decay and obtained higher accuracy. There were quite differences between the 1990 old data and 1992 new data. So it seems still interesting to do it on BES in both methods.
For method 1, the following results were given:
5.14 ± 0.38 KeV as the partial width to lepton,
74.9 ± 12.5 KeV as the partial width to hadron,
85.2 ± 13.2 KeV as the total width, and
(6.04±0.50)% as the branch fraction to lepton.

For method 2, the channel is $\psi'$ firstly to $\pi\pi J/\psi$, then $J/\psi$ decays to leptons or anything else:
$$\psi' \rightarrow \pi^+\pi^- J/\psi, \ J/\psi \rightarrow l^+l^- \text{ or anything}$$

The branch ratio fractions can be given by the number of $\pi\pi$ lepton events, over the number of $\psi' \rightarrow \pi\pi J/\psi$ events.

The big advantage of the method is the whole experiment is based on the pure data sample of $\psi'$. The events identified by $\pi\pi$ are highly effective. So we avoid all the uncertainty and errors from the QED background of $e^+e^-$ to leptons, the total number of triggered events, and the trigger efficiency etc.

The results and conclusion are as following:

$$B(J/\psi \rightarrow \mu^+\mu^-) = (5.94\pm0.19\pm0.18)\%$$
$$B(J/\psi \rightarrow e^+e^-) = (5.98\pm0.18\pm0.20)\%$$

$B_\mu$ and $B_\mu$ are almost the same, which is consistent with $e-\mu$ universality, and gives:
$$B(J/\psi \rightarrow l^+l^-) = (5.96\pm0.14\pm0.20)\%$$

Conclusion:

a) The widths of $J/\psi$ decay have been given by two methods on BES.
b) The results by two methods are consistent with each other.
c) BES results are also in good agreement with MARKIII measurements.
d) This measurement significantly lower the uncertainty.

4). $\xi(2230)$

Brief review of previous experiment results:
GAMS and LASS found some structure near 2.2 GeV. But only MARKIII observed a narrow resonance there. So it still needs confirming.

The $\xi(2.2)$ was studied on BES by using the $J/\psi$ radiative decay
$$J/\psi \rightarrow \gamma K^+K^-, \gamma K^0\bar{K}^0, \text{ and } \gamma P\bar{P}$$
based on 7.8 million $J/\psi$ events.

The results gave following conclusions:

a) $\xi$ does exist in $J/\psi$ radiative decay.
b) The mass and width of $\xi$ we measured are consistent with MARKIII results.
c) We found a new decay mode of $\xi \rightarrow P\bar{P}$
d) What is $\xi$? Is it $s\bar{s}$, 4 quark state or glue ball? which is exciting but needs further study.

5). Ds Physics

a) $22.3 \, pb^{-1}$ $D_s$ data were collected at the energy of 4.03 GeV, which was firstly done by BES.

b) Direct branch ratio of $D_s \rightarrow \phi\pi$ was firstly measured by BES:
\[ B(D_s \rightarrow \phi\pi) = (4.2^{+9.0}_{-1.5}^{+1.7}_{-0.0} \pm 0.5)\% . \]

c) Three pure leptonic $D_s$ decay events were found.

d) The decay constant $f_{D_s}$ was measured:
\[ f_{D_s} = (434^{+153}_{-133}^{+35}_{-33}) \, MeV . \]

The main success in above was the data collected at 4.03 GeV, and from which, double tagged $D_s$ events were found from analyzing, although they were only three leptonic decay events and several others. Without them, the $\phi\pi$ branch ratio and $f_{D_s}$ can’t be measured in the better way.

3. Conclusion

Owing to the continuous efforts of several generations of Chinese physicists, the high energy physics, cosmic ray physics and other researches have developed greatly in the IHEP. They have come into the international field, and significant results achieved. Chinese physicists expect more progress in the coming century. Since we all realize the science must be an international cause, it is hoped we would have more successful collaboration with the world scientific community.
Fluctuations and Correlations of Particles Produced in Ultra-High-Energy Heavy-Ion Induced Interactions

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Abstract

Fluctuations and correlations from nuclear reactions of the performance of heavy-ion experiments at ultra-high energies are discussed. A possible measure for an irregularity of spectra of produced particles is proposed based on the Wigner-Dyson statistical analysis method.

1. Introduction

As well known, a great effort has been made for lepton-lepton, lepton-hadron and hadron-hadron collisions at the region of very high centre-of-mass energies ($\sqrt{s}$), e.g., 100+100 GeV $e^+e^-$ at CERN/LEP, 30+820 GeV $e^+p$ at DESY/HERA, 0.9+0.9 TeV $p\bar{p}$ at FNAL/TEVATRON and 15.4 TeV $pp$ will be at CERN/LHC. Except for them the projects of heavy-ion experiments at ultra-high-energy have been made not only by cosmic ray experiments [1] but also by accelerator experiments at the present BNL/AGS and CERN/SPS [2] (10 ~ 200 A GeV/c) and at the future BNL/RHIC [3] and CERN/LHC [4].

Why do we need to perform a true heavy-ion collision experiment at ultra-high-energy? What is the benefit from heavy nuclear collisions, which can not be gained from the lepton and hadron collisions? The colliding nuclei might provide a possible micro-laboratory to explore a new nuclear state at extreme conditions of sufficiently high density and/or sufficiently high temperature in a
system with larger spatial size and longer lifetime \cite{5}. Theoretically, it is predicted that a new state of matter, called the quark-gluon plasma (QGP), will exist under such conditions. Therefore, to seek the effect of deconfinement, one must study quite large distances ($\gg 1$ fm) compared to the hadronic size. The nuclei, particularly heavy nuclei, having a size of several fm, are then of much interest in this respect.

It is estimated that the multiplicity of produced particles in excess of 1000 per unit rapidity can be measured under such high energies and such heavy nuclei. As a result, it leads to a lot of speculations about the fluctuations and correlations of them, which might be as a signature of collective effect of hadronization or dynamics of multiparticle production.

In this paper we extend the Wigner-Dyson statistical method to analyse the spectra of particles produced in high energy collisions. Monte Carlo simulations from a pure theoretical calculation and a phenomenological model are made for demonstration. We also show some preliminary results of the Wigner-Dyson statistical method from the EMU-01 data in available fixed target experiments at BNL/AGS and CERN/SPS.

2. Multipartile Production

One of the major challenges is to determine the signatures for the formation of QGP and can be distinguished from the ordinary physics in relativistic nuclear interactions. As emphasized by Van Hove \cite{6}, it is imperative to learn and understand the ordinary physics. So to bear the brunt of an attract the very first step should be the question whether the collision between two relativistic nuclei would actually transfer their enough energy into an excited system, which is based on the knowledge that how they interact. Since 1970 when $\sqrt{s}$ rose above 10 GeV for $pp$ and since 1986 the beam energy $E_{lab}$ above 10 $A$ GeV for heavy-ion collisions, the measurement for exclusive reaction with a large number of produced particles became nearly impossible because of the difficulty of the full reconstruction of all measured charged tracks on individual events. Then the single-particle inclusive measurement become in vogue.

A single-particle inclusive reaction involves the measurement of just one particle coming out of a reaction. For each particle, its momentum is usually resolved into transverse ($p_\perp$) and longitudinal ($p_\parallel$) components. In longitudinal space it is convenient to use rapidity

$$y = \frac{1}{2} \ln \left( \frac{\epsilon + p_\parallel}{\epsilon - p_\parallel} \right),$$

and in the limit of $m \ll \epsilon$ it can reduce to the pseudo-rapidity $\eta = -\ln \tan(\theta/2)$, where $m$ and $\epsilon$ are mass and energy of the particle and $\theta$ is its polar angle of emission. As known the space-time
evolution of the strongly interacting system in such a collision is assumed to follow the hyperbolas
\[ z = \tau \sinh \xi \] and \[ t = \tau \cosh \xi \] where \( \tau \) is the proper time and
\[ \xi = \frac{1}{2} \ln \left( \frac{z + t}{z - t} \right) \]

coincides with \( y \).

There are two principal global variables: multiplicities and transverse energy
\[ E_{\perp} = \sum_i \sin \theta_i, \]

either in full phase space or in restricted rapidity windows. The general framework for studying the fluctuations and correlations of multiplicity of produced particles has been addressed to the so-called KNO scaling and its violation \[17\]. In replacement of it some new empirical methods \[18\], e.g. a simple negative binomial distribution, a kind of factorial moments and intermittency, information entropy and coherent production, Bose-Einstein effect and cluster effect, long-range correlation and short-range correlation, etc. have been found. The transverse energy is quite strongly related to the multiplicity.

The analyses of \( E_{\perp} \) distributions from hadron-nucleus to nucleus-nucleus experiments have proved the effect of nuclear geometry. A nucleus seems to be rather transparent so that a nucleon inside the projectile nucleus can be make multiple successive collisions within the target nucleus and vice versa. It appears both unexpected coherence (correlation) and unexpected fluctuation in these multiple interactions, which are different from the behavior predicted in available models \[19\]. To be due to the introduction of a new calorimeter approach, the longitudinal energy flow can be measured. At first glance the energy not appears in the forward direction will be observed in transverse ones. The detailed shape of the negative correlation between energy in zero-degree-calorimeter, \( E_{\text{ZD}} \), and \( E_{\text{T}} \) can provide stringent constraints of the reaction dynamics and the nuclear stopping power. Results from a ellipsoidal decay model compared with recent data of NA35, E802 and E814 collaborations are shown in Ref.[9]. As known, the issue of nuclear stopping power continually surfaces in investigation of the available data which is an important base in estimation of the temperature and density for nuclear matter after heavy-ion collisions.

3. The Wigner-Dyson Method

Though quantum field theory on the strong interaction has made such a rapid progress that it can very successfully calculate various properties of the hard-processes with only few particles,
the soft-processes nowadays with about hundreds even to thousands of particles are practically unable to explain. The existence of strong fluctuations in small domains of momentaum space in multiparticle processes, which may reflect a dynamical origin and a development of collective nonlinear phenomenon, has been recently focussed. Furthermore, it seems questionable whether such a phenomenon can, in principle, be discussed due to the chaotic properties. We will consider the colliding system as a "black box" in which all particles are interacting according to unknown laws, and pay intensive attention on deviations of some quantities from their averaged values. Such deviations are normally thought to be less important and seldom studied carefully in normal statistics.

Consider an event of \( n \) produced particles with \( \eta_1 \leq \cdots \leq \eta_n \) in pseudo-rapidity window \([-L/2, L/2]\). Its density is
\[
\rho(\eta) = \sum_{i=1}^{n} \delta(\eta - \eta_i).
\]

To make reasonable comparison of the structure of different events, one has to make rescale \( x_i = \eta_i/\bar{s} \) where \( \bar{s} = L/n \) is the average value of \( s \).

Introduce a staircase function of \( x \) as
\[
N(x) = \int_{-n/2}^{x} dx' \rho(x'),
\]
where \( \rho(x) = \bar{s} \rho(\eta) \). The event-average of \( N(x) \) will lie on a straight line with slope \( 1/\bar{s} \) if it is a constant. After the operation of unfolding the spectrum, a possible measure of the fluctuations of the staircase function around this straight line, called Wigner-Dyson quantity which was pioneered by Wigner and Dyson\cite{10}, is
\[
D(n) = \min \frac{1}{n} \int_{-n/2}^{n/2} dx [N(x) - a - bx]^2
\]
where \( a \) and \( b \) are determined by \( \partial D/\partial a = \partial D/\partial b = 0 \). For events with same given \( n \), one can calculate the event-averaged value,
\[
\langle D(n) \rangle = \langle \bar{N}^2 - \bar{N}^2 - \frac{12}{n^2} \bar{x} \bar{N}^2 \rangle,
\]
where it has defined
\[
\bar{f} = (1/n) \int_{-n/2}^{n/2} f(x) dx.
\]
It is easy to show that \( \langle D(n) \rangle \) relates to single-particle density and two-particle correlation function of semi-inclusive data.

For a purely random sequence, the \( s \) distribution will be the Poisson type.
A another well known sequence is the Wigner type which can be connected to the random matrix theory\cite{11} and has the following distribution

\[ P_{\text{Wigner}}(s) = \frac{\pi s}{2s^2} \exp \left( -\frac{\pi s^2}{4s^2} \right). \]  

(10)

In Fig.1 we show their distributions by set \( s = 1 \). Correspondingly their Wigner-Dyson quantities are

\[ \langle D(n) \rangle_{\text{Poisson}} = \frac{n}{15}, \]  

(11)

and

\[ \langle D(n) \rangle_{\text{Wigner}} = \frac{1}{\pi^2} \left[ \ln(2n\pi) + \gamma - \frac{\pi^2}{8} - \frac{5}{4} \right], \]  

(12)

where \( \gamma \) is Euler constant. Curves of \( \langle D(n) \rangle \) of these two type are compared in Fig.2.

4. Monte Carlo Simulation and FRITIOF model

For demonstration we give some results of a numerical spectrum from Monte Carlo simulation. It adopts 5000 events. For each event with multiplicity \( n \), the single-particle inclusive rapidity distribution is set as a Gaussian with central value at zero and width \( \sigma = 3 \) and there is no any correlation between particles. Results of \( D(n) \) as a function of \( n \) for selected window \( |y| < 1.5 \) in Fig.3. The averaged values over the events at a fixed \( n \) are also calculated and drawn as a function of \( n \). Theoretical curve of the Poisson type is plotted for comparison. It is shown that the Monte Carlo samples lie on the theoretical curve.

The above observation has examined by using the Monte Carlo simulation of the FRITIOF code of the Lund Model\cite{12}. See Fig.4. We have ran \( 10^4 \) numerical events for \( 32S+\text{Em} \) interactions at 200 A GeV. It is also shown that the averaged values of \( \langle D(n) \rangle \) lie on the theoretical curve of the Poisson type.

5. The EMU01 Experiment

CERN/EMU01 experiment (including BNL/E815 and BNL/E863) used two sorts of detectors of both conventional emulsion stacks exposed horizontally and special emulsion chambers exposed vertically. Data were taken from those of \( ^{16}\text{O} \) and \( ^{28}\text{Si} \) at 14.6 A GeV, and \( ^{197}\text{Au} \) at 10.7 A GeV at BNL/AGS, and from those of \( ^{16}\text{O} \) at 60 and 200 A GeV and \( ^{32}\text{S} \) at 200 A GeV at CERN/SPS.
Fig. 1 The nearest neighboring spacing distributions of
a) Poisson type (solid curve)
b) Wigner type (dashed curve)

Fig. 2 Theoretical curves of
\( \langle D(n) \rangle \) vs \( n \)
a) Poisson type (Solid curve)
b) Wigner type (dashed curve)

Fig. 3 Scattering plot from Monte Carlo simulation of Wigner-Dyson quantity \( D(n) \) vs \( n \) for Inclusive rapidity distribution of a Gaussian (\( \sigma = 3 \)), without correlation. Circles are averaged values for given multiplicity \( n \).
Fig. 4 Lund-FRITIOF simulation of sample-averaged values 
$\langle D(n) \rangle$ vs multiplicities $n$ for 200 A GeV $^{32}$S + Em 
(a) $|\eta| < 0.1$; (b) $|\eta| < 0.3$; (c) $|\eta| < 0.5$; (d) $|\eta| < 0.9$

Fig. 5 Preliminary data from EMU-01 experiments. Event-averaged values $\langle D(n) \rangle$ vs multiplicities $n$ in $|\eta| < 0.3$ 
(a) $^{16}$O; (b) $^{28}$Si; (c) $^{197}$Au, at near same energies.
Fig. 6 Preliminary data from EMU-01 experiments. Event-averaged values $<D(n)>$ vs multiplicities $n$ in $|\eta| < 0.3$ 
$^{16}$O + Em at a) 14.6 A GeV; b) 60 A GeV; and c) 200 A GeV.

Fig. 7 Preliminary data from EMU-01 experiments. Event-averaged values $<D(n)>$ vs multiplicities $n$ for 200 A GeV 
$^{16}$O + Em in a) $|\eta| < 0.3$; b) $|\eta| < 0.5$; c) $|\eta| < 0.9$. 

Poisson
In Fig.5-7 are shown the relevances of data to the projectile nuclei, the incident energies and the pseudo-rapidity window cuts\textsuperscript{13}.

The BNL/AGS gave us the possibility to get events from different projectile nuclei (oxygen, silicon and gold) at nearly same energies. The data comparison is shown in Fig.5 that there is also no evidence for projectile dependence.

For comparison of data from different energies each other we selected the window with size $L = 0.6$ for oxygen induced interactions. Considering the available beam energies of 14.6, 60 and 200 $A$ GeV, the independence of data on energy is obvious, which can be seen in Fig.6.

It looks like that the data points from more narrow window ($L = 0.6$) to wider window ($L = 1.8$) lie on the same curve although the fluctuation is larger for higher multiplicities from Fig.7. That is to say the random emission does dominate over the present selected windows which are all belong to the central region.

As pointed out in our previous work\textsuperscript{14} that the nuclear collision geometry and the number of participating nucleons play an important role in particle production, which result to larger fluctuations and random emission. So that for future experiments with higher energies and heavier nuclei one has to face the dominant effect of random emission from nuclear geometrical fluctuation and intra-nuclear rescattering due to the energy high enough.

Acknowledgement

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References


EMISSION OF HIGH ENERGY $\gamma$-RAYS FROM SPIN-FLIP OF ELECTRONS NEAR A PRIMORDIAL BLACK HOLE

(invited lecture)

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In this speech we like to see if there is some possibility to have a source of high energy cosmic $\gamma$-rays connected with primordial black holes (PBH).

In a recent work [1] Zeng Xinchuan proposed a hydrogenlike atomic system consisting of an electron and a primordial black hole (PBH) of mass $\sim 10^{14}$ to $10^{15}$g. He noted that the electrostatic force and the gravitational force between an electron and such a PBH are of the same order, the proton in the hydrogen atom being replaced by a PBH with a Schwarzschild radius about equal to the proton radius, i.e. a PBH with a mass $\sim 10^{15}$g has a radius $\approx 10^{-13}$ cm.

He then applies the Schrödinger equation to solve for the energy levels and transitions for this PBH hydrogenlike atom taking both electrostatic and gravitational forces into account, that is, for a PBH with mass $M$ and electric charge $Ze$, he takes a potential energy

$$V(r) = -\frac{Ze^2}{r} - \frac{GMm_e}{r} = -B\frac{Ze^2}{r} \quad (1)$$

where $B = 1 + \frac{GM_e}{Ze^2}$ ($Z \neq 0$). Introducing the Schwarzschild radius of this PBH $a_s = 2GM/c^2$ we can express $B$ as

$$B = 1 + \frac{a_s^2}{2Ze^2} = 1 + \frac{a_s}{2r_e} \quad (2)$$

being $r_e = e^2/m_e c^2$ the classical radius of the electron, so that the potential energy is different from that of the hydrogenlike atom only by a coefficient $B$. 

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After giving formulae for the energy transitions of such a system (mutatis mutandis the hydrogen atom) he goes on to discuss the cosmological implications of the system in section 4 of the paper [1].

For that he considers the case in which $a_s$ and $r_e$ are of the same order and shows that the mass corresponding to $a_s = r_e$ is around $10^{14} + 10^{15}$ g.

With PBH's of that kind whose evaporation time due to Hawking radiation is comparable to the age of the universe $t \approx 1.5 \cdot 10^{10}$ yr he makes estimates of such a system's contribution to the background cosmic radiation and concludes that the photon radiation of a PBH with a hydrogenlike atomic system mechanism (i.e. bound to a electron) makes a significant contribution to the cosmic background radiation (CBR) and may even explain the excess sub-millimeter radiation of the CBR.

However in considering such a stable bound hydrogenlike atomic system of a PBH with an electron, he neglects the fact that the PBH is continually emitting intense Hawking radiation which would exert a radiation pressure on any orbiting electrons. So it is not simply a question of replacing the proton in the H-atom by a PBH of Schwarzschild radius equal to the proton radius. Let us estimate the radiation pressure exerted by the evaporating PBH (of mass $M_H \approx 10^{14}$ g) emitting Hawking radiation and compare it to the gravitational force between it and the electron (of mass $m_e$) orbiting at a distance $r$ like in the H-atom.

Now the evaporation time scale of a PBH (i.e. $t_H \approx \frac{G^2 M_H^3}{hc^4}$) due to Hawking radiation implies, as is well known, a rate of energy emission due to evaporation, i.e. a luminosity of

$$L \approx \frac{h c^6}{G^2 M_H^2}$$

(note that $L$ scales as $1/M_H^2$, the appearance of $h$ indicating that it is a quantum effect). For a hole of mass $M_H \approx 10^{14}$ g, eq.(3) implies a $L$ of

$$L \approx 2 \cdot 10^{22} \text{ ergs/s}$$

(4)
The gravitational binding force between the PBH and the electron is

\[ F_G = \frac{G M_B m_e}{r^2} \]  \hspace{1cm} (5)

The force due to radiation pressure exerted by a source with luminosity \( L \) on an electron at a distance \( r \) is given by

\[ F_R = \frac{L \sigma_T}{4\pi r^2 c} \]  \hspace{1cm} (6)

where \( \sigma_T \) is the electron-photon Thompson cross-section given as

\[ \sigma_T = \frac{(8\pi/3)(e^2/m_e c^2)^2}{\frac{G M_B m_e}{r^2}} \]  \hspace{1cm} (7)

Thus the balance between the radiation pressure force given by eq. (6) and the gravitational force given by eq. (5) would imply that the maximal Eddington luminosity of the PBH should be (for stability)

\[ L_E = \frac{G M_B m_e 4\pi c}{\sigma_T} = \frac{4\pi G M_B m_e}{\sigma_T} \]  \hspace{1cm} (8)

Thus \( L \) in eq. (6) must be much less than \( L_E \) for the stability of the system.

For a PBH of mass \( M_B \approx 10^{14} \) g, eq. (8) implies

\[ L_E \approx 10^{15} \text{ ergs/s} \]  \hspace{1cm} (9)

Comparing eqs. (4) and (9), we see that \( L \gg L_E \), which implies that the force due to radiation pressure from evaporating PBH will blow away the electron whatever be its orbital radius (as \( r \) cancels out in the above expressions). So it is impossible to have a stable hydrogen-like system of a PBH with mass \( 10^{14} + 10^{15} \) g with an electron. This is the PBH mass range required in ref. [1], to get significant contributions to the CBR and other important implications.
However it is possible to have a PBH with zero Hawking temperature in two cases:

a. Either it must have an electric charge $Q$ given by:

$$Q^2 = GM_H^2$$

that is

$$Q = (G)^{1/2}M_H$$

(10)

For $M_H = 10^{14} g$ this would give $Q = 10^{21} e$, where $e$ is the electric charge. However this would imply that a PBH with such a large $Q$ would exert an enormous electrostatic force on any electron orbiting it. Moreover it is well known even in atomic physics that any point like nucleus with a charge $Z$ greater than $Z = 137$ ($= 170$ taking finite nuclear size into account), would have unstable electron orbits, i.e. the Dirac equation would give negative electronic energy if $Z \alpha > 1$, ($\alpha = 1/137$), so that the orbits would collapse [2]. So here we effectively have $Z > 10^{21}$, so it is impossible to have an electron forming a bound state with such a PBH like a H atom!

b) The second possibility of the PBH having a zero Hawking temperature (ZHT) is when its spin $J$, is given by [2]

$$J_H = G M_H^2 / c$$

(11)

For $M_H = 10^{14} g$, this would give

$$J_H \approx 2 \cdot 10^{37} h$$

(12)

but a PBH with such a large $J_H$, would give rise to enormous spin-orbit and spin-spin coupling on any electron orbiting it, so that it is impossible in this case also to have a stable PBH-electron, hydrogen atom like, bound system.

However because of its large intrinsic spin as given by eq.(11), such a hole would have a magnetic moment given by [2, 3]

$$\mu_H = (G/c)^{1/2}J_H$$

(13)

with $J_H$ given by eq.(12), this would imply

$$\mu_H \approx 2 \cdot 10^{-4} \text{erg/G}$$

(14)

As electrons have an intrinsic magnetic moment $\mu_e$ (given by the Bohr magneton $\mu_B = eh/2m_e c$), one can have a situation similar to
hyperfine atomic transitions, when electrons passing by the nucleus can undergo spin-flip transitions due to interactions between electronic and nuclear magnetic moments.

The Hamiltonian for this would be given as (for point-like interacting components with magnetic moment which is a good approximation for this system):

\[ H = (\mu_H \cdot \mu_e / \pi a^3 n^3) \sigma_p \cdot \sigma_e \]  

(in the usual case, \( a = \) Bohr radius \( = 10^{-8} \) cm, \( \sigma_p \cdot \sigma_e = 3 \) or 1 depending on whether it is a triplet or singlet state).

For a \( \mu_H \) given by eq.(14), the eq.(15) would imply that the energy of the photon emitted in such a spin-flip transition undergone by the electron when interacting with the hole moment \( \mu_H \) is

\[ E_y \approx 5 \cdot 10^{14} \text{ ev} \]  

i.e. corresponding to a very high energy gamma ray. So such interactions of PBH's in interstellar space may be observable even if they have ZHT. \( \gamma \)-rays in energy ranges of \( 10^{14} + 10^{15} \) ev are known to emanate in cosmic rays and from sources like cygnus X-3, etc. and their origin is not known with certainty.

However since PBH's can have a whole range of masses \( M_H \) and since \( \mu_H \) increases with \( M_H \), one can have high-energy \( \gamma \)-rays with a whole range of energy. For \( 10^{14} \)g we had \( = 5 \cdot 10^{14} \) ev. For \( 10^{13} \)g we would have \( 5 \cdot 10^{12} \) ev, since in eq.(15) is involved \( \mu_H \) that depend on \( M_H^2 \) (eq.(11)). For higher \( M_H \), intensity drops considerably as \( \sim 1/M_H^2 \) (eq.(3)). In fact high energy \( \gamma \)-rays are seen from \( 10^{10} \) to \( 10^{17} \) ev. Still higher energy \( \gamma \)-rays are cut off by interaction with the cosmic background radiation. The intensity of the radiation would depend on the number density of the electrons present in the source and from the observed intensities it should be possible to estimate the electron density.

As shown in ref.[2], the PHB, with spin given by eq.(12), would have a magnetic field \( B_H \) (due to torsion) associated with it of

\[ B_H = (8\pi/3c)(2\alpha G)^{1/2} \sigma_H \]  

where \( \sigma_H \), the spin-density, is given by dividing \( J_H \) (given by eq.(11) ) by the Schwarzschild volume of the hole. This gives a
field of $B_H \approx 10^{35}$ Gauss at surface of the hole. At a distance of Bohr radius $R_B \approx 10^{-8}$ cm, this field (being dipolar as torsion gives dipolar field) is:

$$B_0 \approx B_H (R_H / R_B)^3$$  \hspace{1cm} (18)

where $R_H$, the Schwarzschild radius is $\approx 10^{-13}$ cm; then

$$B_0 \approx 10^{20} \text{ Gauss}$$  \hspace{1cm} (19)

This gives the spin-flip time for an electron with $\mu_e \approx 10^{-20} \text{ erg/s}$ interacting with this field generated by torsion of

$$t_{s-f} \approx h/(\mu_e B_0) \approx 10^{-27} \text{ s}$$  \hspace{1cm} (20)

This $t_{s-f}$ agrees with uncertainty principle estimated from energy of spin-flip transition as given by eq. (16) which gives $t_{s-f} \approx 10^{-28} \text{ s}$.

Now time scale for collapse on to hole of electron moving with speed $c$ at distance of $\approx 10^{-8}$ cm ($R_B$) is

$$t_e \approx R_B / c \approx 10^{-18} \text{ s}$$  \hspace{1cm} (21)

Thus $t_{s-f} \ll t_e$, which means spin-flip will occur well before electron collapse by gravitational attraction on hole.

Moreover the magnetic force on electron (magnetic field generated by spin-torsion) is ($e$ is the electron charge):

$$F_B \approx e B_0 c \approx 5 \cdot 10^{-10} \cdot 10^{20} \cdot 3 \cdot 10^{-10} \approx 10^2 \text{ dyn}. \hspace{1cm} (22)$$

Gravitational force between hole and electron is (at a distance of $R_B \approx 10$ cm) is

$$F_G = G M H m / R_B^2 \approx 5 \cdot 10^{-5} \text{ dyn} \hspace{1cm} (23)$$

Thus $F_B \gg F_G$, i.e. magnetic force is much greater than gravitational force at distance when spin-flip can occur. Even at near Schwarzschild radius of hole $F_B \gg F_G$ so that electron cannot collapse on hole before spin-flip.

Now the Hawking-Page bound on the number of evaporating PBH's from the gamma ray background is [4]

$$n_{PBH} < 10^{11} \text{ pc}^{-3} \hspace{1cm} (24)$$

Incidentally this is much smaller than what is assumed for the
cosmological implications in Ref.1. The interstellar electron density from pulsar dispersion measures is \( \approx 0.1 \, \text{cm}^{-3} \). The geometric cross section \( \sigma \) for the process is about \( \pi \cdot (10^{-13})^2 \, \text{cm}^2 \) (as both the PBH and the electron have sizes \( \sim 10^{-13} \, \text{cm} \)).

Then assuming a velocity \( \sim c \), the flux of the gamma rays due to the spin flip can be estimated in the usual way as (rate \( \approx n_e n_h \sigma v \))

\[
F_\gamma \approx 10^{-17} \, \text{cm}^{-2} \, \text{s}^{-1},
\]

(25)

For eg. for a specific source like Cygnus X-3, the electron density would be much higher \( \approx 10^2 \, \text{cm}^{-3} \), in which case the flux from the source would be \( 10^3 \) times higher consistent with the observed \( \gamma \)-ray pulses.

One can extend this work considering spin-flip of protons near a PBH and also acceleration of protons to see the contribution to the cosmic background radiation and, in case, give an estimate to the number of PBH.

References

The Greeting Telefax for Tibet Symposium

群培教授

大羅桑朗傑教授

梅 東 明教授:

請接受我對你們《國際宇宙線物理研究會》衷心的祝賀。對於西藏的科學發展，這是極端重要的一步。同時，這也使國際上認識到你們科學研究站獨特的地理位置，以及西藏大學對高能宇宙線研究的貢獻。羊八井宇宙線研究站的過去成就，確實極為獨特。我的合作者和我十分認真地考慮，可能不久之後提議在羊八井進行一項實驗。

我很高興有許多世界著名的物理學家，像 Professor Alvaro De Rujula, Professor Spillantini and Professor L. W. Jones 等人，都前來參加你們的會議。

我曾經兩次訪問西藏，對於貴校給予我的款待，至感愉快，由於我研究計劃未預見的發展，我遺憾不能來參加你們的會議。最近我會再來你們的大學和西藏訪問。

請接受我對你們成就的祝賀。

寄上對未來的祝福，並致上我對尊敬的熱地先生誠摯的問候。

丁肇中

94. 8. 8
THE GREETING SPEECH
at the closing ceremony of the symposium
by Weiren Zhao
from IHEP(Institute of High Energy Physics)
Beijing, P.R.China

Dear Chairmen LaBaPinCuo and LuoGa,
Dear Prof. DaLuoSangLangJi, GeSangNiMa and MeiDongMin,
Dear Prof. Jones and all the respective participants of the symposium,
Dear Ladies, Gentlemen and friends,

Thank you for giving me the chance to speech shortly here for the closing ceremony.

However so many nice words and emotion have been expressed by so many scientists here on the symposium, that I don’t think I could have much to talk.

I would like just to tell you some of my impression and imagination, which came to my mind particularly at the wonderful place and on the wonderful days.

We all know, high energy physics is full of charm and strange, just as described by the quark names. And cosmic ray physics is also full of even more unexplored mysteries.

Now the symposium brings high energy physics and cosmic ray physics together to the fascinating Tibet, the third pole of the world.

So many small and huge, modern and ancient things meet here, so much difference of cultures knocked each other here, which inevitably stimulates us more excited and more devoting to the attractive scientific fields.

That explains our success here.

When I firstly came to YangBaJing at the 4.3 kilo meters altitude, I even felt that we are near to touch the heaven. And I suppose, to people who could really touch the heaven, there would be no secret any more.

I would stop my imagining now. And many thanks again to the meeting organizers for all of their kindness to us and for the enthusiasm in their work. Especially I would thank all of you for visiting the YangBaJing observation station and giving good comments to its preliminary achievements.

We expect and welcome more successful international cooperation on the high broad plateau. And we look forward to meeting again on the magnificent roof of the earth in future.

Thank you.
Search for Point Sources Emitting 10 TeV Gamma Rays over Various Timescales

The Tibet AS$\gamma$ Collaboration


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13. Shonan Institute of Technology, Japan

Abstract

We have searched for continuous and sporadic emission of 10 TeV gamma rays over various timescales from 51 potential sources, using the data taken by the Tibet air shower array in the period between 1990 June and 1992 September. The time intervals of 1, 2, 4, 8, 16 and 32 days were examined to search for sporadic emission. No evidence from any source was found on the continuous emission, and the 95% C.L. upper limits were obtained for each source by assuming a power-law type energy spectrum for gamma ray emission. There also exits no evidence on the sporadic emission of gamma rays for any source, since every examination on these timescales has yielded the results consistent with background fluctuations.

1. Introduction

Gamma-ray emission at TeV energies from Crab found by Whipple and other groups[1,2] suggests the acceleration mechanism by the synchrotron-self-Compton model[3]. Recently gamma rays at TeV energies from an active galaxy Mrk421 was found, while gamma rays from such large distance would be
greatly attenuated by extragalactic starlight[4]. It is important to search for point sources of gamma rays to clarify the origin and the acceleration mechanism of cosmic rays.

The upper limit fluxes for continuous gamma-ray emissions by our experiment at 10 TeV region from Cygnus X-3, Crab Nebula, Hercules X-1, Geminga and 3C279 and 15 active galactic nuclei which EGRET on board the Compton GRO discovered were reported elsewhere[5,6]. The upper limit fluxes above around 70 TeV for 51 candidate sources were reported by the CYGNUS group[7].

In this paper, we report on the search for continuous and sporadic emission of gamma rays from 51 potential sources in the northern sky at energies above 10 TeV with the Tibet air shower array.

2. Experiment
The Tibet air shower array is located in Yangbajing, Tibet, China at an altitude of 4300 m a.s.l.(90.53° E and 30.11° N), corresponding to the atmospheric depth of 606g/cm². The array consists of 49 scintillation detectors of 0.5 m² each, which are installed with a grid spacing of 15 m, among which 45 detectors (FT detectors) are used to measure timing with fast response photomultipliers to determine the arrival direction of the air showers. Outside these detectors, 16 scintillation detectors of 0.25 m² each are distributed. The data has been taken at a trigger rate of about 20 Hz with a condition of any 4-fold coincidence among the FT detectors during the period of June 18, 1990 through September 29, 1992. The effective running time in this period was 598.6 days.

3. Analysis and Results
A database with the following conditions was used for the present analysis. 1) Each of four FT detectors produces a signal more than 1.25 particles. 2) Among the four detectors which recorded the highest particle densities, two or more detectors exist in most 5x5 matrix detectors.

The mode energy of primary particles detected by the array is estimated by a Monte Carlo simulation to be about 7 TeV for protons and about 10 TeV for gamma rays.

Angular resolution is found to be nearly 1 degree by the Monte Carlo simulation, which is confirmed by observing the shadow of the Moon with a sufficient significance[8].

To search for the emission from the selected sources, number of events in the on-source region are taken within a circle of a radius of 1 degree centered at each source.

Number of background events for this analysis is estimated by equi-zenith method which uses events inside two regions of 3-23 °/sin ζ in azimuthal direction from the source and ±1.5 ° in zenith direction. A solid angle of the background region Ω_off is, then, becomes 0.03107 sr, and the ratio of the off-source and on-source region is obtained to be Ω_off/Ω_on = 32.47. In case of the zenith angle ζ of the position is less than 7°, we made some correction on the background events.

Significance of the excess of events from the sources are evaluated using maximum likelihood method by Li and Ma [9] which takes into account statistical fluctuation of background number of events.

Continuous Emission
Upper limit flux for these sources for the continuous emission are obtained at the 95 % confidence level by assuming that the signal and the background obey the Poisson distribution using the Protheroe procedure[10] whose results are shown in Table 1. No evidence was found for the continuous emission of gamma rays at the energy region of 10 TeV from these sources.
Sporadic Emission

We have searched for sporadic emissions from these 51 sources with time intervals of 1, 2, 4, 8, 16 and 32 days. Results for single day emission are shown in Table 1. The maximum value of the daily significance ($S_{\text{max}}$) are obtained for these sources. Product of the probability above this maximum significance and the number of trial days gives an expectation value ($N_{\text{expect}}$) to have such significance within the observation period. We did not find any significant excess by the single day analysis.

To study sporadic emissions with time intervals of 2, 4, 8, 16 and 32 days, we first obtained the significance in these intervals and shifted the intervals day by day to avoid the binning effect. Two examples for the intervals of 16 and 64 days for Crab are shown in Fig. 1. As a result we did not find any significant excess from these sources for the time intervals of 2, 4, 8, 16 and 32 days.

![Graph](image1.png)

![Graph](image2.png)

Figure 1: Examples of significance distribution for 16 and 64 day intervals for the Crab nebula.

Acknowledgments

This work is supported in part by Grants-in-Aid for Scientific Research and also for International Scientific Research from the Ministry of Education, Science and Culture, in Japan and the Committee of National Nature Science Foundation in China.

References

Table 1: Summary of Continuous emission and daily excess where F95 is flux upper limit at the 95 %
confidence level ( x10-13cm-2s-l).
Object
Crab
Her X-1
Cyg X-3
Cyg X-1
3C279
MK 421
M31
Virgo A
AM Her
DQ Her
U Gem
SS Cygni
HZ 43
GK Per
V404 Cygni
Kiel 1
Kiel 3
Kiel 4
Kiel 5
Kiel 6
Geminga
IE 2259+58
SS 433
4U 0042+32
4U 0115+63
4U 0316+41
4U 0352+30
4U 0614+09
4U 1257+28
4U 1651+39
4U 1837+04
4U 1901+03
4U 1907+o9
4U 1918+15
4U 1957+40
4U 1954+31
4U 2142+38
4U 2321+58
2CG 065+00
2CG 075+00
2CG 078+00
2CG 095+04
2CG 135+01
2CG 121+04
PSR 0355+54
PSR 0950+08
PSR 1929+10
PSR 1937+21
PSR 1951+32
PSR 1953+29
PSR 1957+20

Non
69578
75228
73319
75525
21391
75332
72827
56029
63913
68678
70211
71721
58597
71253
75262
59534
71913
43377
30741
71863
64310
48681
41296
59577
38777
72483
58438
49877
58556
73770
41396
37775
51016
59255
73828
59931
75302
48774
58412
75596
74141
55772
42397
32730
57106
48442
53235
68195
60620
58040
67117

Noff
225 1194
1001775
3641473
1152022
3948315
2445752
2365201
1815739
2069631
2228094
2272302
2315894
1899678
2305520
576369
1939392
2331265
1409215
987414
688692
3687210
1574450
1345804
1957478
1247676
2362985
1920813
1630748
1900344
2387882
1349377
1230535
1640251
1930946
2386357
1941530
2426804
1576647
1898603
1726011
2'400853
1798117
1369719
1046616
1851863
1572059
1710740
2215722
1964426
1897854
2187638

Sign tficance
0.902cr
1.04cr
-0 .0530cr
0.442cr
0 .535cr
0.0108cr
-0.0767u
0.435cr
0 .657cr
0.199cr
0.834cr
l.44cr
0 .354cr
0.898cr
-0.632cr
-0.803cr
0 .405cr
-0.126cr
1.85cr
-0.910cr
-O. l 72CT
0 .841CT
-0. 749cr
-2 .87u
1. 75CT
-l.08CT
-2.93a
-l.54a
0 .104a
0.8lla
-0.796a
-0.635CT
2.11<7
-0.881CT
l.19a
0.536a
2.00CT
0.953a
-0 .264<7
1.0lCT
0 .706a
l.63a
1.00CT
2.70a
0.283a
0.102CT
2.33u
-0.185a
0.464u
-1.690"
-0.995a

115

Fg5

9.21
G.2G
6.61
6.82
32.6
7.14
9.36
11.0
10.1
8.41
10.4
1.24
8.60
10.4
6.16
5.79
8.71
9.32
12.0
5.71
9.36
12.3
8.02
5.02
17.7
5.30
5.30
5.81
7.92
9.98
7.83
8.55
17.9
6.40
11.3
9.07
14.1
12.8
6.94
10.4
9.65
14.6
13.8
23.8
9.49
9.89
18.4
7.46
8.87
4.46
5.72

No . of da~· s
GG9
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3.16cr
2.82cr
3.19Cr
2.86cr
3.15cr
3.13cr
2.90cr
3.00cr
3.26cr
3.46cr
2.47cr
2.74cr
3.46cr
3.Slcr
3.20cr
2.57 er
3.40cr
2.60cr
2.91CT
2.37CT
3.48cr
2.96CT
3.21CT
3.45CT
2.84a
2.69CT
3.32a
3.00CT
2.560"
3.68CT
3.25a
2.67u
2.90CT
3.53a
3.30CT
3.21<7
2.88CT
3.27 CT
2.50CT
3.37 CT
3. llCT
2.99<7
3.39CT
3.00CT
2.65<7
3.01<7
3.22a
3. lOCT
3.51CT

0.195
0.880
0.507
1.55
0.453
1.35
0.530
0.562
1.20
0.891
0.368
0.176
4.31
1.98
0.174
0.0448
0.440
3.27
0.218
3.03
0.820
5.75
0.155
0.999
0.429
0.181
1.45
2.35
0.289
0.857
3.38
0.0753
0.371
2.44
1.20
0.134
0.315
0.430
1.28
0.346
2.67
0.247
0.602
0.902
0.224
0.882
2.58
0.844
0.412
0.623
0.144


Survey of Supernova Remnants to Search for Emission of 10 TeV Gamma Rays

The Tibet ASγ Collaboration


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Abstract

We have searched for emission of 10 TeV gamma rays from the direction of 20 SNRs in the northern sky (declination: +1.3° to +64.6°), using the data taken in the period from 1990 June through 1991 April with the Tibet Air Shower array. DC significance of excess events to the background was examined on each source to search for evidence of gamma-ray emissions. No obvious DC excess is found from these sources.

1. Introduction

It is widely believed that the Galactic cosmic rays in the energy region of < 10¹⁴ eV have their origin in supernova remnants (SNRs). These cosmic rays are considered to be accelerated by the first order Fermi process at the shocks of SNRs. Recently, Naito and Takahara (1994) have suggested that high energy gamma rays are expected to be efficiently generated through the decay of neutral pions produced by interactions of cosmic rays with dense gas and cosmic rays in SNRs. The Tibet air shower array sensitive to gamma rays of 10 TeV region would give one of the most promissive information on this theoretical prediction. We have analyzed air showers, using the data of about 560 days in the period from 1990 June through 1992 July obtained by Tibet ASγ array (4300 m a.s.l, 90.52°E, 30.11°N).

2. Analysis and results

The event selection was made imposing the following three conditions. First, each of the four FT detectors should give a signal more than 1.25 particles per 0.5 m². Second, among the four detectors
which record the highest particle densities two or more should be inside the central 5 x 5 detector matrix, and the third is that the laser calibration system for the scintillation counter array should be working. These conditions are the same ones as used by Amenomori et al. (b) except for the last condition. By this selection rule we have obtained $2.8 \times 10^8$ events through observation days of about 560 days. Angular resolution is $1.1^\circ$ which has been well confirmed by observing the moon’s shadow with value $8.7^\circ$ as described in Amenomori et al. (a) and (b). In the case of gamma-ray incident, the mode energy of the selected events are estimated to be $10$ TeV (median energy is about $20$ TeV) by Monte Carlo simulation.

In order to search for intensity excess of showers from the direction of a candidate source which may emit VHE gamma rays, the background event density must be carefully estimated. We estimated the background event density by the method of the equi-zenith angle cut.

As shown in Figure 1, the background area is taken within zenith angle band of $\pm 1.5^\circ$ centered at the on-source zenith angle $\theta_{\text{on}}$ and within $\pm \varphi_{\text{max}}$, where $\varphi_{\text{max}} = 20^\circ / \sin\theta_{\text{on}}$, in azimuthal angle from the on-source direction except for the central area of $\pm \varphi_{\text{min}}$, where $\varphi_{\text{min}} = 3^\circ / \sin\theta_{\text{on}}$. Hence the solid angle of the background area $\Omega_{\text{off}}$ is given by

$$\Omega_{\text{off}} = 2 \int_{\varphi_{\text{min}}}^{\varphi_{\text{max}}} d\varphi \int_{\theta_{\text{on}} - 1.5^\circ}^{\theta_{\text{on}} + 1.5^\circ} \sin\theta d\theta = 0.0310674 [\text{sr}],$$

where $\varphi$ is azimuthal angle, and the on-source cell, of solid angle $\Omega_{\text{on}} = 9.56959 \times 10^{-4} [\text{sr}]$, is chosen as a circle of radius $1^\circ$ centered at the on-source direction. Then the ratio of the on-source versus off-source solid angle is

$$\Omega_{\text{on}} / \Omega_{\text{off}} = 1 / 32.4647$$

This method of background estimation is not available when the on-source direction becomes near the zenith, because the background areas will overlap each other and with the on-source cell. So in the case of on-source declination is within $30^\circ \pm 5^\circ$, we have not used the data of this zenith angle range.

The statistical significance of excess of on-source cell is calculated by using the Li and Ma method in which statistical fluctuations, both of numbers of background events and of on-source events, are taken into account.

20 SNRs, which we analyzed for search for gamma-ray emission are quoted from Lang (1991), and remnant name, known distances of some SNRs and other properties are shown in Table 1. Locations of 20 SNRs in the celestial coordinate are illustrated in Figure 2.

Table 2 shows result of analysis 20 SNRs, where $N_{\text{on}}$ and $N_{\text{off}}$ is event number of on-source region and off-source region, respectively. Upper limits on the excess number of events at the 95% confidence level are obtained for these SNRs using the same method described in Amenomori et al. (a) and are shown in the table.

3. Discussion and summary

We have searched for DC emission from 20 SNRs. As shown in Table 2, we obtained Li-Ma significance $s \leq 3.14 \sigma$ as the DC excess. However, they have no obvious evidence for gamma-ray emission from SNRs.

According to Naito and Takahara (1994), gamma ray flux of 10 TeV region emitted from near SNRs
located in 2~3kpc from the sun will be about $0.7 \sim 1.5 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1}$ when protons are accelerated up to $10^{16} \text{eV}$ in SNRs. For the nearby SNRs (W44, Tycho, HB3, and Crab) our results have shown one order greater than the theoretical model.

It, although, may be noted that HB3 is giving the highest Li-Ma significance of 3.14\sigma which corresponds to the rather small upper probability of $8.4 \times 10^{-4}$. If we consider the total number of trial 20, the expected number of SNRs showing significances greater than 3.14 is $1.7 \times 10^{-2}$, which is not large enough to reject HB3 to be potential gamma-ray emitter of 10 TeV region.

Since Monoceros, S91+594 and Cygnus-Loop are widely spreading beyond 2° of the diameter of our ON-source area, it may be better to introduce wider ON-source area for analysis of them.

Acknowledgments

This work is supported in part by Grants-in-Aid for Scientific Research and also for International Scientific Research from the Ministry of Education, Science and Culture, in Japan and the Committee of National Nature Science Foundation in China.

References

Amenomori, M. et al. (b), 1993, Phys. Rev. D, 47, 2675
<table>
<thead>
<tr>
<th>Remnant Name</th>
<th>Right Assention</th>
<th>Decrination</th>
<th>Size(&quot;&quot;)</th>
<th>Type</th>
<th>Distance(kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W44</td>
<td>285.3</td>
<td>+1.3</td>
<td>35×27</td>
<td>F</td>
<td>3.0±1.0</td>
</tr>
<tr>
<td>Tycho</td>
<td>5.7</td>
<td>+63.9</td>
<td>8</td>
<td>S</td>
<td>2.3±0.3</td>
</tr>
<tr>
<td>W49B</td>
<td>287.2</td>
<td>+9.0</td>
<td>4×3</td>
<td>F</td>
<td>10.</td>
</tr>
<tr>
<td>HB3</td>
<td>33.5</td>
<td>+62.5</td>
<td>80</td>
<td>IR</td>
<td>3.</td>
</tr>
<tr>
<td>Crab</td>
<td>82.9</td>
<td>+22.0</td>
<td>7×5</td>
<td>F,CO</td>
<td>2.0±0.5</td>
</tr>
<tr>
<td>HB9</td>
<td>74.3</td>
<td>+46.6</td>
<td>140×120</td>
<td>IR,CO</td>
<td>3.6±0.3</td>
</tr>
<tr>
<td>OA184</td>
<td>78.9</td>
<td>+41.8</td>
<td>90×70</td>
<td>S</td>
<td>1.2±0.6</td>
</tr>
<tr>
<td>VRO 42.05.01</td>
<td>80.8</td>
<td>+42.9</td>
<td>55×35</td>
<td>S</td>
<td>2.5±0.5</td>
</tr>
<tr>
<td>IC443</td>
<td>93.5</td>
<td>+22.6</td>
<td>45</td>
<td>IR</td>
<td>3.6±0.3</td>
</tr>
<tr>
<td>Monoceros</td>
<td>99.0</td>
<td>+6.5</td>
<td>220</td>
<td>S</td>
<td>1.0±0.5</td>
</tr>
<tr>
<td>PKS 0646+06</td>
<td>101.5</td>
<td>+6.5</td>
<td>60×40</td>
<td>S?</td>
<td>1.5±0.5</td>
</tr>
<tr>
<td>S91+S94</td>
<td>292.8</td>
<td>+31.1</td>
<td>310×240</td>
<td>S?</td>
<td>2.0±0.5</td>
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<tr>
<td>3C400.2</td>
<td>294.1</td>
<td>+17.1</td>
<td>28</td>
<td>S</td>
<td>1.0±0.5</td>
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<tr>
<td>CTB80</td>
<td>297.9</td>
<td>+32.8</td>
<td>80</td>
<td>F,CO</td>
<td>2.0±0.5</td>
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<tr>
<td>Cygnus Loop</td>
<td>312.3</td>
<td>+30.5</td>
<td>230×160</td>
<td>S</td>
<td>1.5±0.5</td>
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<tr>
<td>CTB109</td>
<td>344.9</td>
<td>+58.6</td>
<td>28</td>
<td>S,CO</td>
<td>1.5±0.5</td>
</tr>
<tr>
<td>G.C. 126.2+01.6</td>
<td>19.6</td>
<td>+64.0</td>
<td>70</td>
<td>S?</td>
<td>1.5±0.5</td>
</tr>
<tr>
<td>G.C. 127.1+00.5</td>
<td>21.3</td>
<td>+62.9</td>
<td>45</td>
<td>S</td>
<td>1.5±0.5</td>
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<tr>
<td>G.C. 74.9+01.2</td>
<td>303.5</td>
<td>+37.0</td>
<td>8×6</td>
<td>F</td>
<td>1.5±0.5</td>
</tr>
<tr>
<td>G.C. 89.0+04.7</td>
<td>310.9</td>
<td>+50.4</td>
<td>120×90</td>
<td>S</td>
<td>1.5±0.5</td>
</tr>
</tbody>
</table>

Table 1: SNRs data: Type S is shell, F is filled center, plerionic, IR is irregular, and CO is central object. Quoted from Lang (1991).

<table>
<thead>
<tr>
<th>Remnant name</th>
<th>Days</th>
<th>$N_{ON}$</th>
<th>$N_{OFF}$</th>
<th>s : Li-Ma Significance</th>
<th>Upper Probability</th>
<th>Flux upper limit $\times 10^{-13} \text{cm}^{-2} \text{s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W44</td>
<td>551</td>
<td>26701</td>
<td>879458</td>
<td>-2.33</td>
<td>0.99</td>
<td>5.83</td>
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<tr>
<td>Tycho</td>
<td>565</td>
<td>30108</td>
<td>966181</td>
<td>1.98</td>
<td>0.024</td>
<td>20.1</td>
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<tr>
<td>W49B</td>
<td>550</td>
<td>39090</td>
<td>1258838</td>
<td>1.57</td>
<td>0.058</td>
<td>15.8</td>
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<tr>
<td>HB3</td>
<td>566</td>
<td>32846</td>
<td>1047711</td>
<td>3.14</td>
<td>0.00084</td>
<td>27.9</td>
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<tr>
<td>Crab</td>
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<td>55497</td>
<td>1800051</td>
<td>0.21</td>
<td>0.42</td>
<td>8.89</td>
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<tr>
<td>HB9</td>
<td>568</td>
<td>54876</td>
<td>1777348</td>
<td>0.54</td>
<td>0.29</td>
<td>9.58</td>
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<td>OA184</td>
<td>567</td>
<td>58807</td>
<td>1895810</td>
<td>1.67</td>
<td>0.047</td>
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Table 2: result of analysis: Upper probabilities are give by the upper probability integrals of the normal distribution in the region of significance greater than s. Flux upper limits are obtained by the same method presented in Amenomori et al(a)(1992).
Search for 10 TeV Gamma-Ray Emission from Active Galactic Nuclei with the Tibet Air Shower Array

The Tibet ASγ Collaboration

ABSTRACT

A search for 10 TeV γ-ray emission from 15 active galactic nuclei (AGN) which were detected by EGRET, was made with the Tibet air shower array installed at an elevation of 4300 m above sea level. The data set, taken in the period from June 18, 1990 through September 29, 1992, has been used to search for continuous emission as well as emission on the time scale of one day. No evidence for emission from any of the AGNs on any of the time scales examined was found. The 95% C.L. upper limit to the continuous flux is presented on each source and in particular the result for Markarian 421 is compared with other experiments. Further observation of γ-rays at energies around 10 TeV from nearby AGNs will provide reliable information on the strength of the intergalactic background photon field.

Subject headings: cosmic rays – gamma-rays:observations – quasars:individual (Markarian 421)
Detection of MultiTeV gamma rays in the THEMISTOCLE experiment: new results.

THEMISTOCLE Collaboration

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(Revision Sept.16,1994)

Abstract.

A brief description of the THEMISTOCLE experiment is given. The new results, theoretical (simulations) and analysis of new data is presented.

We found a systematic decrease of the energy of our showers after introducing nucleus-nucleus interaction in our shower MC generations. The analysis of all our disponible observations of the CRAB NEBULA is presented. The new developments on the waveform of the Čerenkov impulsion and on coarse imaging in preparation are described.


Keywords: Astrophysics, gamma astronomy, solar power plants, fast electronics.

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The French solar test plant THEMIS is situated in the French East Pyrenees at latitude 42.50° N, longitude 1.97° E at mean altitude 1650m above sea level. In 1986, the energy production was stopped. Some of the 200 mountings for solar mirrors were adapted for γ-ray astronomy: - 7 for ASGAT and 19 for THEMISTOCLE. (Fig. 1)

The THEMISTOCLE experiment.

Cosmic Rays, mostly hadrons and γ's in the TeV energy region, interact with the Earth's atmosphere starting at altitudes of 20km. The general feature of the development of the Čerenkov light emitted by the showers at ground level are roughly identical: same shape, slightly conical (1°) light disk 200m in diameter and typically 1 meter (3 nanoseconds) thick. To observe this flash of (visible) light, we have installed on 19 of the alt-azimuthal mountings (Fig. 2) circular parabolical mirrors of diameter 80cm, which concentrates the Čerenkov light through a 16mm diaphragm (+-20 mrad opening angle) onto the photocathode of Philips XP2020 photomultiplier (Fig. 3). To determine the arrival time of the impulsion independently of their size a Constant Fraction Discriminator is used, its total charge is also measured.

Thus the CR coming from all directions are seen in a window of +-20 mrad, on which we superimpose the single direction of the supposed γ-source, which our telescope is pointing. With the typical pointing precision of 2 mrad, we obtained for energies > 2 Tev the signal of 6.5
standard deviations for the CRAB NEBULA. This is the result of two winter campaigns (90-92), giving 582,200 seconds of on-source observations. The time measurement for up to 18 signals with a mean deviation of 330 picoseconds on a field of 4 ha was achieved by careful calibration of each night's measurements by a laser beam covering the entire field from the 100 m-high Solar tower. (Ref.: 1)(Fig. 3).

Monte Carlo simulations and energy calibration.

The MC program used in this paper, generates without analytical approximations, γ-rays and proton or nucleus showers in the atmosphere, following all particles, charged and gammas, without weighting, down to an energy of 100 MeV, and following their Čerenkov emission down to the detector. All the optical and electronic distortions are taken into account (slowing down the PM response, aberration of mirrors, response of amplifiers and CFD, etc.).

In the MC simulation only two factors are left free to be adjusted using experimental data. These are the global scaling factor (R) on the number of Čerenkov photons, depending on specific atmospheric conditions, and the total electronic gain (G).

The shape of the measured experimental distributions (distributions of ADC values, triggered PM multiplicities, etc.) depend strongly on G and could be adjusted. The temporal variation of trigger rate, mainly due to variations in atmospheric conditions, was taken into account in the analysis of the variations of R.

New results.

We have directed our investigations in both theoretical (simulations), as well as experimental directions. We have compared the results of our DELSIM MC program with other two MC models, better
applicable to the high energy 1-100 TeV region. These two very different models (and programs) (Capdevielle or Gaisser&Stanev) gave results which differed by less than 10% in comparison with more that 30% differences from the DELSIM program. Finally, we used the Capdevielle model.

Up to now, in all the shower simulations, only proton-induced showers were used. We have added to the simulations the nucleus-nucleus interactions. For the proportions of their abundance in the primary cosmic rays in the region 10-45 TeV/nucleus we have taken the proportions (p:He:CNO:NeS:Fe = 33:33:16:9:9).

For the nucleus-nucleus interaction model was used the simplified geometric model of Schmidt ablation-evaporation (Ref.: Djannati-Atai).

The main consequence of adding the nucleus-nucleus interaction in the CR shower production is their faster degradation in energy, which leads to a lower yield of Čerenkov light for a given energy, thus lowering our previous energy estimation, after careful checks, by a factor of 1.37.

New data for CRAB NEBULA.

This new, more realistic estimation of energy, was applied to all our "new data" from 3 winters, from 1991 to 1994. After applying all our standard cuts we finish with 300 hours of clean runs for the on-source measurements, presented in Table I and in Fig.4.( This gives 1,072,342 seconds of on source observation). Note that the values are lower than that of Ref.1. Taking into account the nucleus-nucleus interactions has lowered our energy estimation. In addition, the data, even with exactly the same cuts as applied to the 92-94 data are giving lower results. (see Table I. and (Fig.4).
Data taking on MKN-421.

The energy of the signal of AGN MKN-421 was pushed from GeV to TeV region. To extend it to the 10 TeV region, we started data taking in his direction. Up to now the data, both for data and background are, mainly due to bad meteorological conditions, too small in the volume and are not yet analysed.

The measurement of the waveform of the shower Čerenkov light.

Typical front-end duration of the Čerenkov light impulse for a 5-10TeV γ-shower has total rise time of 1.5nsec near the axis of the shower; this width decreases up to 0.6nsecs 75m from the axis. The electromagnetic shower is always very "clean". In contrast, hadronic showers have the arrival rise time of at least 2.5nsec and frequently there are early pre-impulsions, up to 5nsec, present due to very young generations of µ-mesons.

To check this picture, known from simulations, we added in the THEMISTOCLE field, starting in 1993, one new station, equipped with a new very-fast photomultiplier with rise time of 0.7 nanoseconds, [HAMAMATSU H2083], connected by only 4m of BNC cable directly to the entry of LeCroy Waveform Analyser 6880A (sampling time of 0.742 Nsecs, B.W. of the entry amplifier =300MHz, but acquisition time up to 8 seconds). Since February we have taken 20000 triggers together with the main THEMISTOCLE triggers.

To know exactly the response of our PM, we have measured its response to 300psec laser impulse.
Their exact form (rise-time=1.2ns, width=2.6ns, fall time=6.0ns) was fed to the MC program, which generates for hadron showers the expected impulsion characteristics. In Fig.5a we compare the simulated and measured total width of the impulsions. The agreement is very satisfactory up to widths of 4ns. The distribution of WD50 vs. DIST for the real events (Fig.5b) shows the same general shape as the same MC distribution (Fig.5c). The same distribution for gamma-primary showers is shown in Fig.5d.

Example of analyse of distributions of WD10, width of impulses at 10% of their maximum, very similar to Fig. 5c & 5d follows (3).

To enhance the proportion of gamma's in their pot-pourri with the hadrons, we propose to reject only 10% of gamma-showers. We show in Fig.6a the dependence of the width WD10 on the DISTance from the shower axis. The corresponding proportions of survived hadrons are represented in Fig.6b. We see that the rejections of hadrons>90% are for distances at least 100m. Evaluation of the proportions of remaining hadrons, depending on proportion of remaining gamma-showers is represented in Fig. 7. Here we examine use of only one measure point for Waveform analysis and we include all DISTances from the axis. In this case we enhance the gamma's by a factor 70/8.5~ 8. (arrows in Fig. 7).

Three WA stations selected with circumspection in the THEMISTOCLE field will ensure a factor at least 10 in our gamma selection.

Technical improvements in THEMISTOCLE.

After 4 years of running in arduous mountain conditions, more than usual checks of all apparatus is needed. The main change is replacement of all PM's, which were not new on the beginning of our
experiment.
For waveform measurements at several points we are preparing the DL515 VME module from STRUCK, Heidelberg, which with 4 FastADC in interlaced mode permit sampling up to 0.833nsec of pulses, much more economically than with the LeCroy WA6880A, in a much faster acquisition mode.

Imaging.

The 20th telescope was equipped with an RTC XP 4072 PM of 64 pixels (2.54mm)². With our mirror the total field covered is (2.7°)², each pixel covering (0.33°)².

We hope that imaging shall be efficient for showers beyond 7 TeV at two levels:
- to help to reject the hadrons by the core to halo ratio of the image,
- to add the additional information of the shower position and to introduce more constraints in the fit of the cone on the apex position.

Figure captions:

Fig 1. Layout of mirrors, detectors and the tower.
Fig.2. THEMISTOCLE telescope
Fig.3. The square of the angle between the CRAB direction and the reconstructed cone axis. The grey histogram shows the gamma signal. From Ref. 1.
Fig.4. CRAB NEBULA gamma-ray integral flux, including the Ref.1 and this paper THEMISTOCLE results.
Fig.5a. The half-height width for the measured and simulated impulses.
Fig.5b. The dependence of width on the distance to the axis of the shower for real events.
Fig.5c. The dependence of width on the distance to the axis of the shower for simulated hadrons.
Fig. 5d. The dependence of width on the distance to the axis of the shower for simulated primary gammas.

Fig. 6a. Dependence of the width of the base at 10% of the amplitude of impulsion (WD10) on the distance from the shower axis, asking all the time at least 90% of gamma-showers conserved.

Fig. 6b. Proportions of remaining hadrons, depending on distance, asking all the time more than 90% of gamma-showers conserved.

Fig. 7. Proportions of remaining hadrons, depending on proportions of remaining gamma's.

References.

(1) P. Baillon et al., Astroparticle Physics, 1, (1993), 341-355.
(2) A. Djannati-Atai, thesis (to be published).
(3) O. Riera, Rapport intern CdF, (to be published).
TABLE 1.

Spectrum of CRAB NEBULA - 3 years 91-92+92-93+93-94
No hadronicity cut. N total evts 166404 (PM>10)
N evts "bons runs" 152315 Total time 1072342s

PM > 12  Ellipse 100x95

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PM > 10  Ellipse 140x135

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Figure 2: Themistocle Telescope
Crab Nebula gamma-ray integral flux in the VHE/UHE domains
Fig. 5a

Fig. 5b

Fig. 5c

Fig. 5d
Fig. 6a

Fig. 6b

Fig. 7
SEARCH FOR 10 TeV BURST-LIKE EVENTS COINCIDENT WITH THE BATSE BURSTS USING THE TIBET AIR SHOWER ARRAY

The Tibet AS$\gamma$ Collaboration


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ABSTRACT

A cluster analysis is applied to search for gamma ray bursts in the Tibet air shower data. In this analysis a cluster is defined to be a group of showers having similarity which is expressed by how small the angular distance between them is. This analysis reasonably suggests the existence of 10 TeV bursts, and some of them are shown to be well coincident with the BATSE events at the 99.9 % confidence level. Further observation of our new array, which is now under construction in
Tibet and will be operated at a trigger rate of about 200 Hz, is expected to provide reliable investigation on this subject.

Subject headings; gamma rays: burst - gamma rays: observations

1. Introduction

The nature of the sources of cosmic gamma-ray bursts is a long-standing problem in high energy astrophysics. The BATSE (Meegan et al. 1992, Fishman et al., 1994) on board the Compton GRO has already detected more than 1000 bursts at keV-MeV energies since 1991. The distribution of the observed bursts in Galactic coordinates is consistent with a nearly isotropic source density that falls with distance. The result can not be explained by sources confined to the Galactic plane and permits a cosmological origin (Piran, 1992, Mao & Paczynski 1992, Dermer 1992, Fenimore et al. 1993, Wickramasinghe et al. 1993, Norris et al. 1994). This, however, also permits an origin in the Galactic disk with an extended halo of high-velocity neutron stars (Brainerd 1992, Li & Dermer 1992, Smith & Lamb 1993). Recently the COMPTEL (Winkler et al. 1992, Varendorff et al. 1993, Kippen et al. 1993) and EGRET (Schneid et al. 1992, Sommer et al. 1994, Dingus et al. 1994) detectors detected some bursts at keV-GeV energies simultaneously, but these observations can not yet make a settlement to the controversy between two possibilities on the origin of the bursts and the mystery still remains unsolved. From this point of view, a detection of VHE and UHE (1-100 TeV) gamma-ray bursts coincident with the BATSE events will be a challenge to the cosmological origin since VHE and UHE gamma-rays are strongly reduced by the interactions with the extragalactic infrared photon field (Stecker, De Jager & Salamon 1992, Stecker & De Jager 1993, De Jager, Stecker & Salamon 1994) as well as 3K microwave background radiation field (Gould & Schreder 1966, 1967a, 1967b) in passing through such distances.

Here we report the results on the search for 10 TeV gamma-ray bursts using the dataset obtained from the Tibet air shower experiment (Amenomori et al. 1992). In this analysis a clustering method is introduced to gather showers each being close in the space and time effectively. A group of showers, thus obtained, is called a "cluster" which is a candidate of burst. With use of this method we found several burst-like events coincident with the BATSE events at the confidence level of 99.9%. The following is a brief report on this analysis.

2. Experiment
The Tibet air shower array is located in Yangbajing at an altitude of 4300 m a.s.l. (90.53° E and 30.11° N), corresponding to an atmospheric depth of 606 g/cm². The array consists of 49 scintillation detectors of 0.5 m² each, which are distributed on a grid of 15 m spacing. Among them, 45 detectors (FT detectors) are equipped with fast response photomultiplier (PMT) to measure the arrival direction of air showers with a good accuracy. Since June 1990 the system has operated at a trigger rate of about 20 Hz under any 4-fold coincidence in the FT detectors and recorded about $9 \times 10^8$ shower events during the period of June 18, 1990 through September 29, 1992. The effective running time was 598.6 days. During this period 57 bursts in the second BATSE catalog are located in the effective viewing sky of our array.

A database was made by imposing the following conditions: 1) Each of any four FT detectors produces a signal more than 1.25 particles. 2) Among the four detectors recording the highest particle densities, two or more are in the inmost 5 x 5 detectors. 3) The mean lateral spread of each shower is less than 30 meters. We call these the 'contained' events, and in total about $3 \times 10^8$ contained events are obtained.

Monte Carlo simulations were done to examine the performance of the array. It is found: 1) The mode energy of primary particles detected by this array is about 7 TeV for protons and 8 TeV for $\gamma$-rays. 2) Detection efficiencies of the contained events at 10 TeV are about 26 % for proton-induced showers and 42 % for gamma-induced ones, respectively. Furthermore, the observation of the moon shadow, with a sufficient significance, has well confirmed the angular resolution of the array being better than 1° for all the contained events (Amenomori et al. 1993a, 1993b).

3. Analysis

The selection criteria of burst-like events are as follows: 1) Every shower in each event should be detected within a given burst duration time $\delta t$. 2) The direction of each event should be within a $1\sigma$ BATSE location error box which is made by taking account of the statistical uncertainty plus the 4 degree systematic error. 3) A relative difference between the arrival time of the first shower in the burst and the BATSE triggering time is less than 60 seconds. Since the duration time of each BATSE event changes from hundredths to hundreds of seconds, the following time intervals are examined in this analysis: $\delta t = 1, 3, 5, 7.5, 10, 20, 30, 50, 70, 100$ seconds and so on. We call these shower data satisfying the above conditions the "on-source" data. On the other hand, showers arrived early or late by more than one hour from
the BATSE triggering time are regarded as the background data for estimating the significance of a burst-like event appeared in the “on-source” data.

The BATSE 1σ location error (Meegan et al. 1992, Fishman et al., 1994) ranges from 4° to over 20°, much larger than that by the present air shower array, thus we introduced a clustering method for an effective search of a cluster of showers (burst-like event) from the air shower data. This method has been developed in the analysis of family events observed by the mountain emulsion chamber experiments (Amenomori et al. 1982, Ren et al. 1988) to study their cluster structures which could reflect the nature of nuclear interactions of a primary particle in the atmosphere. When we apply this to the present analysis, a cluster could be defined to be a group of showers having similarity which is expressed by how small the angular distance between them is. The actual procedure is done as follows: Assume the array detects $N$ showers within a time duration from a selected viewing sky. One calculates $\chi_{ij} = \sqrt{\omega_i \omega_j \theta_{ij}}$ between each pair of showers with $i, j = 1, \cdots, N$ and $i \neq j$, where $\theta_{ij}$ is the real angular distance of the pair, and $\omega = \sqrt{\sum \rho}$ since the angular resolution of our array becomes better roughly at the inverse square root of the sum of particle densities over the triggered scintillation detectors. If the minimum value ($\chi_{\text{min}}$) of $\chi_{ij}$ is less than a given cutoff value $\chi_c$ then the $i$th and $j$th showers are combined into a “cluster” with the total $\omega = \omega_i + \omega_j$ and a new vector location for their $\omega$-weighted centroid. The process is terminated when $\chi_{\text{min}} \geq \chi_c$ or $N_c = 1$.

In order to determine a relevant value of the cutoff parameter $\chi_c$, a Monte Carlo simulation has been done. In the simulation the $\omega$ distribution was taken from the experimental data and a Gaussian function with $\sigma = 0.8°$ was assumed as the angular resolution function. Clusters consisting of 3, 5, 7, and 9 showers were sampled as incoming bursts for each of different duration times. We then imposed the condition that after clustering more than 80% of the reconstructed clusters should be the same as the original ones. This trial teaches us that the most probable value of $\chi_c$ is 25 degree/meter for some short burst durations (say $\delta t < 50$ seconds). For long durations $\chi_c$ may be somewhat larger, say $\sim 40$ degree/meter for $\delta t = 100$ seconds. Since the clustering depends weakly on the value of $\chi_c$, however, we used the value of $\chi_c = 25$ degree/meter for all the burst time durations. Every selected showers were examined as the starting showers of the bursts. The “on-source” and background data were processed under the same clustering conditions.

4. Results and Discussions
Figure 1-(a) shows the dependence of the mean number \( (N_0) \) of showers in a cluster on the zenith angle for the burst duration \( \delta t = 1, 3, 10 \) and 50 seconds, obtained from the background data. Shown in Fig.1-(b) are the probability distributions at the zenith angle of 20° for respective burst durations. The attached solid curves in Fig.1-(b) present the Poisson distribution function with the expected values in Fig.1-(a). Some deviations of the data from the curves could be attributed to a non-random behaviour in the clustering procedure. A fitting curve to each case was used in estimating the significance of the burst-like events appeared in the "on-source" data.

Since our keen interest is to search for 10 TeV burst-like events which are coincident with the BATSE bursts, the clusters to be found is as close to the BATSE bursts as possible with higher significance. We then introduce a new parameter defined by \( \eta = N_r p \) for each cluster, where \( p \) is the integral fluctuation probability calculated from the symbols in Fig.1-(b). \( N_r \) is the number of showers within the time interval between the arrival time of the first shower in the cluster and the BATSE triggering time, falling within the directional circle centered at the BATSE location with a radius of the angular distance between the first shower and the BATSE burst location. Obviously the parameter \( N_r \) could represent a degree of closeness between the burst-like event and the BATSE burst. The smaller the value of \( \eta \), the higher the significance of the cluster as a burst. Plotted in Fig.2 are the \( \eta \)-distributions for all the "on-source" data viewing 57 BATSE bursts, where (a), (b), (c) and (d) are for burst duration \( \delta t = 1, 3, 10 \) and 50 seconds, respectively. The histograms in the figures show the background fluctuations. In doing this we made a random sampling on the triggering times and locations for the BATSE bursts in the recording period of the background data and then obtained the artificial (or pseudo) "on-source" data. The total amount of the artificial "on-source" data is 100 times as large as the true "on-source" data. It can be seen from the figure that some "on-source" points distribute far from the background fluctuations, suggesting the existence of 10 TeV burst-like events coincident with the BATSE bursts. The chance probability of finding such a cluster is estimated to be \( 10^{-2} \sim 10^{-4} \). When combining all of them together and taking into account a trials factor of \( _{10}C_4 = 210 \), however, its chance probability becomes much smaller as \( \sim 10^{-8} \). In Table 1 we summarize some characteristic features for each of 4 clusters with the smallest values of \( \eta \) (the most left-handed four points in Fig.2). It should be noted that all these four BATSE bursts are faint events. According to the works (Piran, 1992, Mao & Paczynski 1992, Dermer 1992, Fenimore et al. 1993, Wickramasinghe et al. 1993, Norris et al. 1994), such faint bursts may be at the cosmological distances. VHE and
UHE gamma-rays are strongly reduced by pair productions with the extragalactic infrared photons and 3K microwave background radiations in passing through such distances. Thus, if the present results are confirmed, a question will arise as to the cosmological origin of the BATSE bursts.

Our array will be enlarged by a factor of four on the geometric scale, while the effective area being more than eight times. The data taking will start from the beginning of the next year. If the same events as discussed above are recorded by this new array, its significance will be several orders better. Therefore, the operation of the new array for several more years is expected to provide a reliable understanding on this subject.

Acknowledgments

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References

Figure captions

Fig.1-(a) Distributions of the mean number ($N_e$) of showers in a cluster at different zenith angles from the background data. The symbols of circles, squares, triangles and asterisks are for burst duration $\delta t = 1, 3, 10$ and 50 seconds, respectively.

Fig.1-(b) Probability distributions of number ($N_p$) of showers in a cluster at the zenith angle of 20 degree. The ordinate means logarithm of the differential probability. The symbols are same as those in Fig.1-(a). The attached solid curves denote the Poisson distribution functions with the expected values in Fig.1-(a). For a convenient plotting, the probability values at $\delta t = 1, 3, 10$ and 50 seconds are multiplied by factors of $10^7, 10^8, 10^9$, and $10^{10}$, respectively.

Fig.2 $\eta$-distributions for all the "on-source" data viewing 57 BATSE bursts, where (a), (b), (c) and (d) are for the burst duration time $\delta t = 1, 3, 10$ and 50 seconds, respectively. The histograms in the figures represent the background fluctuations.

Table captions

Table 1 More detailed information for 4 clusters with the smallest values of $\eta$ (the most left-handed four points in Fig.2), where B.No. means the BATSE trigger number, and $N_p$ the number of showers in our cluster, $\theta$ the mean zenith angle of the cluster, $N_e$ the expected (mean) value of $N_p$ from the background data, $\Delta$ the angular distance between the cluster direction center and BATSE location, and $t - t_B$ the triggering time difference between the first shower in the cluster and the BATSE burst, respectively.

<table>
<thead>
<tr>
<th>$\delta t$ (s)</th>
<th>1</th>
<th>3</th>
<th>10</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.No.</td>
<td>1449</td>
<td>820</td>
<td>836</td>
<td>824</td>
</tr>
<tr>
<td>$N_p - 1$</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>$\theta$ (degree)</td>
<td>33.3</td>
<td>23.4</td>
<td>7.7</td>
<td>18.0</td>
</tr>
<tr>
<td>$N_e - 1$</td>
<td>0.026</td>
<td>0.093</td>
<td>0.38</td>
<td>0.92</td>
</tr>
<tr>
<td>$\Delta$ (degree)</td>
<td>2.4</td>
<td>8.5</td>
<td>7.8</td>
<td>3.2</td>
</tr>
<tr>
<td>$t - t_B$ (s)</td>
<td>43.5</td>
<td>-19.5</td>
<td>42.2</td>
<td>-18.1</td>
</tr>
</tbody>
</table>
A Search for Cosmic Point Sources of Muons and for Seasonal Variations in the Underground Muon Flux with The MACRO Detector

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Abstract

An all-sky survey for cosmic sources of an excess muon flux above the expected cosmic ray background has been performed using the muons collected between March 1989 and June 1994 by the MACRO is a large area underground experiment. No statistically significant excesses have been found. Upper limits to the steady muon flux for several sources of interest are given. To improve the signal-to-noise, periodicity analyses have been conducted for Cygnus X-3 and Geminga. These investigations show no statistically significant muon excesses above background. A high efficiency data set of muons from 1993 has been searched for seasonal variations in the underground muon rate. The variations are present with a magnitude of a few percent. The data from 1991 and 1992 are consistent with these results.

1 The MACRO Experiment

MACRO has been described in detail elsewhere [1]. We give here only its characteristics relevant to these investigations. The MACRO detector is located in Hall B of the Gran Sasso National Laboratory (LNGS). This laboratory is at an average depth of 3800 meters of water equivalent (m.w.e.), with a minimum depth of 3150 m.w.e. The laboratory is 963 meters above sea level. The threshold energy for muons is $\sim 1.4 \text{ TeV}$. The modular detector consists of six supermodules (SMs) in two levels, with each SM being further subdivided into 2 equal modules. Each SM is fully instrumented. Data acquisition integrates all operational SMs.

2 Search for Cosmic Point Sources of Muons

The search for an underground muon signal from cosmic point sources faces two main challenges. First, there is no known astrophysical process capable of producing a muon signal in underground detectors above atmospheric background. Any confirmed detection of a muon signal from a point source would demand non-Standard Model physics. Second, there is the expectation that cosmic sources associated with a muon excess would also be high energy photon emitters. However, the observational
evidence of VHE and UHE $\gamma$-ray sources is sparse. The operation of a new generation of $\gamma$-ray detectors with improved performance has not brought a corresponding increase in significance in any previously reported observation. The one exception, the high significance observation of the Crab by the Whipple observatory, is not likely to be relevant to underground muon detectors, owing to the spectral characteristics of the source. For a $\gamma$-ray flux of the form $J_\gamma(> E_\gamma) = KE_\gamma^{-\alpha}$, the results of Berezinsky et al. [2] show the expected flux of muons from the Crab nebula ($\alpha = 1.4$) to be $J_\mu(E_\mu > 1.4 \text{ TeV}) \approx 10^{-15} \text{ cm}^{-2} \text{ s}^{-1}$, well below our present limits.

There have been occasional claims from underground experiments of the detection of signals from the direction of some sources, notably Cyg X-3 [3] and more recently 3C273 [4]. However, MACRO has not found a statistically significant cosmic point source of muons above background in earlier work [5], and the analysis presented in this paper strengthens the previous result.

One of the strengths of MACRO as a muon telescope is its excellent angular resolution. The MACRO resolution is the result of the convolution of the instrumental angular resolution and the effect of multiple Coulomb scattering as the muons traverse the rock overburden. The instrumental angular resolution of the limited streamer tube system which provides the tracking information is nominally less than $0.5^\circ$. After folding in the effect of multiple Coulomb scattering, we obtain an overall angular resolution of $0.8^\circ$. This is consistent with the measured relative angular spread of muons within multimuon events.

2.1 Data Selection

The muon astronomy results reported here include data obtained with several detector configurations. Our data selection criteria require a determination of the detector efficiency on a run-by-run basis. Since our method of determining run efficiencies uses data from both the scintillator and the streamer tube systems, we require both systems to be operational for a run to be included in the analysis. There were three periods of data-taking when both systems were operational.

The first data set (SM1) spans the period between March 1989 and November 1991 when the scintillator and streamer tube systems on the first supermodule were active. The second data set (Interim) spans the period between March 1992 and September 1992. The third data set was a period of data taking with six supermodules and spans the period between December 1992 and June 1993 (6 Month Run). Data selection criteria were then applied in order to assure good uniformity and stability of data taking conditions.
The dates, the live time, the number of reconstructed tracks, and the number of events analyzed (events remaining after selection cuts) for these data samples are given in Table 1.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Dates</th>
<th>SMs Active</th>
<th># Reconstructed Events</th>
<th>Events Analyzed</th>
<th>Exposure (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM1</td>
<td>3/89-11/91</td>
<td>1</td>
<td>1,821,431</td>
<td>1,027,038</td>
<td>8,636</td>
</tr>
<tr>
<td>Interim</td>
<td>3/92-9/92</td>
<td>2, 4, 6</td>
<td>3,051,455</td>
<td>1,570,034</td>
<td>3,948</td>
</tr>
<tr>
<td>6-Month</td>
<td>12/92-6/93</td>
<td>6</td>
<td>2,913,017</td>
<td>2,638,843</td>
<td>3,415</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td>7,785,903</td>
<td>5,235,915</td>
<td>16,000</td>
</tr>
</tbody>
</table>

Table 1: Parameters of Muon Astronomy Data Sets.

2.2 Background Simulation

Background muon events were simulated by Monte Carlo methods. To preserve the effects of detector downtime in the simulated backgrounds, simulated muon arrival times were chosen on a run-by-run basis. For a given run, the mean time between events $\Delta t$ was computed by using the observed number of events and the actual beginning and ending times of the run. The first simulated event was assigned the time of the first observed event, and the intervals between subsequent arrival times were chosen as exponential deviates of the computed mean time: $\Delta t = \bar{\Delta t} \times (-\ln x)$, where $x$ is chosen randomly from the uniform distribution of values between 0 and 1. The arrival time of the $i$th event would then be given by $t_i = t_{i-1} + \Delta t$. The simulation of a run was complete when the number of generated events was equal to the number of observed events. This method successfully reproduces the distribution of time differences between events [7], a particularly important consideration in the search for periodicities. The direction for each Monte Carlo event was chosen from the two-dimensional distribution of zenith and azimuth angles derived from the data. The simulated position and time for each event were combined to calculate the right ascension and declination. The backgrounds used are the averages computed from 25 such simulations.

2.3 All-Sky Survey

The muons were first sorted into bins of equal solid angle, $\Delta \Omega = 2.1 \times 10^{-3}$ ($\Delta \alpha = 3.0^\circ$, $\Delta \sin \delta = 0.04$). These bins have approximately the same $\Delta \Omega$ as a cone of half-angle $1.5^\circ$. To reduce the possibility of missing a
Figure 1: The all-sky survey. The distribution of bin-by-bin deviations between the number of muon events observed and the number of muon events expected from the cosmic ray background. The solid line is the best-fit Gaussian.

For each solid angle bin the deviation from the mean in units of the standard deviation was computed using the Gaussian statistics \( \frac{n_{\text{obs}} - n_{\text{exp}}}{\sqrt{n_{\text{exp}}}} \), where \( n_{\text{obs}} \) is the observed number of events in the bin and \( n_{\text{exp}} \) is the number of events expected from the background. For each of the four different surveys, a distribution of the deviations was plotted and a Gaussian was fitted to the distribution. We are searching for an excess of muons that has large statistical significance given the number of sky bins in the survey. For example, a single 3.5σ excess is not of particularly high statistical significance in a survey with 3360 bins like ours. In addition, we require that this statistically significant excess be apparent at a consistent position in at least two of the four overlapping surveys. Figure 1 shows the distribution of deviations corresponding to survey 1. On this distribution the best-fit Gaussian has been superposed.

The results of the remaining 3 surveys are similar to that shown in Figure 1. The number of large fluctuations in all the surveys are consistent with random fluctuations in the cosmic ray background. Further, large excesses (> 3σ) are not found at consistent positions in more than one survey.

However, there is some chance that a large fluctuation is correlated with the position of a known high energy source. For this reason we have searched through lists of candidate objects to match with the positions of
our excesses. For survey 1 shown in Figure 1, two bins have excess larger than 3.5σ. For the bins with 3.7σ (α = 6h 6m; δ = 32° 41.5′) and 4.1σ fluctuations (α = 20h 18m; δ = 55° 8.1′), we have searched the lists of X-ray binary sources in the catalogues of Joss and Rappaport [8] and Nagase [9], the X-ray sources listed in the HEAO-1 all-sky survey [10], and GRO EGRET extragalactic sources (see Miller [6]). We found no evidence for known high energy sources at the positions of these muon excesses.

The upper limit with 95% C.L. to the muon flux (i.e. number of muons per square centimeter per second) in each bin, \( J_{\mu}^{\text{stdy}}(95\%) \), was computed from

\[
J_{\mu}^{\text{stdy}}(95\%) \leq \frac{n_{\mu}(95\%)}{0.78 \sum_{i}(\bar{\epsilon}_{i} A_{i} f_{i} t_{i})} \text{cm}^{-2} \text{s}^{-1},
\]

where the sum in the denominator is over the four different detector configurations (1 SM, 2 SM, 4 SM, or 6 SM); \( n_{\mu}(95\%) \) is the upper limit with 95% C.L. for the muon signal in the bin computed from \( n_{\text{obs}} \) and \( n_{\text{exp}} \) according to Helene [11]; \( \bar{\epsilon}_{i} \) is the average efficiency, taking into account both the run efficiency (computed from the data) and the geometrical efficiency (the probability that a muon from a particular direction has a reconstructed track, i.e. crosses at least 4 streamer tube planes, computed from the MACRO detector Monte Carlo) [6]; \( A_{i} \) is the average effective area assuming the detector to be a live box; \( f_{i} \) is the fractional exposure time; and \( t_{i} \) is the exposure time for that detector configuration. Except for \( t_{i} \), all of the quantities in the computation are bin specific. The constant factor of 0.78 accounts for the scatter of some muons out of the 1.5° bin. This factor was derived from the analysis of dimuon events. A discussion of the methods used in the evaluation of the factors in eq.(1) are in [6].

2.4 Point Source Studies

The all-sky survey is the standard astronomical technique for locating and identifying sources in a previously unexplored bandwidth or with a detector having an unprecedented level of sensitivity. The technique is unbiased since it makes no a priori assumptions about the locations of possible sources. Nevertheless, we have selected a small, biased set of high energy sources for further study anyhow: Cyg X-3, Her X-1, Geminga, Mrk 421, and 3C273. Cyg X-3 and Her X-1 are X-ray binary sources with reported detections of muons. Geminga is a nearby, strong γ-ray pulsar. The BL Lac object Mrk 421 has been detected in TeV γ-rays by the Whipple Observatory. The Soudan II group has reported steady muon emission from the quasar 3C 273.

2.4.1 Steady Flux Limits

Table 2 gives the 95% C.L. to the steady muon flux for these sources.
based on the all-sky survey.

<table>
<thead>
<tr>
<th>Source</th>
<th>Object Type</th>
<th>$J_{\mu}^{\text{stdy}}(95%)$ (cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg X-3</td>
<td>X-ray binary</td>
<td>8.7 x 10^{-13}</td>
</tr>
<tr>
<td>Her X-1</td>
<td>X-ray binary</td>
<td>1.3 x 10^{-12}</td>
</tr>
<tr>
<td>Geminga</td>
<td>$\gamma$-ray pulsar</td>
<td>1.0 x 10^{-12}</td>
</tr>
<tr>
<td>Mrk 421</td>
<td>BL Lac</td>
<td>1.6 x 10^{-12}</td>
</tr>
<tr>
<td>3C273</td>
<td>quasar</td>
<td>1.5 x 10^{-12}</td>
</tr>
</tbody>
</table>

Table 2: Steady Flux Limits for Selected Sources.

2.4.2 Searches for Modulated Signals

It is well-known that when the emission from a source is modulated with an a priori known period and a small duty cycle, the signal-to-noise ratio can be improved by a periodicity analysis. For Cyg X-3 and Geminga we have performed periodicity analyses.

For the muons used in the all-sky survey with directions pointing back to a 1.5° half-angle cone centered on Cyg X-3, we have constructed a phase diagram based on an extrapolation of the quadratic ephemeris that van der Klis & Bonnet-Bidaud [12] fitted to the X-ray light curve obtained by EXOSAT. The arrival time of each muon was first corrected for the earth's motion with respect to the solar system barycentre, and then the phase was calculated from the extrapolated light curve.

Since the modulated muon emission reported by Soudan 1 and NUSEX [3] was found in a phase bin of width $\Delta \Phi = 0.1$, we have binned the data into 10 phase bins.

The phase diagram is shown in Figure 2. The average expected number of muons in each phase bin is also shown in Figure 2 as a dashed line. From this figure we see that the largest positive deviation in one cycle is found in the phase bin $0.4 \leq \Phi \leq 0.5$ and its magnitude is $\approx 1.0 \sigma$. We have performed the run test [13] to determine the significance of the distribution of positive and negative fluctuations seen in Figure 2. The probability is 1.7% that this sequence of positive and negative fluctuations is due to a random process. We conclude that the present data are consistent with fluctuations in the background.

For the muons used in the all-sky survey with arrival times between 1990.3 and 1993.7 and with directions pointing back to a 1.5° half-angle cone centered on Geminga, we have constructed a phase diagram based on the ephemeris computed by the Compton Observatory EGRET team [14].
Figure 2: Phase diagram for the muon events from a 1.5° half-angle cone centered on Cyg X-3. The orbital period used to compute the phase is taken from the X-ray light curve derived by van der Klis and Bonnet-Bidaud [12]. (crosses – data; dashes – expected background)

<table>
<thead>
<tr>
<th>Source</th>
<th>( J_{\mu}^{\text{mod}}(95%) ) (( \text{cm}^{-2}\text{s}^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg X-3</td>
<td>( 4.6 \times 10^{-13} )</td>
</tr>
<tr>
<td>Geminga</td>
<td>( 6.1 \times 10^{-13} )</td>
</tr>
</tbody>
</table>

Table 3: Modulated Flux Limits for Cyg X-3, Geminga.

The stated accuracy of the ephemeris is \( \Delta \Phi = 0.1 \) over the period listed above, so we again analyzed the data by sorting it into 10 phase bins. The arrival time of each muon was corrected for the earth’s motion with respect to the solar system barycentre and the phase was calculated from the light curve.

The phase diagram is shown in Figure 3. The average expected number of muons in each phase bin is also shown in Figure 3 as a dashed line. From this figure we see that the largest positive deviation in one complete cycle is found in phase bin \( 0.9 \leq \Phi \leq 1.0 \) and its magnitude is \( \approx 1.0\sigma \). These data show no evidence for a modulated muon signal with this period. In Table 3 we give the 95% confidence limits to the modulated muon flux from the directions of Cyg X-3 and Geminga using an equation analogous to eq.(1). In these computations we have used the phase bin which shows the largest positive fluctuation (Cyg X-3: \( 0.4 \leq \Phi \leq 0.5 \); Geminga: \( 0.9 \leq \Phi \leq 1.0 \)).
Figure 3: Phase diagram for muon events from a 1.5° half-angle cone centered on Geminga. The orbital period used to compute the phase is taken from the GRO EGRET γ-ray light curve. (crosses – data; dashes – expected background)

3 Search for Seasonal Variations in the Underground Muon Flux

The time variations of the cosmic ray muon flux recorded by underground detectors are of interest in both astrophysics and geophysics. Because most single and multiple muons seen underground are produced by protons and heavier nuclei that hit the Earth's atmosphere, any variation of the intensity of the underground muon component may reflect an anisotropy of the primary cosmic ray flux that may yield insight into cosmic ray origin and acceleration processes.

One reported variation in the cosmic ray muon flux observed underground [15], however, has a much simpler explanation. Cosmic ray interactions in the atmosphere produce mesons copiously. A density decrease in the upper atmosphere leads to a slight increase in the probability that a secondary meson will decay into a muon before it interacts in air; an increase in the atmospheric density leads to a slight decrease in the probability that a parent meson will decay into a muon before it interacts. Seasonal temperature variations in the upper atmosphere are thought to result in the observed seasonal muon flux variations observed deep underground.

3.1 Data Selection

The reported seasonal variations in the muon flux are small [15], with a magnitude of only a few percent. The unambiguous detection of an
effect this small requires the selection of a data sample that requires no correction for variations in efficiency, dead-time, or geometry. By defining a clear data sample, absolute rates can be compared directly to search for seasonal variations. The following data selection criteria were used on a run-by-run basis:

selected runs:
- runs with 6 SM
  - runs > 1h in length
  - runs with dead-time < 1.5%
  - runs with streamer tube efficiencies > 90%
  - runs whose rate doesn’t deviate by more than 3 standard deviations from the average rate.
  - runs with no spurious data acquisition behaviour

selected events:
- events were required to cross 10 horizontal planes within a single module
- only single muons were analyzed that were reconstructed in both the wire and strip views

Careful study shows that these cuts ensure the selection of a data sample that is at least 99.7% efficient in detecting single muons; moreover the stability in efficiency is even larger. We are interested only in relative variations; no correction was found necessary to an accuracy of 0.23. The data analyzed in this study were obtained between December 1992 and November 1993 when all 6 supermodules of MACRO were operational. The additional requirement that the events must pass through the top and bottom planes of the detector leads to a data set requiring no correction.

A total of 2,785,328 muons passed the cuts and were analyzed here.

3.2 Results

Figure 4 shows the monthly percentage deviations ($\Delta R/R_0$), where $R_0$ is the average rate for the whole year and $\Delta R$ is the deviation from this mean during 1993. The errors shown are statistical errors in the counting rate. There is a clear, statistically significant seasonal variation, with a maximum in June-July (summer) and the minimum in December-January (winter), as expected. The maximum deviation is about 2.6%.

The origin of this effect is probably connected to the seasonal variation of the temperature of muon production levels in high atmosphere. An accurate evaluation of this temperature effect requires the knowledge of monthly averaged temperature measured at different atmospheric levels.

Muon data recorded in 1991 and 1992, although of lower statistical significance because of detector construction, are consistent with the results for 1993, see Figure 4.
Figure 4: Percent deviations of the monthly muon intensity from the average muon intensity plotted vs. month number for 1991-1993.

* For the author list, see C. De Marzo, Results on upward going muons with MACRO and coincidence events with EAS-TOP array, this volume.

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[14] I.A.U. Circular #5649
TeV γ-ray astronomy using Atmospheric Čerenkov Telescope at Pachmarhi


Tata Institute of Fundamental Research, Homi Bhabha Roac Colaba, Bombay - 400 005, India

ABSTRACT

We present the details of the distributed Atmospheric Čerenkov Telescope Array currently operating at Pachmarhi, India. We use the differences in the lateral distribution of Čerenkov photons between the γ-ray and proton induced showers to cut down the cosmic ray background. Preliminary analysis of data on Crab and Geminga pulsars, taken during 1992 - 1993 indicates that it is possible to reduce background, when a cut designed to preferentially select showers with a flat lateral distribution of Čerenkov photons, is made.

1. INTRODUCTION

To search for persistent weak emission of TeV γ-rays from celestial sources one has to reduce the background due to hadronic cosmic ray showers. Monte-Carlo simulations have shown that differences between hadron induced and γ-ray initiated cascades could be exploited to reject cosmic ray initiated showers (Hillas 1985, Hillas and Patterson 1987, Rao and Sinha 1988). The simulations have shown that electromagnetic cascades are flatter in the lateral distribution of Čerenkov photons and more compact in the angular size of the Čerenkov images than those initiated by cosmic ray primaries.

Several groups have used some of the above parameters to reject the background and enhance the signal (Weekes 1989, Baillon et al. 1994, Tumer et al. 1985 and Goret et al. 1993). The Whipple group has detected steady emission of TeV γ-rays from Crab nebula using Čerenkov imaging technique (Vacanti et al. 1992 and Punch et al. 1992) and have established this source as a 'standard candle' of TeV γ-rays. However, not enough attention has been given to the lateral distribution aspect of the atmospheric Čerenkov radiation to reject cosmic ray initiated background. The lateral distribution of Čerenkov photons have a "hump" at distances of 120-140 m from the shower core in γ-ray initiated cascades only (Rao and Sinha 1988). Further, the shower to shower fluctuations in the lateral distribution of Čerenkov photons is much less for a γ-ray initiated shower compared to cosmic ray initiated showers, which

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are rather 'bumpy' due to the contribution of Čerenkov light from muons. The average lateral distribution of Čerenkov photon densities, as calculated by Hillas and Patterson (Hillas and Patterson 1990), clearly show a flat distribution up to the "hump" region for γ-ray initiated showers and a steeper distribution for proton initiated ones. Rao and Sinha (Rao and Sinha 1988) have shown that the signal to noise ratio could at least be improved twice by exploiting these very differences. Calculations made for various array configurations showed (Vishwanath et al. 1993) that unambiguous identification of γ-ray initiated showers could be made with a large number of detectors sampling the Čerenkov photons. Accordingly, the set-up at Pachmarhi is being modified and augmented. In this paper, we describe our set-up, method of observation and data analysis techniques. Data taken during 1992-93 on Crab pulsar is used as a training ground for an analysis technique which rejects background using differences in the lateral distribution of Čerenkov photons between γ-ray and proton initiated showers. Preliminary results on Crab and Geminga pulsars are also reported.

2. TELESCOPE SET-UP

The Atmospheric Čerenkov Telescope Array at Pachmarhi, India (longitude: 78° 26' E, latitude: 22° 28' N and altitude: 1075 m a.s.l.) consists of an array of parabolic reflectors of 0.9 m and 1.5 m in diameter spread over an area of 85 m x 100 m. The reflectors are equatorially mounted and independently steerable both in E-W and N-S directions. The reflector orientation and tracking are controlled by a computer automated system to an accuracy of ±0°.1. A fast photomultiplier (Burle 8575) mounted at the focal plane of each reflector behind a 2° diameter mask is used to detect Čerenkov photons.

Prior to 1992, we had 20 reflectors, each having its own mount. The number of reflectors is steadily and constantly increased to improve the signal/noise ratio over the years. At present, the array is configured to consist of 13 banks of reflectors of 2.5 m² total area each as shown in figure 1. Pulses from photomultipliers of a given bank were linearly added together. The telescope set-up is being further upgraded to have 25 banks, each having a total reflector area of 4.4 m². The mirror mount was also re-designed so as to hold 7 reflectors in a mount. In its final form the banks will be arranged in a 5 x 5 matrix with a spacing of 20 to 25 m.

3. OBSERVATIONS

The modification and expansion of the array was started in Jan '92. While development work was given priority, observations were carried out on isolated pulsars like Crab and Geminga mainly to train the analysis procedures and test the trigger electronics.

Data were taken during clear moonless nights. The source was acquired and tracked by an automated computer-controlled tracking system. Pointing and tracking
accuracy of all telescopes was within ±6'. Typically, a source was tracked for about 1 to 5 hours over the hour angle range of −38° to +38°. Event triggers were generated by a majority logic of various combinations of reflector banks and pulse height threshold levels. Each trigger was tagged for its identification. The minimal trigger corresponds to a threshold energy of 600 GeV for γ-rays. Event arrival times were derived from a Global Position Satellite receiver having a time keeping accuracy of ±100 ns. Each event data consists of the event arrival time to an accuracy of ±1 µs, amplitude and relative time of arrival of pulses at each bank, trigger information and other relevant house-keeping informations which are recorded on a magnetic tape by a real time data acquisition system (Bhat et al. 1990).

Genuine coincidence rates, chance coincidence rates and all the bank rates were monitored throughout a run.

4. ANALYSIS

The observed event times are reduced to that at the solar system barycenter using the JPL ephemeris. The phase of each event is computed using contemporaneous pulsar elements and a phasogram is constructed. Two cuts, one based on the arrival direction of the shower and the other based on the flatness of the lateral density distribution of Čerenkov photons, are applied to reduce the content of cosmic ray initiated showers in the data.

We demand that at least 5 banks trigger for determining the arrival direction of a shower from the time to digital converter (TDC) information, approximating the shower front to a plane. The angular resolution of the system is obtained by the split array method and is about 0°.75. (0°.6 for ≥7 triggered banks). The number of events as a function of the space angle between the two sets of direction measurements is shown in figure 2.

We define a parameter $F$, called the Flatness parameter, as

$$F = \frac{1}{N} \sum_{i=1}^{N} (\rho_i - <\rho>)^2$$

Where $N$ is the total number of banks triggered and $<\rho>$ is the average of the $\rho_i$s, the number of photons in individual banks. $F$ is then computed for each shower. The value of this parameter is expected to be small for showers with a flat and less “bumpy” lateral distribution. This is a $\chi^2$ like parameter except that its distribution is unlike that of $\chi^2$ since the population of photon densities is not drawn from a normal distribution. The Monte-Carlo calculations (Vishwanath et al. 1994) show that a selection of low values of $F$ ($F \leq 0.4$) discriminates γ-rays against cosmic ray background. The actual value of $F$ at which a cut is imposed seems to depend on the assumed fluctuations in the lateral distribution, the geometry of the array and $N$.

5. RESULTS
We have observed Crab pulsar for about 46\textsuperscript{h} from Jan. to Mar. 199(I), for 92\textsuperscript{h} from Oct. 1992 to Mar. 1993 (II) and for 20\textsuperscript{h} in 1993-94 (III). Geminga pulsar was observed for 76\textsuperscript{h} in 1992-93 (II) and for 40\textsuperscript{h} in 1993-94 (III). Preliminary analysis has been done for the first two sets of data while it is continuing for the third set. 9 banks were operating during data set I, 8 banks during data set II and 12 banks during data set III. The angle information could not be obtained for data set I due to lack of TDC information. Two of the TDC channels were malfunctioning during data set II and hence at times we had TDC informations in only 6, 7 or 8 Banks.

The phase plots before and after applying the F cut (F ~ 0.3) for the data set I are shown in fig. 3a and 3b respectively. It is seen that the deviation in the bin corresponding to the radio main-pulse phase is enhanced with this cut. 77\% events got rejected with F ~ 0.3 cut. The observed number of events in the bin corresponding to radio main-pulse phase is 7912 when 7742 events are expected in the uncut data. The corresponding numbers with the F-cut are 1958 and 1739. This deviation of the observed number from the expected corresponds to a Li-Ma significance of 5\sigma. No significant deviation in the number of observed events is seen in the inter-pulse position.

In the II set of data events with a space angle \( \theta \) between the source and the shower axis \( \leq 1.5^\circ \) and \( \geq 5 \) triggered banks are accepted. The 20 bin phasogram is shown in fig. 4a. An angle cut of \( \theta \leq 0.75^\circ \) is then applied resulting in the rejection of about 75\% of data. An F-Cut of \( F \leq 0.4 \) is then applied which rejected about 50\% of remaining data. The over-all rejection by both the cuts was about 87\%. The phasograms for data with \( F \leq 0.4 \), \( \theta \leq 0.75^\circ \), \( F \leq 0.4 \) and \( \theta \leq 0.75^\circ \) cut are shown in figures 4b to 4d. It should be recalled that the F-cut is sensitive to the number of banks used and the geometry of the array. Excess of events over the background (defined as the mean in the phase region between 0.5 to 0.95, the ‘unpulsed’ region) is seen in the main, inter pulse and the region in between them in fig. 4d. The Li-Ma significance of these excess events are 4.1\sigma, 4.6\sigma and 2.5\sigma respectively.

Same cuts were also applied to the Geminga data as the available number of banks were more or less same in data taken of these objects. The resulting light curve with 30 phase bins for data with basic cuts and that with \( F \leq 0.4 \), \( \theta \leq 0.75^\circ \), \( F \leq 0.4 \) and \( \theta \leq 0.75^\circ \) cut data are shown in figures 5a to 5d. A 5.0\sigma deviation is seen in fig. 5d in the pulse position P1 (“the I pulse of EGRET data”) while the Li-Ma significance of the deviation in the P2 pulse position (“the II pulse in EGRET data”) is 2.6\sigma.

6. DISCUSSION

It is evident that a cut based on the lateral distribution of Čerenkov photons enhances the \( \gamma \)-ray signal in addition to the cut on the direction of arrival of the shower. It is intuitively obvious that if there are \( \gamma \)-rays and if they have a flat lateral distribution of photons, a cut like this should reject background and hence enhance
the signal.

Preliminary analysis of data on Crab pulsar taken in 1992-93 indicates emission in the position of radio main pulse, inter pulse and inbetween. The basic chance probability is multiplied by 9, the number of F-cuts tried, and 5 (7 for data set I), the possible trials in deriving the value of F if restricted to a specified number of banks. The final probability that the signal at the Main pulse position in the I data set is due to chance is $4 \times 10^{-6}$. The combined probability of a chance fluctuation in 3 emission regions in the data set II is $\approx 1.5 \times 10^{-8}$. It should be noted that the Whipple experiment (Vacanti et al. 1991) and ASGAT experiment (Goret et al. 1993) did not see any pulsed emission from Crab pulsar.

In the data of Geminga pulsar too, the signal shows up when the same cuts as that for Crab pulsar are applied. The corresponding chance probability is $\approx 7 \times 10^{-6}$, taking all degrees of freedom into account. This result confirms the earlier detection by the Tata and Durham groups using their archival data (Vishwanath et al. 1993, Bowden et al. 1993). However, the Whipple group did not see any pulsed emission from this object (Akerlof et al. 1993).

The data were split into smaller sets to examine the time-variability in the emission of TeV $\gamma$-rays. No evidence for a significant variability is observed. Both Crab and Geminga pulsars seem to emit steady pulsed TeV $\gamma$-rays during 1992-93, the period corresponding to the data set examined. Our analysis to estimate absolute fluxes, by understanding various effects of the cuts imposed, is in progress. We are also in the process of looking for other sensitive parameters to reject maximum background events while retaining a good number of $\gamma$-ray events.

ACKNOWLEDGEMENTS

We are grateful to the Government of Madhya Pradesh (India) for the facilities at Pachmarhi and wish to thank B. S. Ajay Kumar, A. R. Apte, A. I. D'Souza, K. S. Gothe, A. V. John, S. R. Joshi, B. K. Nagesh, P. Sudarshanan, B. L. Venkatesh Murthy and S. S. Upadhyaya for their help with the observations. We are indebted to Drs. A. G. Lyne and R. S. Pritchard (University of Manchester, U. K.) for providing us with the Crab pulsar elements.

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Fig. 1 ACT ARRAY at PACHMARHI ($78^\circ.42$ E; $22^\circ.46$ N; 1075 m above m.s.l.)

Fig. 2 Angular response of the array. Full line for 8 banks and dashed line for 6 banks
Fig. 3 Crab pulsar 1991–92 data

Fig. 4 Crab pulsar 1992–93 data

Fig. 5 Geminga, 1992–93 data
Selection of EAS with constant energy in the Tibet experiment

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Abstract

Characteristics of extensive air showers generated by primaries with energy $10^5 - 10^6$ GeV and observed in the Tibet experiment ($606 \text{ g.cm}^{-2}$) are simulated using Monte Carlo modelings. We show that, in the Tibet experiment, it is possible to select showers initiated by primaries with different masses but with the same primary energy $E_0$. Such a shower selection combined with the analyse of the muon component fluctuations allows the determination of the primary mass composition in the "knee" region excluding the usual biases involved by the non well defined correspondance : EAS size $\leftrightarrow$ primary energy.

1 Introduction

Because the very low flux of cosmic rays with ultra-high energy ($\geq 10^5$ GeV, UHE) the direct observation of the cosmic radiation with such energies is not possible and the only access to information is from the measurements and analysis of extensive air showers (EAS) they generate in the earth atmosphere.

However, the quality of the needed information is such that many basic questions are not solved, one of them being the knowledge of the mass composition of the UHE primary radiation.

In fact, this situation comes from three main reasons :

i) If the nature gives us, as a gift, the earth atmosphere to be used as a giant calorimeter, this gift is somewhat poisoned because as deep the showers are registrated, as diluated the needed information on the nature of the primary or its first interaction is and as difficult the puzzled information to be interpreted is too.

ii) Technical and economical limits to registrate the three EAS components, (electronic, hadronic and muonic) simultaneously with very large detectors.

iii) The logic to analyse experimental data.

However, for the determination of the primary mass composition, this situation can be improved by two ways :
elaborating experiments in high altitude in good accordance with the energy range, i.e. altitude for which showers are registrated not very far from their maximum development to reduce the undesirable too large fluctuation effects.

- using a specific shower selection to increase the precision of the needed information.

The first way is satisfied by the Tibet's experiment because the altitude $t_0=606$ g.cm$^{-2}$ will allow to collect showers in the range of $10^6$ GeV which is very interesting because the 'knee' in the primary energy spectrum.

For the second point, it is possible to reduce significantly one essential bias of the primary spectrum and mass composition determinations. Indeed, traditionally registered showers are selected with fixed sizes $N_e$ or, sometimes, with fixed muon size, $N_\mu$. In both cases, it is well known that showers with given size are generated by primaries with different masses but with different energies too. One consequence of the usual method to classify showers is that, from the registered EAS, information on the identity of the primary cosmic projectile is obtained but not for the same primary energy. However, because the presence of the 'knee' in the primary energy spectrum, it is important to determine the individual energy spectra and the mass composition for given fixed primary energies using the most direct possible way, i.e. not using the not well known correlation 'EAS size $\leftrightarrow$ primary energy'. To do that, one possibility is to define a new parameter specific to the experimental array, such as showers picked up with a given value of this parameter are generated by primaries with different masses but with the same primary energy. Recently, we applied this method for two other experiments placed in mountain altitude, Chacaltaya (1) and the Tien Shan array (2) and the existence of the needed experimental data from the Tien Shan experiment allowed us to confirm the efficiency of the method (2).

2 Method

Because the photo-electronic component is the most easily measured, we define the $\alpha$ parameter as a function of the distance from the shower axis such as:

$$\alpha(r) = r^2 \rho_e(r) s_{6-70}^2 / f_{NKG}(30, s_{6-70})$$

in which $\rho_e(r)$ is the lateral density of the electron component, $f_{NKG}(30, s_{6-70})$ is the well known Nishimura-Kamata-Greisen function in which $s_{6-70}$ is the local age determined from the two densities $\rho_e(6m)$ and $\rho_e(70m)$.

If we draw the $r - \alpha(r)$ dependence in showers generated by primary protons and iron nuclei with different primary energies, figure 2 shows that a crossing point appears at $r = 20m$. In other words, EAS collected with $\alpha(20m) = const$ are generated by primaries with different masses but the same primary energy. We compare on figures 2 and 2 the average energy $< E_0 >$ and the relative standard deviation $\sigma(E_0)/ < E_0 >$ for showers collected, as usual (with constant size $N_e$) and with constant $\alpha(20m)$. It can be seen that the situation is quite favorable because showers collected by $\alpha(20m) = const$ are generated by primaries with the same energy and, in that case, $\sigma(E_0)/ < E_0 > \sim 0.10$ which is a quite reasonable value.
Figure 1

Figure 2
3 Determination of the energy spectra and mass composition for given energy

The experimental determination of the integral spectrum $F_A(\geq \alpha(20m))$ of registered EAS for each primary with mass $A$ according to the new selection $\alpha(20m) = const$ and the function $<E_0> = f(\alpha(20m))$ shown on figure 2 will allow to obtain directly the primary energy spectrum $F(\geq E_0)$ for a fixed energy threshold $E_0$.

Some years ago, the mass composition of the primary radiation has been estimated for energies larger than $10^5$ GeV from the fluctuations of the muon component in showers collected with constant size $N_e$ (3). This method can be applied in the case of EAS picked up with fixed $\alpha(20m)$ (fixed primary energy). Figures 4a compare the number $<N_\mu>$ of low energy muons ($E_\mu \geq 0.6$ GeV) in showers collected respectively with $N_e = const$ and $\alpha(20m) = const$. It can be noticed that, for the new shower selection, the situation is not favorable because $<N_\mu>$ in EAS generated by primary protons or iron nuclei are not widely different which imply that the overlap between the $N_\mu$ fluctuations in showers initiated by primaries with different masses could be too important.

The only way to overcome this problem is to increase the muon energy threshold to obtain $N^{Fe}_\mu \gg N^p_\mu$. We show one exemple on figure 4b where muons with $E_\mu \geq 25$ GeV are registrated. Comparing figures 4a and 4b, it is easily seen that the overlap between the $N_{mu}$ fluctuations is widely reduced for high energy muons.
4 Conclusion

A necessity to understand and explain better the presence of the 'knee' in the energy spectrum of the cosmic radiation is to be able to determine the individual energy spectra and the mass composition of the radiation for given primary energies. Up to now, showers have been selected with constant sizes. A consequence is that, from this usual shower selection, information on the primaries with different masses are obtained for different primary energies too. We show that, in the Tibet experiment, using a new criterium to select showers based on the constence of a measurable parameter $\alpha(20m)$, it is possible to select showers generated by primaries with different masses but with the same primary energy.

Registarting muons with a sufficient energy threshold, such a selection allows the mass composition determination for the same given energies.

References
Primary Energy Spectrum of Cosmic Ray at the "Knee" Region Observed with the Huairou (Beijing) Air Shower Array

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Abstract

650 thousands of air showers recorded by Hairou EAS Array have been used to investigate the energy spectrum of primary cosmic ray around the "knee" region. A Monte Colro simulation have been carried out and the array performance, the size response of the array, the zenith angle distribution, the ascenion and declination distribution as well as the relation between the EAS size and primary energy etc. have been checked carefully.

The size spectrum for different zenith angle ranges and the primary energy spectrum in the range of $10^{15}$ to $5 \times 10^{16}$ are obtained. It shows a clear "knee" shape and has a good coincidence with Akeno spectrum on the breaking point (at $3 \times 10^{15}$ev) and the absolute value of flux but ours with a more smooth changing structure.

Moreover, under the so called rigidity-dependent cut model, by adjusting the breaking energy $E_c$ of primary proton spectrum of cosmic rays in the simulation of size spectrum and compare with the experiment one, we found that the most proper value of $E_c$ is in the energy range of 160 Tev to 240 Tev.
Huairou (Beijing) EAS Array

Integral Size Spectrum measured by
Huairou EAS Array

![Graph showing integral size spectrum with various markers and labels indicating different sections.](image-url)
Differential Energy Spectrum of C.R.

\[ E^{2.5} \times 10^{-15} \text{m}^2 \text{s}^{-1} \text{Sr}^{-1} \text{GeV}^{-1} \]

\[ \log E, \text{ Gev} \]

- N.L. Grigorov et al., 1971
- M. Nagano et al., 1984
- This work
$\chi^2$ as a function of trial values of $E_c$, the bounding point of primary proton spectrum.

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TIME & SPACE FINE STRUCTURE
OF EXTENSIVE AIR SHOWER FRONT

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Abstract

The time & space fine structure of EAS front has been measured for the first time with a high statistics in a core distance range from 0 to 150 m by the GREX/Cover_Plastex array. Arrival times of shower particles have been measured with ns-accuracy. A disk thickness of 5 ns in the EAS core has been found.

1. Introduction

The space-time structure of E.A.S. front detected at ground level reflects the nature of primary particle and its interactions with the atmosphere nuclei. The cascade induced by cosmic rays with energy > \(10^{14}\) eV at sea level covers a large area and produces mainly electrons. In hadron induced showers also muons and secondary hadrons are generated.

The measurement of EAS front thickness was first attempted by B. Rossi [Rossi 1953] who compared the arrival times of particles in two nearby scintillators of an array. This method was followed by other authors [Linsley 1962, Woidneck 1975, Linsley 1986] who measured the time spread of shower front. As regards to the shower front curvature, its knowledge is important to link times measured by remote detectors. Usually in such measurements low statistics is obtained.

The COVER_Plastex experiment [Agnetta 1993] has measured the space-time fine structure in a new and original way, using resistive plate counter detectors (RPC) [Ambrosio 1994] for direct time measurements of the arrival time of each particle crossing the detector. The sampling area was 8 m\(^2\) and a high statistics has been obtained. Data was taken at a core distance from 0 to 150 m.
2. The experimental apparatus

The GREX array (fig. 1) in Haverah Park was built for γ-ray astronomy [Brooke 1985]. A good time resolution of scintillators allows a precision < 1° on the shower axis reconstruction. Core position is measured with a precision of ~ 6 m in the inner part of the array and ~ 9 m at the periphery. Inside GREX a subarray of five tracking telescopes was installed (PLASTEX - fig. 1) with the aim to track particles and to reconstruct their height of production [Agnetta 1990]. Telescopes consist of six layers of limited streamer tubes (fig. 2) separated by a layer of a dense material. This thin absorber aims to separate electrons, photons and muons in the shower front. Telescope dimensions are ~ 6 m² and each plane is read by 1 cm wide x-strips and 1.2 cm wide y-strips. The first two telescopes, named stacks A&B are near the center of the array, while the other three, named C, D and E, are at the periphery, 150 m away from the center (fig. 1).

On the top of telescopes A, B, C and D we have installed a layer of 4 m² RPC, equipped with 24 x 24 cm² pads read by a front-end tracking and timing electronics able to detect the fired pads and to measure the arrival time of signals from each pad with the time resolution of 2 ns [Agnetta 1994]. By this way for each tracking telescope 64 time channels are allowed, which permit to combine the tracking information with timing measurements. For each event triggered by the GREX array a big amount of information is obtained. The array measures the axis direction, the core position, and estimates the primary energy; the PLASTEX telescopes track the incoming particles and the RPCs measure arrival times of each pad fired.

3. Data analysis

To measure the front profile and thickness we have analyzed 250,000 events taken with only stacks A&B running jointly with the GREX array. Up to 128 time measurements in the single event are allowed, corresponding to 128 pads covering two stacks. The delay of each particle from the earliest incoming particle is measured as a function of the core distance from the stacks. A requirement of almost 5 fired pads cuts low density events, and a requirement of no more than 80 pads fired reduces the possibility to have more than one particle per pad. Times are corrected for the shower axis inclination. Only showers with zenith angle less than 25° are processed. Only 60,000 events survive to these requirements.

The distributions presented in fig. 3 show the delay time of all particles in the shower front from the earliest particle arriving for three core distance intervals. To avoid tail effects distributions are fitted by a Γ-function according the relation:

\[ d(t) = a t^b e^{-ct} \]  

(1)

The curve fit is shown superimposed on the distributions. The agreement between the fit and the distributions is better than 10⁻⁴. Fig. 4 shows how arrival time distributions change with the core distance in the range 0 - 150 m. The shape of the shower front is clearly visible.

The curve fit permits to evaluate the front thickness as a function of the core distance. Fig. 5 shows the σ of distributions for core distance intervals of 10 m from 0 to 150 m.
This σ(r) dependence can be approximated by:

\[ \sigma(r) = m_1 + m_2 \left( \frac{r}{r_0} \right)^{m_3} \]  

where \( r = \) core distance, \( r_0 = 79 \) m (Molier radius), \( m_1 = 4.99, m_2 = 3.65, m_3 = 2.20 \).

This figure shows that the front disk has a thickness of 5 ns in the core and 21 ns at 150 m.

The thickness dependence from the particle multiplicity has also been investigated. Fig. 6 shows σ measured for various multiplicity intervals, compared with the previous curve for all multiplicities. No significant difference can be seen.

4. Conclusions

The front thickness of EAS detected by the GREX array has been measured with a large statistics in the range from 0 to 150 m of the core distance. A σ ranging from 5 ns in the core up to 21 ns at 150 m has been measured. Precise measurements of the shower front parameters at small core distances were made for the first time. No correlation between σ and particle density has been observed. Arrival time distributions are in good agreement with a \( \Gamma \) function in this core distance interval.

5. Acknowledgment

We are grateful to the graduating students C. Aramo and L. Colesanti for their careful work in data tacking and analysis.

References

Fig. 1 - The GREX array and the COVER_PLASTEX experiment at Haverah Park.
RPC equipped with pads and T&T electronics

Streamer tubes

Supporting planes

Converter: 0.9 cm Pb = 1.6 $X_0$
3 cm Fe + 1.1 cm Pb = 3.65 $X_0$

Dimensions: (2.5 x 2.36) m²
(2.0 x 2.35) m²

Supporting planes: low density plastic styro-foam

Fig. 2 - Layout of PLASTEX telescopes covered by RPCs.
All multiplicity

\[ CD = 20-30 \text{ m} \]

- \( a = 8.657 \)
- \( b = 1.803 \)
- \( c = 0.3088 \)

Entry = 205359

\[ CD = 70-80 \text{ m} \]

- \( a = 3.470 \)
- \( b = 0.9684 \)
- \( c = 0.1605 \)

Entry = 68193

\[ CD = 120-130 \text{ m} \]

- \( a = 127.6 \)
- \( b = 0.73 \)
- \( c = 0.08162 \)

Entry = 4827

Fig. 3 - Delay time of particles in the shower front from the earliest particle arriving for three core distance intervals.
Fig. 4 - Arrival time distributions of particles in the shower front at different core distances. The superimposed curve gives the average arrival time. Plot entries are reported on the top of the graph. Each distribution is normalized to its maximum value.
Fig. 5 - $\sigma$ of arrival time distributions.

Fig. 6 - $\sigma$ of arrival time distributions for different multiplicity intervals.
"Muon Eye" as a new EAS detector

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Abstract

Principles and characteristics of a new EAS detector are discussed. It is based on the so called TTC (time-track complementarity) method, which implies the simultaneous measurement of incidence angles and arrival times of EAS muons.

1 Introduction.

In (1) we have shown that, when the muon arrival time and track data are used complementary, this so called TTC-method can improve the accuracy of the of the muon production height determination at the initial stages of the EAS development. In 1983 the "father" of the TTC-method, J. Linsley, proposed an idea to upturn the problem of the muon production height determination (2). He suggested to use the muon TTC-information to locate the position of this axis in the space. In this case, experimentators would have just the information about muon coordinates $X_\mu$ and $Y_\mu$, their incidence angles $\theta_\mu$, $\varphi_\mu$ and arrival times $t_\mu$ from multiple muons in the detector and nothing about similar EAS axis parameters : $X_0$, $Y_0$, $\theta_0$, $\varphi_0$, $t_0$, which should be determined.

2 The Muon Eye

2.1 Physics of the idea

The physical arguments which lie inside the Linsley's idea are similar to those which constitute the basement of the "Fly's Eye" experiment (3). Like Cherenkov photons, muons with the energy of a few GeV, are penetrating particles which can traverse the whole atmosphere not decaying and losing a minor part of their energy. Their trajectories are also nearly straight lines. since the multiple coulomb scattering has not a very strong effect on them. The same small effect has the deviation in the earth magnetic field. Because GeV pions and kaons, which give birth to GeV muons, have
relatively narrow LDF around the shower axis, then straight trajectories of detected muons point out to this axis pretty accurately.

The TTC- muon detector combines both the trajectory and the timing information. The muon arrival time depends on the distance from its birth point to the detector (figure 1a).

![Figure 1a](image)

\textit{Schematic view of muons in the extensive air shower, coming to the detector from different points along the shower axis.}

The arrival time difference between different muons in such a detector is determined by how far is the axis from the detector and how is the former one orientated in the space. So TTC-detector is able not just see the axis, but also locate it in the space. Basing on the analogy with the "Fly’s Eye" detector, which can get this information by observing optical Cherenkov photons, we called such a TTC muon detector the "Muon Eye", since it can get the same information by means of observing muons.

2.2 "The long distance" approximation.

In all our simulations we used the so called "long distance approximation". The latter means that the distance between the location of the shower axis and the muon detector has to be much larger than the lateral size of the muon detector. In this approximation we can neglect the separation of muons inside the detector and consider them as incident at the same point, i.e. the detector center $X_d, Y_d$. Because muon birth points are close to the EAS axis and muon trajectories are nearly straight lines, they all lie almost in the same plane which connects the axis and the detector center (figure 1a). All the further consideration we shall perform
in this plane, which we call the projection plane, reducing the three dimensional picture to the bilateral one. In our subsequent simulations the projection plane was determined as the best fit plane, found by the minimization of its deviation from all muon trajectories.

![Figure 1b](image)

*Schematic view of muons in the projection plane, coming to the detector from different points along the shower axis.*

In this plane muon zenith angles $\theta_i$, their arrival time delays with respect to the arrival time of the shower front at the point $C$: $\tau_i = t_i - t_C$ and the zenith angle $\theta$ and impact parameter $p$ of the shower axis (figure 1b) are connected like in (3) as

$$\theta_i = \theta + 2\arctan\left(\frac{C\tau_i}{p}\right)$$  \hspace{1cm} (1)

Since we don't know the arrival time of the shower front $t_C$ we plotted for each shower $\theta_i$ versus the absolute arrival time $t_i$. Then we used the Minuit code to find the best fit parameters of $\theta, p$ and $t_C$, which fitted the set of our points in the plot by the expression (1).

### 2.3 The accuracy of the axis location

In order to estimate the possible accuracy of the EAS axis location, we used the same simulation code as in (1). We simulated showers initiated by primary protons with the energy of $2 \times 10^7$ GeV and observed at the mountain level of 690 g·cm$^{-2}$, which corresponded to Tien-Shan and Aragats levels. To save the computing time we simulated showers incident on the array of 6 Muon Eyes, placed at the vertices of the hexagon of the variable radius $R$. Showers at the first stage of simulations
were taken vertical with \( \theta = 0^\circ \) and their axis, located at the center of the hexagon (figure 2).

![Figure 2](image)

*The layout of six Muon Eyes around the simulated vertical EAS incident at the center of the array.*

These showers were observed by single Muon Eyes, then by 3 Muon Eyes, chosen at vertices of equilateral triangles and eventually by the whole array of 6 Eyes. The radius \( R \) varied as 50, 100 and 200 m. The size of one Muon Eye was also variable and equal to \( 2.5 \times 2.5 \text{m}^2 \), \( 5 \times 5 \text{m}^2 \) and \( 10 \times 10 \text{m}^2 \) respectively for \( R = 50, 100 \) and 200m. Threshold energy of detected muons was chosen as 5 GeV.

Coordinates, where the found axis crosses the observation plane \( X_0', Y_0' \) were compared with the real position \( X_0, Y_0 \).

\[
\delta_R = \sqrt{(X_0' - X_0)^2 + (Y_0' - Y_0)^2}
\]

(2)

The same comparison was made for obtained and real zenith and azimuthal angles : \( \theta_0' \), \( \theta_0 \) and \( \varphi_0' \), \( \varphi_0 \) respectively.

\[
\delta_\theta = \theta_0' - \theta_0 \quad \delta_\varphi = \varphi_0' - \varphi_0
\]

(3)

Mean values \(< \delta_R >, < \delta_\theta >, < \delta_\varphi >\) and their standard deviations \( \sigma_{\delta_R}, \sigma_{\delta_\theta}, \sigma_{\delta_\varphi} \) were found as estimates of the EAS axis location accuracy. Below we present some results related to different array configurations.

The distribution of \( R_{\text{exp}} \) - impact parameter values, found in individual events, around the true value of \( R_{\text{theor}} \) is shown in figure 3 for the distance of \( R = 200 \text{ m} \) from the single "Muon Eye".

The mean value and the standard deviation of \( R_{\text{theor}}/R_{\text{exp}} \) distribution is indicated in the same figure. It has been shown that the accuracy is better for higher muon multiplicities.

Like the stereoscopic sight by two eyes gives much better spacial resolution, the view of the EAS axis by two or more "Muon Eyes" results in the better location
The distribution of the $R_{th}/R_{exp}$ ratio for EAS incident at the distance $R_{th} = 200\, m$ from the single Muon Eye. The mean value of this distribution $< R_{th}/R_{exp} >$ and its standard deviation $\sigma$ are presented on the figure.

accuracy. In upper sub-lines of Table 1 we present simulation results for the "Muon Eye Net", which consists of 3 or 6 Muon Eyes and compare them with the relevant results for the single "Muon Eye". Here we used for the accuracy estimates of $\delta_R, \sigma_{\delta_R}$ the true spatial position of the located shower axis, because the impact parameter, used in the analysis of the single "Muon Eye" data, cannot be applied for the "Muon Eye Net".

<table>
<thead>
<tr>
<th>R (m)</th>
<th>50 m</th>
<th>100m</th>
<th>200m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Numb. Muon Eyes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; \delta_R &gt;$ (m)</td>
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<td>27.5</td>
<td>17.9</td>
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<tr>
<td>$\sigma_{\delta_R}$ (m)</td>
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<tr>
<td>$&lt; \delta_\theta &gt;$ (°)</td>
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<tr>
<td>$\sigma_{\delta_\theta}$ (°)</td>
<td>0.46</td>
<td>0.24</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 1: Accuracy of the EAS axis location by 1, 3 and 6 Muon Eyes, placed at the distance $R$ from the vertical $2\cdot10^7$ GeV proton induced shower. Upper sublines show accuracy values, obtained without experimental errors, lower ones with inclined numbers - with experimental errors included.

In the same table we indicated values, obtained with the account for experimental errors. For that purpose, we sampled the muon zenith and azimuth angles around their true values $\theta_\mu', \varphi_\mu'$ with the gaussian distribution of the width $\sigma_{\theta, \varphi} = 5 \, \text{mrad}$. The same procedure was applied to muon arrival times, where the width of the
quasi-experimental gaussian distribution was taken as $\sigma_r = \ln n$. Quasi-experimental accuracy of $\langle \delta_R \rangle$, $\sigma_{\delta_R}$, $\langle \delta_\theta \rangle$, $\sigma_{\delta_\theta}$ determination for the same set of showers is presented in lower sub-lines of Table 1. To illustrate the shape of obtained distributions we present them in figure 4 for 6 Muon Eyes in the configuration with $R = 200$ m.

**Figure 4**

Positions of shower axes determined by the Muon Eye Net with 6 detectors. Vertical showers were incident at the center of the Muon Eye Net, its radius is 200 m.

### 2.4 The aperture of the "Muon Eye" array.

The aperture of the "Muon Eye" detector is determined by the triggering condition which requires the number of detected muons not being less than three: $m_\mu \geq 3$. We estimated the aperture of the single "Muon Eye" for two muon energy thresholds: $E_\mu \geq 2$ GeV and $\geq 5$ GeV using our own LDF obtained by simulations for proton initiated showers at the mountain level. Since the number $m_\mu$ of detected muons depends on the product of the total muon number $N_\mu$ and the detector area $S$, in figure 5 we presented the result of these estimates as a function of this product $N_\mu S$. For the comparison in figure 5 results are presented for the aperture estimated in the limited zenith angle $\theta_0 \leq 60^\circ$ and $\theta_0 \leq 30^\circ$.

It is seen that even the single "Muon Eye" could be the real super-mini array with a large acceptance. It approaches the acceptance of the single Fly's Eye $\sim 1$ km$^2$sr. As regards the "Muon Eye Net" simple estimates, applied for the net with $R = 200$ m and $\theta_{max} = 60^\circ$ give $A_{total} \approx (0.4-0.5)$km$^2$sr.
The acceptance of the single Muon Eye versus $N_{\mu}S$ - the product of the total number of muons $N_{\mu}$ in the shower and the sensitive area $S$ of the detector. Curves are for $E_{\mu}^{thr}$ of 5 GeV: full line - $\Theta < 90^\circ$, dash-dotted line - $\Theta < 60^\circ$, dashed line - $\Theta < 30^\circ$; for $E_{\mu}^{thr} = 2$GeV: dotted line - $\Theta < 90^\circ$.

3 The advantage of the "Muon Eye" as the new EAS detector

The advantage of the "Muon Eye" for the EAS study is typical for the super-mini array: it is able to collect data from the area larger than its own by several orders of magnitude. In that aspect, it is similar to the Fly’s Eye 1 (FE1) detector. Due to the rapid rise of its aperture with the shower size "Muon Eye" enables one to study the wider energy range compared with ordinary shower arrays.

The "Muon Eye" has the good opportunity to estimate the shower energy, because the number of muons is better correlated with the primary energy than, say, the number of electrons at the observation level (5).

Surely, in comparison with optical photon measurement there are not only advantages of this method based on the measurements of shower muons, but disadvantages too. The apparent disadvantage is that muons are less numerous than photons and therefore, they are the subject of larger fluctuations. The second one is that they are charged particles. Due to the multiple coulomb scattering and the earth magnetic field, their trajectories deviate from the straight lines. The accuracy of the shower axis location has to be principally lower in this case than for the case of straight trajectories of optical photons.

However the one of the apparent and strongest advantages of the "Muon Eye" is its longer duty cycle. It can operate not just in the night time, but all over the day.
It means that to accumulate the same amount of data it could have the aperture one order of magnitude less than the similar optical detector. Due to its independence of the weather and the light conditions the "Muon Eye" is indispensable when combined with other, more traditional shower arrays, which also work the full time. Such a combination could give an unique angular resolution of about 0.1°, which is indispensable for neutron astronomy studies.

4 Conclusion

So we think that the "Muon Eye" can be realizable, useful and promising device to study large air showers. It is able to locate the shower axis and estimate its energy at the territory much larger than its own size. In this sense it is indeed the super-mini array. One of its most attractive advantages is the continuous and long duty cycle. Hence it is more applicable when associated with other EAS arrays, than, say, optical devices. In any case such a device seems to us worth of being prototyped and tested.

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Shadowing of cosmic rays by the Sun near maximum or at the decreasing phase of Solar activity

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ABSTRACT. The shadows of the Sun and Moon have been detected in the 10-TeV cosmic ray flux by the Tibet air shower array at an altitude of 4300 m a.s.l.. The observation have been started in the early of 1990 and we have accumulated the data over four years. In before papers, we reported the shadow of the Sun was observed in the direction significantly away from the apparent solar position, under the influence of the solar and interplanetary magnetic fields. A further analysis shows that the shadows by cosmic rays coming from the away and toward field sectors in the interplanetary space are shifted in opposite directions each other according to its polarity of the fields. Moreover, we notice that the Solar activity was maximum phase in 1990 and the activity becomes to quiet period. In this paper, we report the yearly time variation of the positions of the
shadow of the Sun. The observation of the cosmic ray shadow by the Sun can produce new information on the relation between a time variation of the large-scale structure of the solar and interplanetary magnetic fields and the cycle of solar activity.

1 Introduction

High sensitivity air shower arrays specially designed to search for gamma ray point sources should have a capability of detecting the shadowing of cosmic rays by the Sun and Moon as a collimator with the apparent angular diameter of about 0.5°. This was first suggested by Clark [1] and recently several groups [2][3][4] have observed the shadows of the Sun and Moon to confirm the angular resolution of the air-shower array using cosmic rays with energies upwards of about 50 TeV.

Almost all the cosmic rays are charged and propagate through the interplanetary space while arriving at the earth. Therefore, these particles will measurably bend under the influence of solar and interplanetary magnetic field, as well as geomagnetic field, if their energies are the order of 10 TeV or lower. Thus, observation of the cosmic ray shadow by these objects at these energies may give some new information on the solar magnetic field as well as the interplanetary magnetic field (IMF) [1].

The Tibet air shower array [5][6], being successively operated from January of 1990, has a good angular resolution better than 1° at 10-TeV energies and is just suitable for examining this interesting anticipation. Using this array, actually we observed for the first time the Sun shadow shifted from the apparent solar position to the west-southwest by about 0.9° [6]. We showed that this observed displacement can not be explained by statistical deviations nor by systematic pointing errors of the array, and then concluded that it is caused by the combined effect of the magnetic fields between the Sun and the Earth. In another paper [7], we further studied the shadowing of cosmic rays by the Sun in order to examine how the shadow was influenced by the solar and interplanetary magnetic fields. Here, we summarize our results about the shadows of the Sun and Moon.

2 Event Analysis

In order to measure a small decrease in event density around the object (Sun and Moon), the background was carefully estimated using the events which come from the following eight off-source positions. These fake objects are located on the same zenith angle as the object, but apart by ±5°, ±10°, ±15° and ±20° in the azimuth angle. The average of the event densities around these eight off-
source positions was taken to be the background while some appropriate choices were done depending on the zenith angle. The background density distribution was then obtained for each of the Sun and Moon. The cosmic ray deficits around these objects were examined as follows. First, the area of $4^\circ \times 4^\circ$ centered on each object was divided into $32 \times 32$ cells each size being a $0.125^\circ \times 0.125^\circ$ in real angle, and a two-dimensional histogram of event densities per cell was obtained. Same histogram was also made for the background obtained above, while it was once smoothed out by taking a moving average on the event densities over 401 cells within a circle of radius $1.5^\circ$ from each concerning cell. We then subtract this smoothed background from the event histogram. The deficit event density obtained at each cell was again smoothed out over 69 cells within a circle of radius $0.6^\circ$. The weight of the deficit event density at each cell is defined by $(E-B)/\sqrt{E}$, where $E$ and $B$ are the event and background densities, respectively.

3 Moon Shadow and Array Performance

The contour map of the weights of deficit event densities around the Moon, thus obtained, is shown in Fig. 1 Contour lines start from $0\sigma$ deficit with a step of $1\sigma$. The shadowing of cosmic rays is clearly perceived on this contour map, while its profile seems to be on the whole shifted westward. The maximum-likelihood method was used to estimate the angular resolution. To use this method, a priori angular resolution function $P_r(\theta, R)$ is assumed to be a linear combination of three two-dimensional Gaussian distributions including a scaled angular resolution parameter $R$ [6].
The likelihood function is the product of the differential probability as \( dP/dz \propto \{N_{BG}(z) - \pi \theta_M^2 P_r(\theta(z), R)\} \) for each event in the sample, where \( z \) is a scaled variable defined as \( z = (1 - \cos \theta)/(1 - \cos \theta_{\text{max}}) \) with \( \theta_{\text{max}} = 4.0^\circ \), \( N_{BG}(z) \) the normalized background function and \( \theta_M \) the angle radius of the Moon. The likelihood is computed numerically for many trial \( R \)'s for the Moon data set; its natural logarithm is plotted against trial \( R \) in Fig. 2. The curves become maximum at \( R = 0.88^\circ \) for all events and at \( R = 0.52^\circ \) for events with \( \sum \rho_{FT} > 100 \), respectively. From this figure, the angular resolution of our array is estimated to be \( 0.88^\circ \pm 0.11^\circ \) for all events and \( 0.52^\circ \pm 0.09^\circ \) for those with \( \sum \rho_{FT} > 100 \). If we use a single two-dimensional Gaussian distribution, however, the resolution becomes \( 0.67^\circ \pm 0.09^\circ \) for all events, though the statistical significance is 6.2\( \sigma \) for the shadow of the Moon. Using the maximum likelihood method, the maximum deficit position of the shadow profile is found at \( 0.16^\circ \pm 0.11^\circ \) to the west and \( 0.02^\circ \pm 0.07^\circ \) to the south when the angular resolution of the array is \( 0.88^\circ \).

As a statistical significance, the shadow at the maximum deficit is calculated to be 7.1\( \sigma \) level. The shadow profile and its westward displacement become more clear than the previous result [6] with increasing statistics. The geomagnetic field will bend incident positively charged cosmic rays to make their apparent arrival directions shift to the west. Using a Monte Carlo method, the displacement of the Moon shadow is calculated to be \( 0.15^\circ \) for all showers, which is comparable with the observed one. Moreover, the shadow by high energy cosmic rays with \( \sum \rho_{FT} > 100 \) was ascertained to fall almost on the Moon, as expected. Thus, the observed displacement can be attributed to the geomagnetic effect. Taking these into consideration, the overall pointing error of the Tibet array is estimated to
be less than 0.1°. The results obtained above are used as reference standards in the following.

4 Sun Shadow

To begin with, we show the contour map of the deficit event densities around the Sun in Fig. 3 for all showers. A large displacement of the shadow from the Sun direction is evident in this figure.

The profile is slightly disordered when compared with that for the Moon, and this may be partly attributed to a complex structure of the solar and interplanetary magnetic fields. The primary composition will also complicate this somewhat. The maximum likelihood analysis shows that the most probable position of the center of the deficit is at $0.70° \pm 0.10°$ to the west and $0.40° \pm 0.09°$ to the south when the angular resolution of the array is $0.88°$. The logarithm of likelihood is calculated to be 10.6 at this position, while it becomes -6.0 at the true Sun position. With a ratio of likelihoods between observed and true Sun positions and a trials factor of 1024 (total number of cells), the probability of chance occurrence of this displacement is given as $6.3 \times 10^{-5}$. This value is still so small that the shadow's displacement is highly significant. The significance of the maximum event deficit is also calculated to be $4.6\sigma$.

For cosmic rays with $\sum \rho_{FT} > 100$, the Sun shadow was also clearly observed,
but its maximum deficit position is calculated to be $0.25^\circ \pm 0.15^\circ$ W and $0.10^\circ \pm 0.10^\circ$ S as shown in Fig. 3(b) (The significance of the shadow is 4.3$\sigma$). The displacement is about one third of that for all showers. When the displacement of the shadow is mainly caused by the magnetic field effects, this decreasing tendency for high energy showers is quite reasonable, since the median primary energy for these showers is about three times higher than that for all showers.

After subtracting the displacement due to the geomagnetic field, the resultant center of the Sun shadow for all events is given at $0.54^\circ \pm 0.10^\circ \pm 0.10^\circ$ W and $0.38^\circ \pm 0.10^\circ \pm 0.10^\circ$ S, where the second errors are from the positioning error of the center of the Moon shadow. This net displacement can be attributed to the effect of the solar and interplanetary magnetic fields.

4.1 EFFECTS OF THE INTERPLANETARY MAGNETIC FIELD

As well known, the configuration of the solar and interplanetary magnetic fields considerably changes with solar cycle. Note that almost all the data used for this analysis were taken in the period between June 1990 and July 1992 when the solar activity was near maximum or rather at the decreasing phase. At that time, the solar magnetic field had large deviations from a pure dipole, i.e., small dipole moment with large contributions from higher multipoles, and the dipole field axis was almost sideways especially in the period from 1990 to 1991 just after the reversal of the polar fields [8]. Thus, the structure of the solar magnetic field at this time is too complicated to give a quantitative estimate of its effect on the shadow.

On the other hand, the effect of IMF may be directly examined as follows. It is known that the IMF has a sector structure with the field direction reversing across the sector boundary [9][10]. This sector structure, with the “away” and “toward” field directions, varies with the phase of solar activity cycle and near maximum it is highly modified, while keeping almost the two-sector structure [11]. During the declining phase, however, the IMF structure rather simplifies and becomes rather stable [12]. According to the solar geophysical data [8], the IMF had almost the two-sector structure in the period when the data were taken, while gradually changing to the four-sector structure in the last period after April 1992.

Because of the opposite polarity of the fields, cosmic ray particles arriving through the away and toward sectors will bend in opposite directions to each other. If the effect of IMF is significant, then the Sun shadows by cosmic rays from respective sectors should be shifted oppositely each other with respect to the shadow center obtained above. Although the statistics becomes worse for each case, the expected behavior is well found. The most probable position of each
shadow center is calculated to be at 0.57° W and 0.48° S for the toward-sector cosmic rays and at 0.86° W and 0.29° S for the away-sector cosmic rays, using the maximum likelihood method. After removing the geomagnetic displacement, these centers are given as (0.41° W, 0.46° S) and (0.70° W, 0.27° S), respectively. The angular distance between two centers is found to be about 0.34°.

Figure 4 shows a summary of these results. This well confirms that the IMF gives a large contribution to the displacement of the Sun shadow. This figure also suggests that a weak magnetic field component facing nearly north-west-northward steadily exits to make the apparent arrival directions of cosmic rays shift to the southwest. A displacement of the Sun shadow due to IMF will generally occur in the north-south direction, since the sector fields are almost parallel to the plane of the ecliptic due to the high-speed solar wind blowing from the rotating sun [13]. This component may be unexpectedly produced by a large-scale disordered structure of the solar and interplanetary magnetic fields in the period near solar maximum.

4.2 SUN SHADOW AT SOLAR MAXIMUM AND AT DECREASING PHASE

The solar cycle is now coming into a quiet phase. From this point of view, it is very interesting and important to compare these results with those which will be obtained in the near future. Then, we made a preliminary analysis to find a change of the Sun shadow near solar maximum and at the decreasing phase. For
the solar maximum, we selected the data taken in a period from June 1990 to October 1990. The periods From April 1991 to October 1991 and from March 1992 to July 1992 are used for the decreasing phases. Figure 5 shows the contour maps for each period. While statistics are not enough high, it seems to be found that not only the center of deficit moves to the apparent position of the Sun, but also the separation of the two peaks becomes wider. These results imply that the magnetic fields shifting the Sun shadow have at least two components: that is, solar magnetic field near the Sun and large scale interplanetary magnetic field. The new Tibet-II array may provide a new clue to study the solar and interplanetary magnetic fields.

5 Tibet-II Experiment

5.1 TIBET-II ARRAY

The Tibet air shower array will be enlarged by a factor of about four in 1994. As schematically shown in Fig 6, the fast-timing (FT) detector array consists of 185 scintillator detectors of 0.5m² each. For new detectors (not filled), plastic scintillators of 3cm thickness each (Bicron BC408A) are used and 2” φ PMTs (Hamamatsu H1161) are equipped. They are placed in a grid pattern of a 15m spacing. Moreover, each of 52 FT-detectors contains a 1.5” φ PMT (Hamamatsu H3178) for a wide-range particle density measurement. This FT-array is surrounded by 32 density detectors of 0.5 m² each to obtain a good core location for individual shower event. The effective area for detecting the contained events is estimated to be about 8 times as large as the old one, and a trigger rate is...
Figure 6: Layout of the Tibet-II scintillation counter array.

estimated to be about 200Hz. In order to achieve a high speed and low dead time data acquisition, a FASTBUS system is employed. Event buffers and zero-suppress system will work well to reduce a dead time and it is estimated to be about 5% at a trigger rate of 200Hz.

Gain of each PMT and time offset value of each channel are calibrated by a newly developed LED and mismatched-reflection monitoring system at the beginning of every data set segment. All the TDCs and ADCs are also calibrated by using a CAT module in the FASTBUS system. These data are recorded using the 8 mm tape drivers (EXB-8505) with about 10 Gbytes/tape capacity in the format of variable-length binary (400 byte in average).

5.2 EXPECTATION

For the Sun’s shadow, sufficient data allow us to estimate the displacement of the shadow at every one-two months. Then, we could get new information on the relation between a time variation of the large-scale structure of the solar and interplanetary magnetic fields and the solar activity, which may considerably contribute to the study of solar terrestrial physics.

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Operation Results of Underground Muon Detector Array on MT. Liang Wang

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Abstract

In order to detect the muon content in a shower and to study the \( \mu \)-poor events and primary elements of cosmic rays near the "knee" energy range, an underground muon detector array is added to the Observatory of Mt. Liang Wang (24.5° N, 735 g/cm\(^2\)) in which an EAS particle array and an air Cerenkov array have operated. This paper gives the structure, characteristics and initial operation results of the \( \mu \)-array.

Introduction

An underground muon detector array (\( \mu \)-array) set up early in this year is a new one of the Observatory of Mt. Liang Wang (24.5° N, 735 g/cm\(^2\)) in which an EAS particle array (p-array) and an air Cerenkov array (C-array) have operated since 1989(1). The construction of the \( \mu \)-array is for the purpose of identifying \( \mu \)-poor events, which are considered to be very important for the detection of UHE \( \gamma \) points, and of researching the primary elements of cosmic ray near the "knee" energy range because the content of the muon will be sensitive to it. So that, we'll naturally pay
much more attention to the events with energy of about $10^{16}$ ev which are not only important to our purpose but have the highest event rate under the present conditions of the arrays on Mt. Liang Wang. This $\mu$—array was designed according to the main points mentioned above.

The $\mu$—array includes three underground detector carpets with a total area of the detectors equal to 150m$^2$ and a trigger system with 3—fold coincidence on the ground. The optimum arrangements have been made so as to obtain more muon count in a shower and still keep better signal/noise, which is essentially dependent on the underground $\rho_\mu/\rho_\mu$ the ratio of $\mu$ and $e$ densities. Fig. 1 shows the arrangement, three detector carpets are laid symmetrically at the location with their horizontal distance from the centre of $\pi$—array equal to 40m, and with their underground depth equal to 4m. On this arrangement, for a typical event (energy $E_\pi=10^{16}$ev, age $s=1.1$) the average moun number hitting one carpet and the ratio in the underground depth of 4m against the distance from a shower core to the carpet are given in Fig. 2.

**Structure and Characteristics of the Muon Detector**

A detector carpet includes 21 muon detectors which are independent each other. The structure of the muon detector is shown in Fig.3, it consists of an acrylic sheet of 75” × 51” × 0.25” and a 5” hemispherical photomultiplies (PMT), EMI 9870B. At the centre of the sheet, a topped hole was bored to fit the curvature of the PMT. The PMT is pushed against the acrylic sheet by three springs and enclosed in a light—tight and water—proof house. Because most of the light produced in the sheet has to undergo a series of internal reflections and then reach PMT, the sheet was wrapped with aluminium foil to increase the light collection.
efficiency. The present design is the amended version of D. Sinclair [2].

The signal pules from the pre-amplifier will be delivered to the amp. / ADC board (Fig.4) in the control room and further amplified by the differential voltage amplifier with a gain of approximately 10. The amplified signal pulse will be transferred into the pulse current which will be delivered to the storage capacitor C. The switch S3 and S4 perform the set function by discharging the storage capacitor C to ground continuously except a coincidence pulse appears. Thus, unwanted signals will be rejected from entering the ADC.

Spectral peaks of muon at different location of a detector sheet were measured in the laboratory [3]. After the first detector carpet and electron system were set up on Mt. Liang wange, the thorough field calibrations of the single particle spectrum (SPS) were carried out for every detectors so as to choose an appropriate threshold level for the discrimination of "Yes or No" muon.

Fig.5 gives an example of SPS. An adjustment of the working voltage for every PMT was made again and again to obtain both a better spectral response and a higher consistancy of the triggered sensitivity in each other. The results show that for most detectors, 86% in total, the sensitivity dispersions to average value are laying with in the range of 15%. And there is only one in the rest runs out of the range and reaches —20%.

Operation Results
The underground muon detector array has a self-contained trigger
system which consists of three ground scintillator detectors with an area of 1m² each. Three detectors are set up just over the three underground carpets respectively, and thus their horizontal distances from the centre of the array are also equal to 40m. Now, the first detector carpet has been completed. When it is put into combined operation with p—array, two trigger models have been employed: the arrays are trigged as p—array or/and µ—array coincide (let’s call it trigger model A), or µ—array coincide alone (let’s call it trigger model B). For these two trigger models, the average trigger rates are 1.13/min and 0.47/min respectively.

Fig.6 shows the size spectra obtained in these two trigger models respectively. Obviously, the events elected by trigger model B have higher energy; and , the events with energy near 10¹⁶ ev (about 6×10⁶ at the level of Mt. Liang wang) have the highest event rate in both of the two trigger models.

In order to test the arrays for muon detection, we researched the distribution of the shower moun number, especially the events with their size (N), age (S), zenith anlge (θ) and core locatien (r) in the following ranges respectively: 5×10⁴ ≤ N ≤ 7×10⁵ (about 10¹⁶ ev), 0.6 ≤ s ≤ 1.6, 0 ≤ θ ≤ 30°, 0 ≤ r ≤ 10m. In the efficient events, 3403 in total obtained with trigger model B, there are 26 events which satisfies all of the conditions mentioned above. Fig.7a shows the distribution of the muon numbers. It can be seen that the events of two muons hitting the detector carpet shows a very high peak and their ratio to the total of 26 events approuches 40%. The average muon number of a shower is equal to 3.19 which is in agreement with the calculated value shown in Fig.2. Fig.7b shows the results with a extended range of the size, 4.5×10⁴ ≤ N ≤ 7.5×10⁵.
As we know, the total muon number of a shower will increase with the shower size, so will the average muon number detected by an array do. In the total efficient events of $1.9 \times 10^4$ obtained with trigger model A, we chose 4739 events the core locations there of lay within a circular area with its radius of 20m and its centre at the array centre so that the influence of “punch through” can be neglected [4]. From these chosen events we can obtain the data shown in Fig.8, and find that the average number increases linearly with the shower size $N$ in the logarithmic diagram although the fluctuation is rather large (This is not given in the diagram). Fitting the data, we obtain

$$\lg \Sigma u = 0.732 \lg N - 3.576$$

and the increasing rate which is in good agreement with the rate $\Delta Nu/\Delta N$ given by simulations [5, 6].

Acknowledgments
We wish to express our thanks to university of Michigan, USA for its unconditional prevision of the acrylic sheets. We would like to thank the members of the groups of University of Hong Kong and Yunnan University for their important contribution to the construction of this array. We are very much grateful to Yunnan Commission of Science & Technology and the National Science Foundation for their financial support.

Reference

![Diagram of the arrangements of the arrays on Mt. Liang Wang.](image)

**Fig. 1** The arrangements of the arrays on Mt. Liang Wang.

**Fig. 2** For the typical events ($E_p = 10^{18}$ eV, $\text{age} = 1.1$), the dependence of the average muon number, $\Sigma \mu$ detected by one carpet, and the $\mu - e$ density ratio, $\rho_\mu / \rho_e$, in underground depth of 3 m upon $r$, the core location distance from the carpet.

Underground 4.0m
$\rho_\mu / \rho_e$, $\Sigma \mu$
Black pvc
Black paper
No. 9 Count—6000
Fig. 3 The structure of the muon detector.

Fig. 5 One of the single particle specticle spectra of the 21 muon detectors
Fig. 6 Distributions of the shower size detected with two trigger model respectively.

Fig. 7 Distributions of muon number detected by one carpet.

Fig. 8 The average muon number $\mu$ detected by one carpet against the shower size.
RESULTS OF THE EXPERIMENT "PAMIR"
AND THE STRONG INTERACTION MODEL AT ENERGY HIGHER THAN $10^{15}$ eV

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Summary

Results of the Collaboration "Pamir" and nuclear-electromagnetic cascade simulations based on a quark-gluon string model are discussed. Conclusions on a rather good agreement between the total set of data and simulation predictions are given. Model modifications are proposed by the author to improve the description of experimental data.

1. INTRODUCTION

In spite of the complexity of methodical problems of emulsion chamber (EC) investigations of the Collaboration "Pamir" [1], our understanding of multiple generation processes in hadron-nucleus interactions at $E > 10^{15}$ eV is much better than it was 20 years ago. At present there is no need to discuss both a high multiplicity hypothesis or a CKP-like model and a pure scaling interaction picture although for a long time these models as well as a number of others [2] played an important role in cosmic ray physics. As a result we can conclude [3,4] that predictions based on a most improved theoretical quark-gluon string model (QGSM) [5] give the best description of the total experimental data, both characteristics of gamma-ray - hadron families (groups of correlated high-energy particles) and single component. Thus it is rational to discuss strong interaction characteristics on the basis of QGSM predictions. However, some experimental results cannot be easily explained within its frames. These problems are discussed below.

2. Some characteristics of QGSM and simulation algorithms

At present the Collaboration "Pamir" uses two computer QGSM-based algorithms to simulate nuclear-electromagnetic cascades (NEC), namely so-called models MQ [6] (and its version MQ1) and MCO [7]. The models have many common properties, namely the inelastic cross-section $\sigma_{h-air}$ and inelasticity coefficient $k_{inel}$ in hadron-air nucleus interactions increasing with energy; a moderate steepening of secondary particle generation spectra in the fragmentation region with energy increase. Diffraction
processes are taken into account; the creation of not only pions but also of other types of particles occurs. There are some differences in the models. Particularly, MQ simulates various diffraction channels and has an effective mechanism of parameter modification. The model MCO treats a larger set of particle types and takes into account and semi-hard jet generation as well as a few nontrivial processes [34]. These models reproduce inclusive spectra predicted by QGSM [5] as well as realize experimental fluctuations. For example, the multiple generation in MCO can carry out through the diffractive dissociation with a multiplicity \( \langle n_{\text{diff}} \rangle \) and a relatively hard particle spectrum, or soft processes (\( \langle n \rangle \approx 2\langle n_{\text{diff}} \rangle \)), or jet generation accompanied by soft processes (\( \langle n \rangle \approx 4\langle n_{\text{diff}} \rangle \)). The most important difference between MQ and MCO is the pion inelastic charge-exchange (\( \pi \text{T}_\text{ex} \)) process \( \pi^\text{ch} \rightarrow \pi^0 \) with probability \( W_c = 0.72 (0.5) \) taken into account only by MQ (MQ1) as well as the smaller value of \( K_{\text{in}}^\text{h-air} \) in MCO (\( \approx 0.7 \) instead of \( \approx 0.8 \) at \( E \approx 10 \text{ PeV} \)) [35].

Main differences of the models MSF [2,35] and MCP [45] will be mentioned below from the above models are \( K_{\text{in}}^\text{h-air} \approx 0.5 \) in MSF and \( K_{\text{in}}^\text{h-air} \) decreasing with energy to \( \approx 0.4 \) in MCP. Both models simulate pions only as secondaries.

3. ON COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

A comparison of simulation predictions with emulsion experiment results is reasonable with simulations of detection processes only. It requires good computer programs and a lot of time. Thus, at present, predictions of MQ are compared with results obtained in so-called carbon emulsion chambers (C-EC) [8]. Predictions of MCO are analyzed only together with lead chamber (Pb-EC) data [8]. Two sets of partial inelasticity coefficients (\( K_1^\gamma \) and \( K_2^\gamma \)), i.e. parts of energy transferred by hadrons into the electromagnetic (EM) component in h-Pb interactions, are used. In first case only \( \pi^0 \) generation is taken into account whereas in second case \( \eta \)-meson creation additionally is. A comparison of the results of MQ and MCO models is not easy.

Note the importance of a correspondence between models used for NEC simulations in the air and in chambers. Particularly, \( K_{\text{in}}^\text{h-air} \) has to be close to \( K_{\text{in}}^\text{h-carbon} \). In the opposite case results on hadron spectra cannot be correct [9,46].

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4. PRIMARY COSMIC RAY SPECTRUM

Both the slope and chemical composition of the primary cosmic ray (PCR) spectrum are very important for EC experiments. The investigations [10,11] carried out within the framework of the Collaboration "Pamir" concluded that at $E \geq 10^{15}$ eV the chemical composition is normal [10] and the fraction of iron nuclei does not exceed 27% [11]. JACEE [12] measurements give evidences in favor of a small increase of the proton integral spectrum index up to $\beta \approx 1.75 \pm 1.85$. On the other hand, the analysis [46] shows that joint description of EAS and $\gamma$-h family characteristics is possible only by means of normal-composition PCR. Results [49,50] give evidences in favor of this conclusion. So we assume the normal chemical composition of PCR. Both MQ and MCO use primary spectra close to the so-called Nikolsky spectrum [15]. In simulations [3] two following proton spectrum fits are used:

$$I(>E/TeV)=2.69 \times 10^{-4}(E/0.1)^{-1.62}(1+6 \times 10^{-4} E)^{-0.4}(cm^2\cdot sec\cdot sr)^{-1}$$ [15]

$$I(>E/TeV)=3.30 \times 10^{-4}(E/0.1)^{-1.70}(1+6 \times 10^{-4} E)^{-0.4}(cm^2\cdot sec\cdot sr)^{-1}$$ [16]

Points of nucleus spectrum steepening are proportional to nucleus charges.

5. SPECTRA OF HADRONS AND ELECTROMAGNETIC COMPONENT

The first data to be described by any model are spectra of single particles. Intensities and slope indexes of electromagnetic (EM) particles (hereafter, called $\gamma$-quanta) and hadrons are very sensitive to $K_{\text{air}}$ and $\sigma_{\text{air}}$ as well as to spectra of secondaries, $\pi$CE process and so on. Up to now these problems have, in fact, been analyzed only by means of analytical calculations which cannot give quantitative predictions of characteristics of $\gamma$-h families and take some methodical problems into account. On the other hand, the Monte-Carlo method is not used, practically, to calculate single component intensities. As a result, there has not been any model so far which describes simultaneously both single components and family characteristics.

The intensity and slope indexes of $\gamma$-component at the Pamirs level have been calculated by means of MCO [7] for PCR spectrum by [15]. One can see from Table 5.1 including also results [39,40] that the experimental value $\beta_\gamma$ [1] in the energy interval from 5 TeV up to $\approx 100$ TeV is close to the simulated one.

However, an essential part of spots rising with energy is
produced by electromagnetic cascades from air, but not single \( \gamma \)-quanta [37]. It is impossible to separate these types of events because of limited sizes of measuring diaphragms. It can lead to the energy overestimation and spectrum hardening [18]. A difference between the real and measured index values equals to \( \Delta \beta = \beta_{\text{real}} - \beta_{\text{meas}} \approx 0.15 \pm 0.2 \), i.e. the real value to be compared with analytical predictions is \( \beta_{\text{real}} \approx 2.25 - 2.3 \) [18].

In part, this problem could be connected with the following problem. Quasi-scaling models predict a reasonable index values and too high family intensities in comparison with the experimental data, whereas models assuming strong scaling violation predict the intensity close to the experimental one but too big index values [44]. This contradiction can be reduced taking the above effect into account in favor of models with scaling violation.

The situation with the hadron spectra is not evident also. In Table 5.2 the experimental slope indexes \( \beta_h \) of various authors in the energy interval from \( E_{\text{thr}} \) up to \( \approx 100 \) TeV are listed. Spectra obtained by means of Pb-chambers are steeper, in average, than ones obtained by C-chambers are. It could be explained by the following methodical reasons.

Table 5.3 displays the relative intensities and slope indexes of vertical integral spectra of different types of hadrons at the Pamirs level calculated with MCO taking into account the hadron registration efficiency [8] in C-EC. The indexes of spectra at \( E_h > 20 \) TeV above chambers are listed in third column. The efficiency rises from \( \approx 0.1 \) at \( E_h \approx 3 \) TeV to \( \approx 0.7 \) at \( E_h \approx 70 \) TeV [8]. As a result, the measured spectrum is harder and not really power law one. It is seen from last three columns, where the index values are shown for various minimal energies. Even at \( E_h^Y > 20 \) TeV the "measured" spectra are harder than the arriving hadron spectra. In Pb-chambers this effect has to be weaker and, as a result, a difference between the indexes of measured and real spectra has to be less, not more than \( \approx 0.05 \). From Tables 5.2 and 5.3 one can see that the real hadron spectrum index can be \( \beta_h \approx 2.1 \), i.e. close to the simulated one.

In the case of lead chambers the experimental and simulated results agree also rather well both in intensities and absorption path values \( \lambda_{\text{abs}}^L \) (100±6 and 98±2 g/cm\(^2\) at \( E_h^Y \approx 6.3 \) TeV
correspondingly). Note that the simulated value $\lambda_{h\text{-}air}^{ab}$ is obtained from intensity values at different altitudes whereas the experimental one is calculated from the angular distribution and can depend on accuracy of the energy measurement at large angles.

However, the most important result of the simulation concerns the equality of slope indexes of both the $\gamma$-component and total hadron spectrum. It contradicts the results of \cite{18,19} obtaining by means of a new method the difference equaled to $\Delta \beta = \beta_{\gamma} - \beta_{h} \approx 0.3 \pm 0.4$. Taking into account the energy dependence of hadron registration efficiency, we can assume $\Delta \beta \approx 0.2$. This difference is very important, since it is possible only in models with strong scaling violation in the fragmentation region \cite{38,52}. In models with a moderate scaling breaking $\beta_{\gamma} \leq \beta_{h}$ \cite{38,52}.

Thus the QGSM-based model MCO cannot explain differences between slope indexes of $\gamma$- and hadron components. How can the model be changed to make its predictions agree with the data \cite{18,19}? One can see from Table 5.3 that various hadron components have different slope indexes. The pion spectrum is steep, but rather not enough. One could think that the $\gamma$-spectrum has to be parallel to the pion one but it is essentially harder. It can be explained in the following way. First, the main part of $\gamma$-quanta is produced by nucleons. Their spectrum is harder than the pion one. Second, the observed EM-component originates from $\gamma$-quanta generated at some effective altitude above chambers where the pion spectrum is harder. The scaling-like EM-cascade development produces the $\gamma$-spectrum at the observation level with the same slope. To steepen the $\gamma$-spectrum it is necessary to steepen the neutral pion spectrum in hadron-nucleus collisions more strongly than in QGSM \cite{5}. This model modification can be connected with a relative decrease of $K_{h\text{-}air}^{\text{inel}}$ in the case of the invariable multiplicity dependence on energy.

Table 5.1. The slope indexes $\beta_{\gamma}$ of vertical simulated and experimental integral $\gamma$-spectra at $E > 5$ TeV.

<table>
<thead>
<tr>
<th>Type of data</th>
<th>$\beta_{\gamma}$ (&gt;5 TeV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>2.11±0.03</td>
<td>\cite{7}</td>
</tr>
<tr>
<td>Experiment</td>
<td>2.07±0.06</td>
<td>\cite{1}</td>
</tr>
<tr>
<td></td>
<td>2.00±0.08</td>
<td>\cite{39}</td>
</tr>
<tr>
<td></td>
<td>2.00±0.05</td>
<td>\cite{40}</td>
</tr>
</tbody>
</table>
Table 5.2. The slope indexes $\beta$ of the experimental integral hadron spectra at $E_h > E_{thr}$.

<table>
<thead>
<tr>
<th>$E_{thr}, \text{TeV}$</th>
<th>$\beta(E_h &gt; E_{thr})$</th>
<th>Chamber type</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>1.96±0.06</td>
<td>Pb</td>
<td>[1]</td>
</tr>
<tr>
<td>6.3</td>
<td>2.01±0.08</td>
<td>Pb</td>
<td>[3]</td>
</tr>
<tr>
<td>5.</td>
<td>2.03±0.08</td>
<td>Pb/Fe</td>
<td>[39]</td>
</tr>
<tr>
<td>5.</td>
<td>2.0±0.1</td>
<td>Pb</td>
<td>[40]</td>
</tr>
<tr>
<td>20.</td>
<td>1.90±0.15</td>
<td>C</td>
<td>[19]</td>
</tr>
<tr>
<td>7.</td>
<td>1.90±0.1</td>
<td>C</td>
<td>[41]</td>
</tr>
</tbody>
</table>

Table 5.3. The simulated slope indexes $\beta(E_h, E_{h} > E_{thr})$ and relative intensities $I_{h}(E_{h} > 20, \text{TeV})$ of integral hadron spectra.

<table>
<thead>
<tr>
<th>Hadron type</th>
<th>$I_{h}$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>$E_{h} &gt; 20 \text{TeV}$</td>
</tr>
<tr>
<td>nucleons</td>
<td>100</td>
<td>2.08±0.01</td>
</tr>
<tr>
<td>A/\Sigma</td>
<td>60</td>
<td>2.10±0.01</td>
</tr>
<tr>
<td>pions</td>
<td>2</td>
<td>1.42±0.02</td>
</tr>
<tr>
<td>kaons</td>
<td>25</td>
<td>2.22±0.01</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>2.03±0.01</td>
</tr>
</tbody>
</table>

6. CHARACTERISTICS OF GAMMA-RAY - HADRON FAMILIES WITH $E_{\gamma} > 100$ TeV

6.1. Intensity of gamma-ray families

In Table 6.1 experimental and model intensities of $\gamma$-families detected with Pb-EC [3] are given. The good agreement is darkened by poor statistics only. The model MQ (MQ1) predicts the family flux with $E_{\gamma} = 80-400$ TeV ($R \leq 15$ cm, $E_{\gamma} > 8$ TeV) $I_{\gamma}^{\text{simul}} = 0.9 \pm 0.07$ (0.6±0.1) ($m^2\cdot$year)$^{-1}$ for C-EC [9] and PCR [15] whereas the experimental flux $I_{\gamma}^{\text{exper}} = 0.45\pm0.05$ ($m^2\cdot$year)$^{-1}$ [54]. The difference of simulated intensities is due to difference in $\pi$IC$E$ probability $W_c$ values. Decrease of $W_c$ to $\approx 0.3$ can make predictions agree with $I_{\gamma}^{\text{exper}}$. Note that a large degree of the azimuthal asymmetry of $\gamma$-h families (Sect. 8) is the only serious argument in favor of existence of $\pi$IC$E$ process at superhigh energies. An asymmetry explanation with processes different from $\pi$IC$E$ can do it to be superfluous to describe the soft interactions.

Table 6.1. Total and vertical experimental and calculated intensities of $\gamma$-families in Pb-chambers [3]. $E_{thr} = 6.3$ TeV.

<table>
<thead>
<tr>
<th>Type of data</th>
<th>$I(\Sigma E_{\gamma} &gt; 100 \text{ TeV})$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\text{total} (m^2\cdot$year)$^{-1}$</td>
<td>$\text{vertical} (m^2\cdot$year$\cdot$sr)$^{-1}$</td>
</tr>
<tr>
<td>experiment</td>
<td>0.38±0.10</td>
<td>0.67±0.15</td>
</tr>
<tr>
<td>MCO</td>
<td>0.37±0.02</td>
<td>0.70±0.08</td>
</tr>
</tbody>
</table>
6.2. Angle distribution of gamma-ray families

As it has been mentioned above (Sect. 5) experimental and simulated results accumulated by means of lead chambers on hadron angle distributions agree rather well in mean absorption path value [3] being about 100 g/cm². The absorption path $\lambda_{abs}^{fam}$ of $\gamma$-families with $\Sigma E_\gamma > 100$ TeV by the Collaboration "Pamir" is 73±8 g/cm² at $\theta < 30^\circ$ [62]. This value can rise up to the upper limit equal at $\theta < 45^\circ$ to 80±5 if various methodical factors will be taken into account [62]. This value is rather larger than the corresponding value predicted by MQ, i.e. 70 g/cm², but essentially smaller than 100 g/cm² obtained in experiments at Mt. Chacaltaya and Canbala. Thus, QGSM-based models predicts too strong family absorption in the atmosphere.

6.3. Transversal characteristics of $\gamma$-h families

In Table 6.2 average transversal characteristics of $\gamma$-h families with $\Sigma E_\gamma = 100$-400 TeV are listed. One can see a rather good agreement between experimental and simulation results within the error limits for both Pb- and C-chambers. Results [42,48] show that at $E_R > 1.5$ GeV·km experimental $E_R$-distributions are situated higher than simulated ones. It can confirm a hypothesis about appearance of a new processes with large $<p_t>$ value at $E_0 > 10$ PeV. However, statistics is not large, so this result is preliminary.

Table 6.2. Average transversal characteristics of $\gamma$-h families; $\Sigma E_\gamma = 100$-400 TeV; $E_{thr} = 6.3$ TeV ($^\star$ - $E_{thr} = 4$ TeV; $^\# - E_{thr} = 10$ TeV)

<table>
<thead>
<tr>
<th>Type of data</th>
<th>Type of EC</th>
<th>$&lt;R_\gamma&gt;$ mm</th>
<th>$&lt;E_R&gt;$ TeV·mm</th>
<th>$&lt;R_h&gt;$ mm</th>
<th>$&lt;E_R&gt;$ TeV·mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>experiment</td>
<td>Pb</td>
<td>20±4</td>
<td>273±47</td>
<td>26±5</td>
<td>375±70</td>
</tr>
<tr>
<td>MCO</td>
<td>K$^1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K$^2$</td>
<td>21±1</td>
<td>269±18</td>
<td>27±2</td>
<td>350±30</td>
</tr>
<tr>
<td></td>
<td>K$^3$</td>
<td></td>
<td></td>
<td>32±2</td>
<td>404±35</td>
</tr>
<tr>
<td>experiment</td>
<td>C</td>
<td>20±1$^\star$</td>
<td></td>
<td>23±2$^#$</td>
<td></td>
</tr>
<tr>
<td>MQ</td>
<td></td>
<td></td>
<td>23±1$^\star$</td>
<td>20±3$^#$</td>
<td></td>
</tr>
</tbody>
</table>

Ref. [3]
6.4. Longitudinal characteristics of families

The spectrum of family hadrons is more sensitive to interaction parameters than the $\gamma$-spectrum. Both in MQ [4] and MCO [24] it agrees well with the experimental data. It depends on family-hadron composition (mainly, on nucleon fraction) as well as $K_{\text{inel}}^{\text{air}}$ and $K_{\text{inel}}^{\text{chamber}}$. Generators MQ, MSF, and MCP predict very different spectra "above" chambers (the difference can be as large as one order). The "measured" spectra in this models are much closer if one uses the same $K_{\text{inel}}$ values in chamber simulations which are used in air cascade simulations. The spectra can differ very much in the contrary case as it is seen well from comparison of [9] and [46]. Taking into account that a large fraction of family hadrons consists of kaons (23%) and nucleons (23%) while the pion's one is 54% [3], it would be possible to vary the pion spectrum slope within certain limits without contradictions with the experimental data.

6.5. Multiplicity and correlations

In Table 6.3 the multiplicity $<n_\gamma>$ of "rejuvenated" events (i.e. families consisting of cascades ordered with respect to energy decrease and including particles with energy $E_i \geq 0.04 \sum_{j=1}^{i} E_j$ only) and hadron multiplicity $<n_h>$ of families with energy $\Sigma E_\gamma = 100 - 400$ TeV for different installations and simulations are listed. The average ratio of $\gamma$-family energy to total event energy detected in chambers ($Q_\gamma = \Sigma E_\gamma / (\Sigma E_\gamma + \Sigma E_h)$), the fraction $W_Q$ of families with $Q>0.9$ and the fraction $W_n$ of families with the hadron number $n_h=0$ are given as well.

One can see a rather good agreement of the experimental and simulation results both for Pb- and C-EC, excluding absence of events with $n_h \geq 10$ among MQ-simulated events. This problem is not connected with QGSM properties as MCO simulates families of such multiplicity. However, the both models, as well as other models, cannot explain Centauro-like events with extremely large $n_h$.

Summing up, both the models MQ and MCO describe rather well longitudinal and transversal characteristics of $\gamma$-h families with $\Sigma E_\gamma = 100-400$ TeV. However, the single-component spectrum slopes predicted by QGSM-based models differ from the experimental data.
Table 6.3. Values of $<n_1^f>$, $<n_h>$, $<Q_\gamma>$ = $<\Sigma E_\gamma/(\Sigma E_\gamma + \Sigma E_h^\gamma)>$, $W_Q$ ($Q > 0.9$) and $W_n$ ($n = 0$) for $\gamma$-h-families with energy $\Sigma E_\gamma = 100-400$ TeV and $E_{thr} = 6.3$ TeV (\# $- E_{thr} = 4$ TeV; $\ast - E_{thr} = 10$ TeV).

<table>
<thead>
<tr>
<th>Type of data</th>
<th>$&lt;n_1^f&gt;$</th>
<th>$&lt;n_h&gt;$</th>
<th>$&lt;Q_\gamma&gt;$</th>
<th>$W_Q$ ($Q &gt; 0.9$)</th>
<th>$W_n$ ($n = 0$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>experim. Pb</td>
<td>$10.6 \pm 0.6 \ast$</td>
<td>$2.2 \pm 3$</td>
<td>$0.83 \pm 0.06$</td>
<td>$0.44 \pm 0.09$</td>
<td>$0.20 \pm 0.07$</td>
<td>[3]</td>
</tr>
<tr>
<td>MCO $K_1^\gamma$</td>
<td>$10.7 \pm 0.3 \ast$</td>
<td>$2.0 \pm 0.2$</td>
<td>$0.86 \pm 0.01$</td>
<td>$0.40 \pm 0.04$</td>
<td>$0.18 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>MCO $K_2^\gamma$</td>
<td>$10.7 \pm 0.3 \ast$</td>
<td>$2.6 \pm 0.2$</td>
<td>$0.82 \pm 0.01$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>experim. C</td>
<td>$10.0 \pm 0.2 \ast$</td>
<td>$0.92 \pm 1 \ast$</td>
<td>$0.63 \pm 0.04 \ast$</td>
<td>$0.54 \pm 0.03 \ast$</td>
<td></td>
<td>[9]</td>
</tr>
<tr>
<td>MQ</td>
<td>$9.8 \pm 0.2 \ast$</td>
<td>$0.9 \pm 1$</td>
<td>$0.65 \pm 0.03$</td>
<td>$0.48 \pm 0.04$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7. SUPERFAMILY CHARACTERISTICS

The main part of information on interactions at energies higher than $10^{16}$ eV is is accumulated by means of analysis of $\gamma$-superfamilies with $\Sigma E_\gamma > 500$ TeV obtained in a lot of works [1, 25, 53, 55-61]. Summing up their results, the QGSM-based model describe rather well longitudinal and transversal characteristics of the periphery of superfamily $\gamma$-component corresponding to $\lg(E_0/1$ TeV) $\approx 4.2 - 5.1$ [23]. Both the central part of high energy concentration including the halo phenomenon and the hadron component of these events are not investigated yet in detail. We will use below some results of these works.

8. AZIMUTHAL EFFECTS IN FAMILIES

8.1. Brief introduction

Observation of some essential excess of the $\gamma$-family azimuthal effects over the simulated background (azimuthal asymmetry, binocular events, alignment etc.) stimulated attempts to explain the phenomenon either by trivial kinematics effects [67, 68], or by means of gluon jet generation [64], or considering it as a result of rupture of quark-gluon string semihardly stretched between fast constituents of the projectile hadron [65] or in the framework of a quark compositeness model [63]. However, a final conclusion is not obtained yet.

Specific parameters, namely $\alpha = \sum_{i \neq j}^N \cos 2\varphi_{ij}/(N \cdot (N-1))$ [28, 29] and $\lambda = \sum_{i \neq j \neq k}^N \cos 2\varphi_{ijk}/(N \cdot (N-1) \cdot (N-2))$ [32] are used by the Collaboration "Pamir" to calculate the azimuthal asymmetry and
alignment of family particles respectively. Their values equal to \( \alpha_{N} = 1 \) for \( N \) points placing in a straight line and decrease to \( \alpha_{N} = -1/(N-1) \) in the isotropic case. To calculate \( \alpha_{N} \) angles \( \phi_{ij} \) between vectors drawn from the energy-weighted event center to \( i \)-th and \( j \)-th points are used whereas to compute \( \lambda_{N} \) angles \( \epsilon_{ij} \) between vectors from \( k \)-th point to \( i \)-th and \( j \)-th points are calculated.

Table 8.1. Experimental and simulated values of \( \langle \alpha \rangle \) for families with \( \Sigma_{E_{T}} = 100-400 \) TeV in Pb-EC \( (n \geq 5) \) and C-EC \( (n \leq 3) \).

<table>
<thead>
<tr>
<th>Type of data</th>
<th>Type of EC</th>
<th>( E_{\text{thr}}, ) TeV</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>experiment</td>
<td>Pb</td>
<td>0.19±0.04, 0.15±0.02</td>
<td>0.24±0.05, 0.19±0.02</td>
</tr>
<tr>
<td>MCO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>experiment</td>
<td>C</td>
<td>0.29±0.02, 0.33±0.02</td>
<td></td>
</tr>
<tr>
<td>MQ</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.2. Azimuthal asymmetry

Attempts to analyze the azimuthal asymmetry in terms of \( \alpha_{N} \) in the framework of the semi-hard jet generation and \( \pi \)ICE process were made in [30]. However, the experimental asymmetry degree can be explained only by means of \( \pi \)ICE process [9]. The main reason is a slower development of subcascades from \( \gamma \)-quanta carrying the considerable part of energy of parent pions. Thus, the subcascades can begin higher and go farther from the NEC axis magnifying the event asymmetry. It is illustrated by Table 8.1 listing the experimental and model values of \( \langle \alpha \rangle \). One can see some difference between Pb- and C-EC experimental values. It could be explained by means of different selection criteria of the family particle numbers, various types of fluctuations of hadron energy fractions transferred into \( \gamma \)'s and measured by means of different methods. It seems that the value predicted by MCO is smaller than the experimental one. No doubt, MCO considering the jet generation but not \( \pi \)ICE predicts the smaller asymmetry degree than MQ including \( \pi \)ICE does. This difference can be particularly reduced if energy measurement errors would be taken into account in Pb-EC. However, the rate of \( \pi \)ICE process used by MQ is not observed in accelerator experiments at relatively high energies [31]. A resolution of this contradiction could be found in some new way connected probably with an explanation of the alignment phenomenon which cannot be explained by means of \( \pi \)ICE.
8.3. Alignment

The phenomenon of family object alignment in a straight line is another azimuthal effect manifestation discovered first for multicore halo events [32] and then for the so-called energy distinguished cores (EDCs) [33]. An experimental probability \( W(\lambda_4 > 0.8) \) of finding aligned four-EDC events with \( \Sigma E > 700 \) TeV in Pb-EC and C-EC is 0.43±0.17 [62] and 0.26±0.09 [43] respectively while the background value is 0.08±0.02 only [33].

In [34] three possible causes of this phenomenon were analyzed, namely, fluctuations, external fields, and, finally, hadron interaction physics.

Two experimental family set under consideration with \( \Sigma E > 700 \) TeV consist of 14 [62] and 35 [43] events including 6 (A) and 9 (B) aligned events respectively. To test the first effect origin, 500 (A) and 250 (B) family sets involving the corresponding event numbers were simulated for either case. Resulting distributions of the number of aligned \( \gamma-h \) families \( N_{\text{fam}}(\lambda_4 > 0.8) \) in each of the sets are shown in Fig. 8.1 (A,B). In either case one cannot see a single simulated set coinciding with the experimental ones. Thus, the fluctuation origin of the phenomenon is improbable.

![Fig. 8.1. Distributions of family sets as functions of the number of aligned \( \gamma-h \) families \( N_{\text{fam}}(\lambda_4 > 0.8) \) in each of the sets. Each of the rectangles corresponds respectively to four (A) or one (B) family set consisting of 14 (A) or 35 (B) events simulated by MCO. Rectangles marked as 'E' correspond to the experimental sets.](image-url)
To analyze the phenomenon external origin, two factors capable of producing azimuthal effects, namely, the Earth's magnetic field and atmospheric electric fields were considered. As it is seen from Table 8.2 the magnetic field cannot explain the effect, independently from primary particles. Here the notations are the following:

EMD denotes the projectile nucleus electromagnetic dissociation in electric fields of air nuclei.

MF denotes the Earth's magnetic field.

Two models were analyzed, namely the vertical and horizontal electric fields with gradients of 1 and 2 GV respectively, i.e. close to maximal values possible in the atmosphere. In Table 8.3 results for cascades initiated by protons are given, for gammas and hadrons separately. One can see that the fields are not too strong to eliminate chaotic transversal hadron motion whereas the vertical field can magnify the alignment of $\gamma$-quanta essentially.

To analyze the hadron interaction origin, simulations were made by means of various NEC development models. In Table 8.4 simulation results [34] for primary nucleons are listed. Abbreviations of model variants taken into account are as follows.

ALG denotes a particle coplanar generation of the usual $<p_t>$.

DDD denotes the double diffraction dissociation of projectiles with a large momentum transferred into clusters decaying into secondaries with the usual $<p_t>$ in the cylindrical phase space.

ISD denotes the single diffraction dissociation of the enlarged cross section (the usual one times 10).

PNP denotes the photonuclear processes of the weakly rising cross section [14] taking place in EM cascades.

ROT denotes the high-spin rotation of the noninteracting part of the projectile nucleus with its following coplanar destruction.

SHIDID denotes the semihard diffractive inelastic dissociation with the momentum squared $Q^2 \sim (n \cdot \text{GeV/c})^2$ transferred to the projectile hadron and rupture of a quark-gluon string stretched between semihardly scattered fast constituents [65].

X denotes unknown long-flying component having a rather small cross section $\sigma_{X \text{-air}} \approx 0.2 \cdot \sigma_{P \text{-air}}^{\text{inel}}$ and interacting through the coplanar hadron generation of secondaries with $<p^X_t> \approx 10 \cdot <p_t>$. One can see from Table 8.4 that only a process of secondary particle alignment with the usual $<p_t>$ together with very large
diffraction cross-section can increase the fraction of aligned events a little. The same conclusion can be derived for cascades initiated by primary nuclei and gamma-quanta.

It is possible to explain the effect assuming [34] existence of a hypothetical particle with \( \lambda_{int}^\gamma \cdot \chi_{p-air}^p \) (for theoretical suggestion see, e.g., [66]) interacting through the coplanar particle generation. However, the experimental zenith angular distributions of both aligned and usual families [43] does not confirm this hypothesis.

The experimental results can be described [69], in part, in the framework of SHID model [65]. However, it is necessary to assume additionally that the normal-to-string momentum of secondaries is \( \approx 0.02 \pm 0.05 \) GeV/c, i.e. several times lesser than the corresponding value in \( e^+ e^- \) collisions at the same invariant energies, whereas the cross section of SHID interactions \( \sigma_{shid}(Q \geq 8 \ \text{GeV/c}) \approx 0.05 \cdot \sigma_{inel} \) and the average transversal momentum transferred to a constituent quarks \( \langle Q \rangle \approx 5 \pm 6 \) GeV/c.

In this connection a hypothesis [47] is of interest assuming that the alignment is a result of new strong interactions above the electroweak scale at energies \( \sqrt{s} > 4 \) TeV characterized by very large transverse momentum as well as generation of heavy hadrons interacting with small \( K_{inel} \).

Summing up, the alignment also is an evidence in favor of processes with large \( \langle p_t \rangle \) taking place at super high energies.

Table 8.2. Values of \( \langle \lambda_4 \rangle \) and \( W(\lambda_4 > 0.8) \) for all particles of \( \gamma-h \) families initiated by primary protons, \( \alpha \)-particles and \( \gamma \)-quanta. Statistical errors are lesser than 0.01.

<table>
<thead>
<tr>
<th>Primary particle</th>
<th>( p )</th>
<th>( \alpha )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>MCO +MF</td>
<td>MCO +MF</td>
<td>MCO +MF +EMD</td>
</tr>
<tr>
<td>( \langle \lambda_4 \rangle )</td>
<td>0.23</td>
<td>0.22</td>
<td>0.06</td>
</tr>
<tr>
<td>( W(\lambda_4 &gt; 0.8) )</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 8.3. The same as in Tab. 8.1 separately for hadrons and \( \gamma \)-quanta of \( \gamma-h \) families initiated by protons. Horizontal and vertical electric fields are taken into account.

<table>
<thead>
<tr>
<th>Field</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>( \langle \lambda_4 \rangle )</td>
<td>( W(\lambda_4 &gt; 0.8) )</td>
</tr>
<tr>
<td></td>
<td>0.24 ± 0.01</td>
<td>0.06 ± 0.01</td>
</tr>
</tbody>
</table>
Table 8.4. Values of $<\lambda_4>$ and $W(\lambda_4 > 0.8)$ for all particles of $\gamma-h$ families initiated by primary protons, $\alpha$-particles and X-component in the framework of various hadron interaction models at 350 g/cm$^2$ in the atmosphere for $E_{thr} = 200$ TeV [34].

<table>
<thead>
<tr>
<th>Primary particle</th>
<th>$p$</th>
<th>$\alpha$</th>
<th>$\gamma$</th>
<th>$X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>+DDD +ALG +ISD +ISD+ALG +ROT +PNP +PNP+ALG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt;\lambda_4&gt;$</td>
<td>0.21</td>
<td>0.27</td>
<td>0.21</td>
<td>0.28</td>
</tr>
<tr>
<td>$W(\lambda_4 &gt; 0.8)$</td>
<td>0.05</td>
<td>0.09</td>
<td>0.06</td>
<td>0.10</td>
</tr>
</tbody>
</table>

9. DISCUSSION

There are some indications of possible differences between certain of interaction characteristics at $E > 10^{15}$ eV and the QGSM predictions. It seems that the leading hadron spectra are probably harder. The registration of the Elena event [26] with the distinct hadron leader may be a circumstantial evidence for this point of view. The relative intensity of energetic hadrons with and without accompaniment has to be sensitive to this parameter [27].

Thus, one can propose some relative decrease of $K_{h-air}$ and pion spectrum steepening in hadron interactions in comparison with QGSM predictions. How can these assumptions change results?

As regards intensities of components, the proposed modifications act in the opposite directions. Thus it is possible to keep the calculated intensities close to the same values. Then the hadron spectrum has to be harder. So the PCR spectrum fit [16] would be more suitable. The single $\gamma$-spectrum has to be steeper.

The pion spectrum slope in families depends on model parameters rather weakly [9]. The arriving pion intensity will be larger if we decrease $K_{\pi-air}^{inel}$. However, it could be compensated by decreasing the energy transferred into $\gamma$'s by interacting hadrons and steepening the pion generation spectrum. Therefore, the registered pion intensity would be almost the same if modifications are not very large. The only problem is a slope of the spectrum of the maximal hadron energy depending on $K_{\pi-air}^{inel}$ [9]. Its decrease has to lead to some spectrum hardening. However, for the accurate comparison with experimental data it is necessary to use, contrary to [9], the same model both for the atmospheric and chamber simulations. In this case a more slow increase of $K_{inel}$ in comparison with the QGSM predictions will keeps the simulated spectrum within reasonable limits.
As regards lateral characteristics, the smaller $K_{inel}$ the larger $R_h$. It does not contradict to experimental results.

The parameter $<n'>$ is not very sensitive to moderate changes. It seems that $<n_h'>$ and its fluctuations will be larger and the fraction of energy carried by hadrons will increase a little.

At last, azimuthal effects as well as some excess of wide families are an evidence in favor of a new channel appearing at $E \geq 10^{16}$ eV, additional to traditional ones.

10. CONCLUSIONS

The total set of the Collaboration "Pamir" data corresponding to interaction energies $E \geq 10^{15}$ eV can be explained rather well by means of simulation algorithms based on the quark-gluon string model [5]. Nevertheless, it could be better described by means of an interaction model assuming the following changes in comparison with the above models.

- a smaller $K_{h-air}^{h-air} < 0.6$;
- a steeper spectrum of the secondary particle generation;
- appearance of a new channel characterized by a (very) large transferred momentum related to SHIDID [65] or a new higher-color quark sector [47] at $E \geq 10^{16}$ eV;
- absence or small cross-section of $\pi$ICE process;
- a PCR spectrum like to the fit [16] or more steep.

11. ACKNOWLEDGMENT

This work was supported, in part, by a Soros Foundation Grant.

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RECENT RESULTS FROM MACRO AT GRAN SASSO

The MACRO Collaboration*

(Presented by C. N. De Marzo)

Abstract

Several topics in high energy cosmic ray physics can be investigated by the MACRO apparatus at the Gran Sasso National Laboratory in Italy. The MACRO is a large area underground detector at 3200 m.w.e. of minimum depth. One of its unique feature is the possibility of studying events in coincidences with the extensive air shower array EAS-TOP, located on top of the Gran Sasso mountain at an average distance of 3300 m.w.e. Another feature, presently under test, is the possibility to measure the residual muon energy by a Transition Radiation Detector.

Among the most recent results obtained by the MACRO experiment, particular attention is given to the high energy neutrino flux measurements.

Besides that, in conjunction with EAS-TOP collaboration, last results on MACRO/EAS-TOP coincidences are presented. The contribution of these last data to a quantitative study of cosmic ray composition is discussed.
1. Introduction

One of the primary design goals of the MACRO apparatus has been a sensitive search for supermassive, grand unified, magnetic monopoles. Because of its large area, it became immediately evident that, using this apparatus, cosmic-ray physics with high energy muons and other penetrating cosmic radiation can also be investigated systematically with high statistics. Today MACRO is a large area multi-purpose apparatus whose performance are been continuously improved.

In this communication I shall briefly present the last evolution of the detector configuration, in particularly the addition of a Transition Radiation Detector for muon energy measurement. I like to report on the improvements expected from this new equipment which is at present under test.

I shall also present last results on upward-going muons and on coincidences with the Extensive Air Shower array EAS-TOP, located on top of the Gran Sasso mountain.

2. Description of the MACRO apparatus

The MACRO apparatus is located in the underground Gran Sasso Laboratory, Italy, at 963 m a.s.l., 3100 m. w.e. of minimum rock coverage. It has a lower and an upper part ('attico') with overall dimensions of about 12x77x9 m³, as shown in figure 1.

MACRO has a modular structure whose basic block is a super-module of size 12x12.6x4.8 m³ (bottom
part), equipped with planes of limited streamer tubes, with two-dimensional digital readout (wires and strips), track-etch plastic modules and liquid scintillator counters [1]. In its full configuration MACRO has an acceptance for isotropic particle flux of \( \Sigma \Omega \approx 10^4 \, \text{m}^2 \, \text{sr} \) and a total scintillator mass of \( 10^3 \, \text{t} \).

The angular resolution for muon tracks is less than 1° and is dominated by multiple scattering in the rock. Space point accuracy is of order 1 cm and track resolution is at level of 5 cm.

The horizontal scintillation layers consist of PVC tanks (12mx75cmx25cm) filled with liquid scintillator and equipped with two 20 cm diameter hemispherical photomultipliers (PTMs) at each end. After calibration, which is performed on a weekly basis, the time resolution for muons in a scintillator box is about 500 ps, corresponding to a position resolution along the box of about 11 cm, as determined using difference in time at the two box ends. Several general and specialized trigger are implemented according to the various items of physics to be investigated.

The data-acquisition system includes several MicroVAXes acting as front-ends to the CAMAC digitizing electronics and a VAX-8200 computer.

3. The Transition Radiation Detector

A long experimental effort has been devoted in order to optimize the parameters of a Transition Radiation Detector (TRD) suited for measuring the residual energy of muons arriving underground [2]. One module of this detector (2x2x6 m³) has been built
and is at present under test using underground muons detected by MACRO.

The Transition Radiation Detector (TRD) built for MACRO consists of 11 layers of polyethylene radiator layers sandwiching 10 layers of polystyrene streamer tubes operating in proportional mode (Ar 90% - CO₂ 10%), so that a symmetry for downgoing and upgoing muons is obtained, as shown in figure 2. The transition radiation produced in the radiators and converted in the streamer tubes is read with the 'cluster counting' method. This detector operates in 3 muon energy intervals: from a few GeV to about 100 GeV ($\gamma$-Lorentz $\leq 10^3$); from a 100 GeV to about 1 TeV ($\gamma$-Lorentz $\approx 10^4$); and greater than 1 TeV. Muons with energy less than 100 GeV release energy by ionization only; for muons with energy between 100 GeV and 1 TeV there is a linear-logarithmic increase of the number of transition radiation X-rays produced, up to a saturation for muons greater than 1 TeV. This behaviour is shown in figure 3 which represent the calibration curve of the detector. The description of the TRD prototype has been reported in [2]. It has been located on the 10th module of MACRO.

One month of data took with this configuration has been analyzed. Only single muons crossing all the 10 TRD layers, and in coincidence with MACRO, are considered. We have 1886 events of this kind for 15 days of effective live time. Starting from the detected number of clusters per event, and using the calibration curves of figure 3, we obtain the preliminary underground muon energy distribution of figure 4, in which the incident angle of incoming particles has been.
taken into account and only statistical errors are considered.

From this distribution appears that more than one half of the collected muons are tagged in energy. We have drawn a Montecarlo simulation of how a given differential energy spectrum of muons at surface will propagate down to the Gran Sasso Laboratory and be detected by the TRD. The simulated distribution are also given in figure 4 for two different spectral indices. The compatibility with the spectral index $\gamma = 3.7$ is evident. A simulated distribution with spectral index $\gamma = 2.7$ is also shown in the same figure as a way to evaluate the Montecarlo sensitivity.

4. Muon energy tagging

Since the preliminary results of the TRD test appear encouraging, we plan to have 3 TRD modules, for a total surface of 6x6 m$^2$, during 1995. This configuration will measure about 100,000 single muons and about 6,000 multiple muons per year, providing subsets of muons selected to have laboratory residual energy greater than a given threshold. Because of the energy inverse dependence of the multiple Coulomb scattering, this subset of muons have a more precise angular definition useful to explore several issue of physics like astrophysical point sources, prompt muons and multiple muons energy balance, opening a yet unexplored line of research.
5. Upward-going muons

Up-going muons are generated by high energy muon neutrinos traversing upward through the Earth and interacting in the rock below the detector. In MACRO the primary discrimination of these events comes from accurate measurement of the time of flight in the scintillators associated with a track seen by the streamer tubes. The time resolution of the scintillator boxes ($\sigma = 500$ ps) and the angular resolution of the tracking system make the rejection factor of the detector better than $10^{-6}$, where the ratio:

$$\frac{\text{downgoing muons}}{\text{upgoing muons}} \approx 4 \times 10^4$$

The data presented here have been taken over the following periods:

<table>
<thead>
<tr>
<th>Period</th>
<th>live time</th>
<th>$\mu$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar. 89 - Nov. 91</td>
<td>2.0 years</td>
<td>$2.3 \times 10^6$</td>
</tr>
<tr>
<td>Dec. 92 - Jun. 93</td>
<td>0.42 years</td>
<td>$3.0 \times 10^6$</td>
</tr>
</tbody>
</table>

Data of a third period (Mar. 92 - Dec. 92), when the detector was in a construction phase, have been used only for searching for point sources of neutrinos and not for flux measurement.

On these samples of data the particle velocity was calculated using the time-of-flight between two different layers of scintillator counters of the lower detector. The path length between scintillator boxes was calculated by projecting streamer tube tracks to
the center of each plane of scintillator. Downgoing muons will have $\beta$'s near +1 while upgoing muons are aspected to have $\beta$'s near -1.

Incorrect timing information can arise for several causes like when muons are in coincidence with radioactive decays, muons stopping in the detector or when they are accompanied by e.m. showers. These effects contribute to non-Gaussian tails in the $1/\beta$ distribution which must be removed with appropriate cuts. In applying cuts there is always the danger of removing good events, for this reason the efficiency of the cuts used have been carefully studied on downgoing muon events to understand their effect on upgoing muons also. This is possible due to the symmetry of the detector construction, trigger and analysis, respect to both downgoing and upgoing events.

Table 1 shows all the cuts used along with their effects on the data set. After all the analysis cuts are applied a clear peak centered on $1/\beta = -1$ appears in the $1/\beta$ distribution shown in figure 5.

We define upward going muons those events satisfying the condition:

$$-1.25 < 1/\beta < -0.75$$

The number of these events is:

51 for 6 supermodules data
26 for 1 supermodule data
Geometric cuts | Acceptance for downgoing muons
---|---
- Streamer tube track | 100 %
- Scintillator hit at ends of track | 85 %
- Pathlength > 3 m | 87 %

Background removal cuts | Eff. for downgoing muons
---|---
- Valid raw TDC values | 99.6 %
- Scint. position within 70 cm of posit. determined from ST tracks | 98.1 %
- Less than 4 clusters of sc. boxes | 98.6 %
- Removal of 'out of time' coincid. | 99.6 %

Total effic. of background cuts | 96 %

Table 1: Effect of various cuts on downgoing muons

After background subtraction and evaluation of the statistical error and systematic uncertainty we obtain:

\[ N_{\nu,\text{exp}} = 74 \pm 9_{\text{stat}} \pm 8_{\text{sys}} \]

where the number of events expected by the so-called 'Bartol Flux' [3], as obtained by a Montecarlo simulation of the entire process of production and detection of the atmospheric neutrinos, is:

\[ N_{\nu,\text{cai}} = 101 \pm 15_{\text{sys}} \]

We have the zenith angle distribution of this events which is given in figure 6 that contain the detector acceptance folded in. To obtain the zenith angle dependence of the flux of upgoing muons we use
the Montecarlo expectation for this flux at each particular angle. This distribution is given in figure 7 for muons of energy > 1 Gev, which is the approximate energy threshold of the detector.

Overall, the measured flux is somewhat less than the prediction based on the Bartol flux of neutrinos. If all the experimental and Montecarlo systematic errors are accounted for, then the integrated number of events in all zenith bins agree between data and Montecarlo within 1.1 σ.

In fig 8 the distribution in celestial coordinates of the measured upgoing muons is shown. So far we have no evidence of astrophysical point sources in our data.

6. MACRO and EAS-TOP coincidences

EAS-TOP at Campo Imperatore (2000 m a.s.l.) is an array tailored for the detection of several different EAS components: e.m. component, hadrons, muons, Cherenkov light and radio emission as well [4]. For this work the e.m. component only is considered, as detected by an array of 35 modules of scintillator, each 10 m² area, distributed over ~10⁵ m². We consider events in which the maximum number of particles Ne is detected by an inner module and at least seven counters are fired. For these events primary arrival direction, core location and shower size are reconstructed with accuracy Δθ = 0.5°, Δρ ≲ 10 m, ΔNe/Ne ≤ 20% for Ne ≥ 10⁵ respectively, as discussed in ref [5].
The MACRO events considered for coincidence are muon tracks having at least 4 aligned hits in both views of the horizontal streamer tube planes. For this analysis all events have been visually scanned, reducing the typical systematic uncertainty in $N_{\mu}$ reconstruction at $\pm 1$, at the highest observed multiplicity.

The EAS-TOP array is aligned with MACRO along an average zenith direction of $33.5^\circ$. They are separated by a thickness of rock ranging from 1100 up to 1300 meters, depending on the angle. The corresponding minimum energy for a muon to reach the depth of MACRO ranges from $\approx 1.3$ to $\approx 1.8$ TeV. The MACRO detector sees the EAS-TOP array with a solid angle $\Delta \Omega \approx 0.06$ sr. Event coincidences are established off-line, using the absolute time given by atomic clocks with an accuracy better than 1 µs. Three run periods have been performed with the full EAS-TOP e.m. array and the complete lower part of MACRO detector operating in coincidence during winter 92-93, for a total live time of 87.5 days. In this period we have selected 1821 coincidence events, where the expected accidental contamination is 2.8 %.

Experimental data have been compared with the results of a simulation of the full process of event production: primary interaction, shower development in the atmosphere, muon propagation in the rock and response of the two detectors. The HEMAS Montecarlo code [6] - based on the UA5 multi-cluster parametrization of minimum bias events in p-p and p-pbar high energy collisions - provided the physics generator, the shower
development and the three-dimensional muon propagation in the rock. The e.m. component of the shower at the EAS-TOP depht has been obtained from the results of a detailed simulation of showers using GEANT [7], FLUKA [8] and EGS [9] codes with an energy cut of 1 MeV.

The simulated sample of events correspond to 2.8 times the measured one. These events have been processed with the same procedure and codes of the real events.

In this analysis we require that any tested input spectrum and composition should reproduce the e.m. size spectrum as measured by the surface detector alone [10].

Two kind of primary beams have been tested:

1) Pure composition (p, He, Fe) with energy spectra constructed to fit the size spectrum measured by EAS-TOP alone.

2) A priori constructed mixed composition obtained by the combination of spectra fitting direct measurements extrapolated up to the knee region. The proton and helium spectra are derived from the 1991 JACEE data [11], the heavier mass group spectra from CRN data [12]. This set of spectra we call $\Sigma$ model.

Some results of the test of these primary beams are given in figure 9 and 10, which allow us to conclude that the coincidente EAS-TOP and MACRO data, in the energy range $5 \times 10^{14} - 5 \times 10^{15}$ eV can be interpreted by the extrapolation of the direct measurements performed at lower energies. The
presence of elements heavier than helium is needed in the whole energy range, unless substantial changes in the hadronic interaction process is invoked. These data do not favour the hypothesis of a dramatic change towards pure extreme compositions around the knee of the cosmic ray energy spectrum.

7. Conclusions

The MACRO large area underground detector is near to full completion. It is acquiring advanced instrumental characteristics with the unique possibility to measure the residual muon energy with a Transition Radiation Detector, suitable to open a new line of research.

Among several other topics not covered by this presentation, interesting results on underground neutrino flux have been achieved, not inconsistent with a deficit of the atmospheric neutrino flux.

In collaboration with the EAS-TOP group, coincidences with the EAS array located on top of the mountain have been studied. Results on the composition of the primary spectrum indicate that the coincidence data can be explained by an extrapolation of the direct measurement performed at lower energies.
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Figure 1: General layout of the full MACRO detector.

Figure 2: Cross section of the TRD layout.
Figure 3: Average number of clusters versus $\gamma$-Lorentz factor.

Figure 4: Integral energy distribution of single muons detected by TRD. Superimposed are simulations with 2 spectral index.
Figure 5: Distribution of $1/\beta$ after analysis cuts.
Figure 6: Distribution for $\cos(\text{zenith})$ of upgoing muons. The Montecarlo expectation using Bartol flux is shown in shaded regions.

Figure 7: Distribution for $\cos(\text{zenith})$ of upgoing muon flux. The Montecarlo expectation using Bartol flux is shown in shaded regions.
SKY SURVEY
Upward going muons in MACRO

+90

24h

-90

0h
Figure 9: Correlation between $\langle N_\mu \rangle$ and $\langle \log N_e \rangle$. Only statistical errors are shown.

Figure 10: Measured and expected distribution of muon multiplicity for $\log N_e \geq 5.75$. 
Figure 11: Measured and expected integral distribution of detected muon multiplicity for $5.25 \leq \log N_e \leq 5.75$. 
Multiple Muon Physics at MACRO

The MACRO Collaboration*

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Abstract

The large size \((76 \times 12 \times 9 \text{ m}^3)\) and the excellent tracking capability of the MACRO detector at Gran Sasso allow detailed studies of multiple coincident penetrating cosmic ray muons. In this paper we concentrate on the studies of the ultrahigh energy primary cosmic ray composition using muon bundle multiplicities, muon pair lateral and angular separation distributions.

1. INTRODUCTION

The MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) detector \([1]\), a large area, deep underground detector, was fully completed recently at the Gran Sasso National Laboratories in central Italy. The full MACRO detector \((76 \times 12 \times 9 \text{ m}^3)\), including its upper deck, started to take muon data in March 1994. This paper uses data collected from the lower deck only, which commenced data taking in June 1991. Consisting of six supermodules, the lower deck measures \(76 \times 12 \times 4.8 \text{ m}^3\). It is surrounded on the sides by planes of large liquid scintillator counters. Its tracking system consists of ten horizontal layers of streamer tubes separated by \(\sim 60 \text{ g/cm}^2\) of crushed rock absorber. Six additional vertical layers of streamer tubes cover each vertical side. The intrinsic angular resolution is \(0.2^\circ\) for muons crossing ten horizontal planes. Taking into account multiple coulomb scattering in the rock overburden, the overall angular resolution is estimated to be \(\sim 1^\circ\). In addition, there are plastic track-etch detectors, offering the third redundant technique (in addition to liquid scintillator counters and limited streamer tubes) for monopole searches, the primary physics goals of MACRO. The rock overburden has a minimum thickness of 3200 meters of water equivalent, setting the surface muon energy threshold of \(\sim 1.4 \text{ TeV}\).

MACRO accumulates underground muon data at the rate of \(\sim 6.6 \times 10^6\) events/live year. Approximately \(\sim 4.0 \times 10^5\) events/live year exhibit multiple muon tracks with lateral separations up to 70 m and \(\sim 1.6 \times 10^3\) events/live year have multiplicities of ten or greater. The rates of underground muon bundles of different

*For a list of the members of the MACRO Collaboration, see the MACRO paper presented by C. DeMarzo in these proceedings.
multiplicities, as well as their lateral and angular separations, are sensitive to the chemical composition and energy spectra of the primary cosmic rays above a threshold determined by the rock overburden (~ 50 TeV at Gran Sasso). Therefore, the MACRO muon data provide a unique opportunity to study ultrahigh energy cosmic rays.

In this paper we report results from analyses [2] of the multiple coincident penetrating cosmic ray muon data collected by the MACRO detector. We have measured the muon bundle rate as a function of multiplicity as well as the muon pair lateral and angular separation distributions. These measured quantities are compared with Monte Carlo predictions for different primary cosmic ray composition models and interaction models.

2. COSMIC RAY COMPOSITION

We have studied the primary cosmic ray composition using the muon bundle rate as a function of multiplicity. This analysis uses a data sample collected in 3295 hr live time with all six lower supermodules. This data sample contains ~ 2.5 x 10^6 muon events, of which ~ 1.5 x 10^5 are multiple muons. The event selection uses the criteria established in a previous analysis [3], which used data from only two supermodules. In the previous analysis [3], a considerable amount of visual scanning was performed to establish the actual multiplicity. In this analysis, we correct the reconstructed multiplicity using an improved version of the GEANT-based [4] detector simulation program. The following physics and detector effects are taken into account: electromagnetic showering down to 500 keV, charge induction of the streamer signal onto the stereo strip, electronic noise, inefficiencies, and failures of the tracking algorithm especially for high multiplicity events, track shadowing at small separations, etc. The simulated data are used to calculate the correction factors for transforming the reconstructed multiplicities in the two projective readout views into an actual multiplicity. This allows an objective assignment of the muon multiplicity, reducing significantly the errors in the previous analysis [3] dominated by the scanning uncertainties. Figure 1 shows the muon bundle rates for the one, two, and six supermodule data samples. The increase of acceptance with detector size is reflected in the increase in muon rates and sampling of high multiplicity events.

The experimental data are compared with the results of full simulations of the primary interaction, the atmospheric cascades, the muon propagation in the rock, and the aforementioned detector response. Two different shower simulation codes are used: HEMAS [5] with the addition of nuclear fragmentation based on the semi-superposition model [6] and SIBYLL [7]. The simulations are described in more detail below in Section 3. This paper reports results based on the HEMAS
We considered three different primary composition models: light and heavy compositions used in our previous analysis [3], and a constant mass composition (CMC) with fixed spectral indices [8]. The light and heavy compositions are extreme models: at increasingly higher energies the light composition contains a large proton component while the heavy composition contains a large Fe component. Moreover, the models are constrained to reproduce the known abundances and spectra directly measured at \( \leq 100 \) TeV and to agree with extensive air shower measurements at higher energies. Therefore a comparison of the muon experimental rates with the predictions of these models gives an indication of the sensitivity of the experiment to primary composition.

MACRO multi-muon events are produced by primaries in the energy range of \( \sim 50 \text{ TeV} \) to \( \sim 10^5 \text{ TeV} \). The range of energy corresponding to the detection of muon events of a particular multiplicity increases as a function of that multiplicity. Specifically, events with detected multiplicities of four or less originate from primaries with energies less than a few hundred TeV, while events with multiplicity of ten or greater come from primaries in an energy region entirely above the "knee," the steepening point of the cosmic ray energy spectra. This correspondence is roughly independent of the primary composition model.

Figure 2 shows the dependence of the average primary mass \((A)\) on energy for the
three composition models described above, as well as for the SIGMA model which is based on fits to direct measurements from 1-100 TeV and extrapolated up to the "knee" region [9]. Therefore the SIGMA model can be viewed as a reference $\langle A \rangle$, following the energy dependence of direct measurements at low energy. As one can see from this figure, the light and CMC models are in the same range of $\langle A \rangle$ as the direct measurements. The heavy model, on the other hand, has a completely different energy dependence in nearly the entire energy range relevant to MACRO multi-muon events.

The ratios between the rates predicted by the HEMAS simulations and the experimental data are shown in Figure 3. One feature of this figure is that the measured multi-muon rates at low multiplicities ($N_\mu \leq 4$) are higher than those predicted by the Monte Carlo regardless of composition model. These events originate in primaries with energies less than a few hundred TeV, for which the three models are very similar and in agreement with direct measurements. We investigated the effects of our present uncertainties in the rock overburden and muon propagation as possible sources of this disagreement, and found from Monte Carlo simulations that while these uncertainties affect the absolute muon rates they do not affect the shape of the multiplicity distribution. An analysis based on this shape is in progress.

Figure 3 shows that our data are inconsistent with the predictions of the heavy composition at high multiplicity and favor a lighter model. Therefore our data do not favor the hypothesis, as used in the heavy model, of a dramatic change of primary composition toward the pure iron element immediately above the "knee." The data provide a better fit to models with flat or slowly increasing $\langle A \rangle$ as a function of primary energy, as in the light and CMC models.

3. MUON DECOHERENCE

The lateral separation of underground muon pairs has been demonstrated to be sensitive to hadronic interaction models, as well as to the primary composition models, allowing the rejection of some simplified cascade treatments [10]. Here we report an analysis of a data sample of $\sim 5.8 \times 10^6$ muons and $\sim 7600$ hr live time, in which $1.9 \times 10^5$ muon pairs are reconstructed using the criteria described in [11].

The muon pair lateral separations are traditionally analyzed using a detector-independent "decoherence function" [12] defined as the rate of muon pairs per unit area, per steradian, per pair separation determined on a plane orthogonal to the pair direction:

$$G(r) = \frac{1}{\Omega T} \int \frac{d^2N_p(r, \theta, \phi)/d\rho d\Omega}{A(\theta, \phi)} d\Omega$$  \hspace{1cm} (1)

where $d^2N_p/d\rho d\Omega$ is the density of pairs at distance $r$ and incidence angle $(\theta, \phi)$, $A$ is the projected detector area in the $(\theta, \phi)$ direction, $\Omega$ is the total solid angle.
Figure 2. Average primary mass as a function of energy for various composition models.

Figure 3. Ratio of predicted to observed event rates for the light, heavy, and constant mass (CMC) compositions.
defined by the limits of integration, and $T$ is the exposure time. In this analysis, the two independent methods described in [10] are used to compute the decoherence function and they yield the same results.

To compare with composition and interaction models, a detailed Monte Carlo calculation is required to simulate the production and propagation of muons through the atmosphere and mountain overburden. The previous work [10] used the parameterized results of the HEMAS code [5] to generate cosmic ray showers, in order to save computer time. The parameterized formulae gives the number and the spatial distribution of the underground muons as functions of primary mass, energy, and direction, but it ignores the correlation between muon multiplicity and lateral distribution. Therefore we have chosen in this new analysis to perform full simulations of the atmospheric cascade and muon propagation. In preparing the full HEMAS based Monte Carlo, we investigated several possible systematic effects on the simulation, including: (1) biases due to the failure of the parameterization to account for the correlation between muon multiplicity and lateral distribution; (2) uncertainties in the primary interaction cross section; (3) different possible models of nucleus-nucleus interactions (superposition vs. fragmentation); (4) the treatment of energy loss and multiple scattering in the rock; and (5) the effect of the geomagnetic field on cascade development.

The results generally showed that the dependence of the underground muon separation on the details of the Monte Carlo was weak. A comparison of the full HEMAS based Monte Carlo to the parameterized version using the constant mass composition [8], for instance, showed that the average muon pair separation increases by only 2% in the more complete version. A 10% increase in the primary interaction cross section raises the muon production height by 3%, and consequently increase the average underground muon separation. There is a great deal of uncertainty in the nucleus-nucleus interaction model, due to the lack of accelerator experimental data for the energies of interest. The HEMAS code handles cascades generated by heavy nuclei (mass $A$, total energy $E$) in the superposition scheme, as $A$ independent nucleons of energy $E/A$. Replacing this with a more realistic model [6] causes larger fluctuations in shower development, but the decoherence distribution is not affected within the present statistics of the simulated data. HEMAS muon transport through the rock was compared to that implemented in GEANT [4], a more recent simulation developed to model high energy accelerator events; we found no noticeable difference as far as the lateral spread of muons is concerned. Finally, an increase in the average muon separation of about 5% is achieved by considering the effect of the geomagnetic field on cascade development.

In Figure 4 the experimental pair separation distribution for the entire data sample is compared with Monte Carlo predictions for two extreme (light and heavy) composition models. In the previous analysis [10] of data from only two super-
modules, we found a good agreement with the Monte Carlo predictions up to the maximum attainable separation ($\sim 20$ m). With all six lower supermodules the measured decoherence function at large separations is higher than that from the simulations. The average separation is $10.9 \pm 0.2$ m for the real data, $10.5$ m for the heavy model, and $9.4$ m for the light model. The measured separation is larger than the one from the simulations. We have also investigated the dependence of muon pair separation on rock depth and zenith angle.

Since the heavy model is a disfavored extreme model (see Section 2), Figure 4 may indicate that the shower development is not yet treated properly in the Monte Carlo and that the hadronic interaction model presently used for this analysis may need further improvement. In particular, we are investigating factors which affect the transverse momentum distribution, including possible nuclear effects.

In order to better understand the role of the hadronic interaction model, we have performed a comparative simulation with the SIBYLL code [7]. No substantial changes, however, were observed as far as muon separation is concerned. Such a model in fact predicts a slightly lower average muon separation (on the order of 10% less). In the future, other models will be considered, such as the DPMJET code [13], which has a more complete treatment of nuclear effects than does SIBYLL.

4. MUON DECORRELATION

Detailed measurements of quantities relative to underground multiple muon events can provide information on primary interactions and muon propagation through the rock overburden. In particular, the differential distribution of spatial and angular separations ($x$ and $\phi$) in multiple muon events, $dN/dxd\phi$, is sensitive to the physics
of muon production and propagation. It provides information on the total primary cross section as well as to the transverse momentum distribution of the parent hadrons of the underground muons. It also provides a measure of the effects of muon interactions in the rock overburden, which introduce displacements of the muons from their original direction and position. The aim of this analysis is to attempt to disentangle these effects.

For a real experiment of finite size and finite live time, it is generally impossible to reconstruct the full distribution, $dN/dx d\phi$. Grillo and Parlati [14] has suggested the use of its first moment, \[ \langle \phi(x) \rangle = \frac{\int \phi \frac{dN}{dx d\phi} d\phi}{\int \frac{dN}{dx d\phi} d\phi}, \] which they have named as the “decorrelation function.” An analytic expression for $\langle \phi(x) \rangle$ has been derived [14] using some approximations.

In this analysis, we have used only double muon events and employed track reconstruction only in one projective view, namely the wire view. The results are still preliminary. Since the position of the shower axis is not known, the measure is relative; that is, the quantities $\phi$ and $x$ are defined between pairs of muons in the same bundle. The distance is always taken to be positive, while the angle is positive if the tracks are diverging, and negative otherwise. Since the average angle as a function of distance is normalized to the number of events at that distance, the influence of apparatus effects (efficiency, working conditions, containment) should not be important. We have made no run selection on the data sample, but we have made an event selection rejecting too short tracks, to avoid contamination of the sample by locally produced pions and small showers. The experimentally measured decorrelation function is presented in Figure 5.

Figure 5 also shows the decorrelation function computed from the HEMAS code. It is evident that there is a strong disagreement between the data and Monte Carlo at relatively small distances. We have investigated several possible causes for this disagreement. Different composition models have essentially no effect, nor do more refined muon transport codes which include Molière tails beyond the Gaussian approximation for multiple scattering. It is not impossible to modify the average interaction cross section (and hence primary interaction height) to make the Monte Carlo results agree with the data, but the required modification is rather extreme and is likely inconsistent with reasonable extrapolations of accelerator data. We are presently investigating more subtle effects, both derived from the finite space resolution of the apparatus and from high energy interactions of muons in the rock overburden. Preliminary results are encouraging, but a more refined analysis is not yet complete.
5. CONCLUSIONS

The large amount of underground muon bundle data collected by the MACRO experiment offer significant capability in the studies of primary cosmic ray composition and of interactions at very high energies. Our data do not favor the hypothesis of a dramatic change of primary composition towards pure Fe element immediately above the “knee”. The discrepancy between the experimental muon pair lateral separations and the Monte Carlo results is under investigation. A new analysis based on the muon decorrelation function is being pursued.

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The depth-intensity distribution of single and double muon events measured by the LVD underground experiment in the Gran Sasso laboratory

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Abstract

We present here the preliminary data on single and double muon events collected by the first tower of LVD during 11556 hours operation. For the first time the depth-intensity distribution for double muon events is measured, which decreases with depth more rapidly than that of single muons. We also display our preliminary data out to a slant depth of 20 $hg/cm^2$ of standard rock.
1 Introduction

The muon intensity underground has been the subject of experimental investigations for about 30 years, e.g. [1, 2, 3, 4, 5, 6]. These investigations have been concerned with problems in both high energy astrophysics and elementary particle interactions. The muon depth-intensity curve is related to the primary cosmic-ray spectrum.

Beside the depth-intensity curve of single muons, measured also by other underground experiments, we present here for the first time the depth-intensity curve for double muons.

2 Detector

The LVD (Large Volume Detector) underground experiment [7] is located in the Gran Sasso Laboratory in the center of Italy. The minimum rock cover is about 1100 meters (A = 22.88, Z = 11.41 and density = 2.71 g/cm³) [5].

LVD is designed for the study of various phenomena in neutrino astrophysics, cosmic rays and elementary particle physics [8]. The whole apparatus will contain 5 identical aligned towers with 38 modules in each tower. Each module contains 8 scintillation counters, each of which is viewed by 3 photomultipliers, and an L-shaped tracking detector attached to the bottom (horizontal leg) and one vertical side (vertical leg) of a module.

Each leg of an L-shaped tracking detector contains two layers of 6.3 meters long limited streamer tubes. The basic tube element has 8-cells with $9 \times 9$ mm² active cross sectional area for each cell. Below and parallel to, and above and perpendicular to, the streamer tube wires are 4 cm wide pickup strips (x and y strips) to provide bidimensional information about an ionizing particle’s impact point. The staggered double layers of streamer tubes and their orthogonal readout strips yield an effective strip width of 2 cm with no dead space, high overall tracking efficiency, and an angular resolution better
than 4 milliradians.

One tower of LVD (Fig. 1) has been running since June, 1992. It has a volume of 13m x 7m x 12m and the geometric acceptance about 1,768 m^2sr. The detailed characteristics of the detector are described in [9].

Figure 1: The front view of the LVD one tower.

3 Data Selection

The data presented here were taken from June 1992 to the end of May 1994, corresponding to 11,556 hours of live time.

The selection of the data sample required that at least one scintillation counter was triggered in the event and that three different legs of the L-shaped tracking detectors should be hit. Moreover, the double muon events
having an angle between two tracks greater than 3° were rejected in order to exclude non-parallel secondary particles produced by muon interactions in the surrounding rock or in the detector absorber. A sample of the double muon candidates was scanned visually, as showers or a muon plus a shower can be reconstructed as double muons. It was determined that this was a problem only for double muon candidates whose separation was less than 60cm. All such candidates were scanned and evaluated visually. In all 978,074 single muon and 21,947 double muon events were selected.

4 Detector Acceptance Correction

The detector acceptance correction for the single muon events is described in [9]. Here we will present the method of acceptance correction of double muons. The detector acceptance for double muons depends not only on the direction of the muon tracks, but also on the separation of the muon pairs. This makes the acceptance correction for double muons more complicated than that for single muons.

In the correction procedure, the form of the muon separation distribution of the double muon events is assumed to be:

\[
\frac{dN}{dr} = r e^{-r/r_0}
\]  

(1)

where \( r(\text{cm}) \) is the distance between muon tracks and \( r_0 \) is a characteristic distance which can be obtained from the data.

We obtain \( r_0 \) in the following way. We assume a two muon distribution incident on the LVD detector with a fixed separation distance \( r_0 \) given by formula (1). The two muons are then passed through LVD, including the tracking inefficiencies of LVD. The resulting tracks are reconstructed using the same programs that are used on the real data. The two muon separation distribution obtained from the Monte Carlo reconstructed tracks is compared
with the two muon separation obtained from the real data by forming a $\chi^2$ between the two distributions. We find that $r_0 = 450 \text{ cm}$ yields the smallest $\chi^2$.

Our analysis is quite insensitive to the value of $r_0$ (see Sec.5)

![Distributions of two muon separation.](image)

Figure 2: Distributions of two muon separation.

To obtain the detector acceptance, $10^7$ double muon events with the separation chosen according to formula (1) with $r_0 = 450 \text{ cm}$ were generated isotropically on a sphere of $20,160 \text{ m}^2 \text{ sr}$, which contains the entire five towers of the completed LVD. These Monte Carlo events were processed by using the standard offline chain of analysis with detector inefficiencies taken into account. We found that the acceptance of the LVD first tower for double muon events is about $153 \text{ m}^2 \text{ sr}$. The acceptance as a function of $\cos \theta$ and $\phi$ in the LVD reference system (Fig. 1) is shown in Fig. 3. Note that the acceptance extends to $\cos \theta = 0$ (horizontal) along the $\pm z$ axes at $\phi = 0$ and
±180°, and is zero in the regions near the ±y axes. However, in this region the slant depth is large and hence there are few muons.

Figure 3: Lego plot of the acceptance of LVD one tower for two muon events.

5 Depth-Intensity Relation

The thickness of rock crossed by muons was determined from the mountain map of Gran Sasso. The intensity of muons at zenith angle θ was assumed to be related to the vertical intensity $I_v$ through the classic relation $I(h, θ) = I_v(h)/\cos(θ)$, valid for conventional muons of atmospheric origin in the relevant range of slant depth less than $10^4$ hg/cm². Therefore, the vertical intensity in a given depth interval $(h \pm \Delta h/2)$ was obtained from the number of events for corresponding slant depth, by the following formula:
where \( m = 1, 2 \) for single muon and double muon events respectively, \( \Delta T \) is the live time of the experiment, \( \Omega(h) \) is the solid angle corresponding to the slant depth interval, \( n \) is the number of \((\theta, \phi)\) bins contributing to the slant depth interval, \( N_{im} \) is number of events of multiplicity \( m \) in bin \( i \) of slant depth \( h \), \( A_{im} \) is the acceptance of the detector, \( \theta_i \) is muon zenith angle and \( \phi_i \) is muon azimuthal angle. In this way, we get single muon and two muon vertical intensity distributions versus slant depth in \( hg/cm^2 \) of standard rock as shown in fig. 4. \(^1\)

Note that the data with slant depth less than 13,500 \( hg/cm^2 \) of standard rock are reliable, beyond this region our knowledge about the mountain map is limited at present. Therefore the data seen in figure 4 beyond 13,500 \( hg/cm^2 \) are preliminary.

We have obtained the vertical intensities of single muon and double muon events as follows.

For the single muons:
\[
I_{v1} = [1.54 \pm 0.003(stat) \pm 0.08(syst)]10^{-8}cm^{-2}s^{-1}sr^{-1}, \quad \text{at } h = 3300 \text{ } hg/cm^2
\]
\[
I_{v1} = [1.76 \pm 0.01(stat) \pm 0.09(syst)]10^{-9}cm^{-2}s^{-1}sr^{-1}, \quad \text{at } h = 5000 \text{ } hg/cm^2
\]

This result agrees with other experiments such as \([3, 5, 6]\).

For the double muon events, we have:
\[
I_{v2} = [1.69 \pm 0.02(stat) \pm 0.11(syst)]10^{-9}cm^{-2}s^{-1}sr^{-1}, \quad \text{at } h = 3300 \text{ } hg/cm^2
\]
\[
I_{v2} = [1.66 \pm 0.19(stat) \pm 0.10(syst)]10^{-10}cm^{-2}s^{-1}sr^{-1}, \quad \text{at } h = 5000 \text{ } hg/cm^2
\]

In order to compare the slopes of depth-intensity curves for single muon and double muon events, we fit the measured depth-intensity curves with the

\(^1\)Ref. [3] has used a similar method to correct data, but they do not display the depth-intensity curve for double muon events.
Figure 4: Intensity of single and double muons versus the depth in the standard rock.

following function for the 1st order approximation:

\[ I_{vm}(h) = C_m e^{s_m h} \]  

This simple function fits our data quite well at least up to \( 6 \cdot 10^3 \text{hg/cm}^2 \) (fig. 5). We obtain the estimates of the parameters:

\[ C_1 = (0.116 \pm 0.001)10^{-5} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \]

\[ S_1 = (-0.1313 \pm 0.0003)10^{-2} \text{ (hg/cm}^2)^{-1} \]
Figure 5: Vertical intensity of single and double muons versus the depth in the standard rock.

\[ C_2 = (0.27 \pm 0.02) \times 10^{-6} \, \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

\[ S_2 = (-0.153 \pm 0.002) \times 10^{-2} \, (\text{hg/cm}^2)^{-1} \]

The errors are only statistical. From this result it is obvious that the intensity of double muon events decreases with depth more rapidly than that of single muons.

We computed these final fit parameters with \( r_0 = 450 \, \text{cm} \) and with \( r_0 \) increased and decreased by 10%. There was a spread of only 1.5% on the value of the fit parameters and therefore they are quite insensitive to the choice of \( r_0 \).
6 Conclusion

Using the data collected by the first LVD tower during 11,556 hours of operation, we have obtained the depth-vertical intensity curves for single muon and double muon events. We found that the intensity of two muon events decreases with depth more rapidly than that of single muons.

References

Opportunities and Challenges
of a High Altitude
Multipurpose Observatory

Lawrence W. Jones
University of Michigan

At earlier cosmic ray conferences I have discussed the concept of developing a cosmic ray laboratory/observatory at a very high elevation; one figure used was an elevation of 6500 m, or a depth in the atmosphere of less than 450 g/cm². This was first discussed in the small occasional circular “Cosnews” in 1980[1], and subsequently presented at the Paris “17th International Cosmic Ray Conference” in 1981[2]. Later, at the Emulsion Chamber Symposium in LaPaz and Rio de Janeiro, 1982, I discussed the possible elaboration of the Chacaltaya cosmic ray station in Bolivia in this context[3]. In 1986 at the IV International Symposium on Very High Energy Cosmic Ray Interactions in Beijing, I reviewed the earlier discussions and explored the topic in the context of the then-current cosmic ray situation[4].

In view of the location of this conference in Lhasa, so close to the highest mountains on Earth, it seemed altogether timely to review the topic once again, and to explore the practicality, the need, and the science related to such a laboratory. As noted in my earlier discussions, there is only one area on the Earth’s surface where such a laboratory could be located, and that is in the mountain arc of the Himalayas.

In my earlier presentations I argued the advantages of observation at the highest possible altitude. Balloons and satellites are limited to exposure areas of at most a few square meters, and exposure times typically of days, although some satellite payloads could be aloft a year. A mountain top installation, of course, can employ an area of perhaps a square kilometer; emulsion chambers typically employ areas of tens of square meters, and air shower arrays have areas of hundreds of square meters. While the atmospheric overburden certainly reduces this area advantage for the direct observation of primary interactions, emulsion chambers at mountain sites have proven capable of making interesting discoveries.

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The controversial issues which motivated my suggestion in 1980-81 were:
a) the primary cosmic ray composition near the “knee” (one to ten PeV),
b) determination of the inclusive parameters of primary nucleon-nucleus inter­
actions (such as scaling in the forward region, inelasticity, etc.), and c) the nature, source, and frequency of exotic phenomena such as Centauros,
Chirons, etc. It is interesting to note that each one of these problems remains
unresolved to this day, and from reports at this and other recent cosmic ray
meetings, no really definitive solutions appear close at hand. Cancellation
of the SSC together with delays in the LHC make the cosmic ray studies of
the primary interactions above one PeV (approximately the energy of the
Fermilab Tevatron Collider in equivalent C.M. energy) particularly relevant.

The flux of primary cosmic rays of $10^{16}$ eV (10 PeV) and above is about
one per (m$^2$ sterad year) at the top of the atmosphere. At this energy the
interaction mean free path of a proton in nitrogen is about 50 g/cm$^2$[5].
However the absorption length of nucleons is greater; from the zenith angle
dependence of flux, Slavatinsky quotes $\lambda$ (abs) = 68 ± 6 g/cm$^2$ [6]. Yuda
notes that the attenuation length characteristic of gamma families is even
greater; 100-110 g/cm$^2$ [7]. There is therefore great pressure for placing large­
area detectors as high as physically possible, if one is to draw unambiguous
conclusions concerning the nature of the primary interactions at energies
much above a PeV.

Recently it has been emphasized that gamma ray astronomy also benefits
from very high altitude observation. The Yangbajing surface scintillator
array benefits from its 4300 meter elevation by being able to lower its primary
gamma threshold to 8 TeV; a higher elevation site could explore to a lower
energy still. Ahlen and Salamon have proposed the location of a very large air
Cherenkov telescope at Yangbajing, also to study primary gamma rays, at a
lower energy than the surface air shower arrays; D. Kieda reported on studies
of this concept at this meeting[8]. The radiation from a primary gamma of
a TeV or less occurs so high in the atmosphere that the location of an air
Cherenkov telescope is optimized by a site with the cleanest, clearest air.
The atmosphere is certainly more transparent at high mountain elevations,
and these authors argued a significant improvement in performance of such a
telescope for the study of 10 to 500 GeV gammas from a Yangbajing location
relative to a 1000 - 1500 m elevation site, such as the Whipple telescope.

Other research areas would also profit from a very high altitude site. The
air scintillation technique for studying primary cosmic ray composition over
the energy interval between 0.1 PeV to 10 PeV is one example. The competition between air scintillation and air Cherenkov radiation favors scintillation at lower atmospheric densities, so that a study of the composition in the "knee" region with the Flys Eye technique would profit from such a location.

Atmospheric water vapor falls more rapidly with elevation than air pressure, and water vapor is the primary problem in surface-bound infra-red and microwave astronomical observations. Hence it is attractive to consider location of an infrared telescope at a new high-altitude site. Another installation might be a microwave detector system to map out in greater resolution than possible up to this time the primordial black body radiation temperature fluctuations.

And finally, an established laboratory at an elevation well above any permanent habitation will invite exploitation by human physiologists and by atmospheric scientists, among others.

For completeness, it should be noted that a very high elevation site offers no advantage for the study of the highest-energy cosmic rays (of energies of an EeV and above); the shower maximum in air at these energies is close to sea level (for vertical showers). Even vertically incident primaries of a PeV would induce showers with a maximum often at or below the elevation of this proposed installation.

In order to put these thoughts on a new high altitude station into proper perspective, let me emphasize that I enthusiastically welcome the development of Yangbajing and the continued exploitation of the Pamirs and Chacaltaya stations. I believe that the research capabilities of these sites are under-utilized. I, of course, welcomed the discussions at this meeting by Piazzoli[9] and Kieda relevant to expanded exploitation of the Yangbajing site. It may be useful to summarize the existing active mountain cosmic ray stations; as noted below.

In spite of my enthusiasm for more intensive exploitation of these sites, I remain convinced that a new station at least 100 g/cm² above the highest existing sites would have great usefulness in our study of primary cosmic rays in the PeV region. There are areas in the Himalayas at or above 6500 m where there are reasonably flat sites. As argued in my earlier reports, such a site would almost surely require supply and communication by air, would require special pressurized enclosures for habitation and instrumentation, and would probably require self-contained power; nuclear power or some kind of solar cell-battery systems. Personnel working in "the field" (outside the
enclosures) would require both appropriate clothing and an oxygen system; a special helmet connected to an oxygen-tank back pack, for example.

Table I. Current Cosmic Ray Mountain Stations

<table>
<thead>
<tr>
<th>Elevation Range, meters</th>
<th>Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000 - 4000</td>
<td>South Pole*#</td>
</tr>
<tr>
<td></td>
<td>Tien Shan*</td>
</tr>
<tr>
<td></td>
<td>Aragatz*</td>
</tr>
<tr>
<td></td>
<td>Norikura*</td>
</tr>
<tr>
<td>4000 - 5000</td>
<td>Pamirs</td>
</tr>
<tr>
<td></td>
<td>Fuji</td>
</tr>
<tr>
<td></td>
<td>Yangbajing*</td>
</tr>
<tr>
<td>5000 - 6000</td>
<td>Chacaltaya*</td>
</tr>
<tr>
<td></td>
<td>Kamba La</td>
</tr>
</tbody>
</table>

* Electric power available
# Elevation is barely 3000 m, but the equivalent atmospheric pressure is lower due to the very cold ambient temperature.

To be sure, this will be more expensive to establish and maintain than the stations listed in the table above. However the challenge of this frontier of human environmental experience will propel this concept to reality, I am convinced. Mankind reached the South Pole in the early years of this Century, and about mid-Century humans first ascended Mount Everest. A few years later men were placed into orbit around the earth and reached the moon. Now we have a permanently-staffed installation at the South Pole, and are planning a Space Station to be manned indefinitely. The high-mountain environment is surely next! And Cosmic Ray research has been at the forefront of each of these frontiers. Van Allen’s sounding rockets were early harbingers of the Space Age, and the first massive satellite payloads were Grigorov’s calorimeters. And at this conference we heard from Wang YuFang of a proposal by S.C.C. Ting for a serious cosmic ray instrument for the Space Station.[10] Meanwhile, at the South Pole, the AMANDA neutrino detector and the SPASE air shower array are significant cosmic ray research facilities justifying the investment in that station.

Against the perspective of this summary, I believe that a cosmic ray laboratory/observatory/station will surely be established at an elevation of
over 6000 or 6500 meters. I do not know when this will happen; it may be far in the future. However I do know that, whenever it is built, it will not be far from Lhasa; there is no place else on Earth!

References


The "TTC" muon distribution in γ-showers

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Abstract

In the universe, the only way to localize the local sources of the cosmic radiation with ultra-high energy (\( \geq 10^5 \text{GeV} \)) is to prove the existence UHE cosmic gamma-quanta. The present methods are based on the analysis of fluctuations in the lateral muonic component in extensive air showers. We suggest, among all showers registered at mountain altitude (3200m a.s.l.), to select showers generated by primary UHE photons using the TTC method (Time Track Complementarity). This method is based on the study of the longitudinal development of the EAS muonic component.

1 Introduction

During the last ten years, the TeV gamma-ray astronomy has been widely used and developed for the determination of local point sources in the universe. However, if the registration of the Cerenkov radiation and the fluorescence light generated in the showers gave promising results to track objects generating VHE gamma-quanta, these methods show two important limits:

i) because the too slow increase of the radius of the Cerenkov front, they cannot be used to register UHE primary gamma-quanta (\( E \geq 100 \text{ TeV} \)).

ii) Optical telescopes are tracking the possible sources individually and, consequently, are not able to be used to analyse the diffuse gamma-rays in the galaxy.

Therefore, to study UHE photons and the diffuse gamma-ray flux, it is necessary to come back to the traditional extensive air showers (EAS) study. In other words, the problem is to be able, among all EAS registered by experiments, to select those generated by UHE primary gamma-quanta.

Recently, the gamma-shower selection has been analysed taking into account the specific structure of EAS generated by primary gamma-quanta: their abnormal poorness in muons and hadrons. Indeed, because the photoproduction cross-section, \( \sigma_{p-\text{air}}(E) \), cannot be largely increasing for ultra-high energy (1), γ-showers have to be poor in muons and hadrons. Therefore, is is possible to determine threshold values for these muon and hadron poornesses under which registered showers can be
claimed to be $\gamma$-shower. For example, these analyses have been made quantitatively for the Tien Shan experiment (2-3) from the study of the fluctuations of the muon number, $N_\mu$, and of the hadron energy $E_h$ in the central calorimeter. The problem is to underline threshold values able to pick up, among the registered EAS, the $\gamma$-EAS with the following constraints:

i) to select the largest proportion of primary photons colliding the earth atmosphere.

ii) among the selected showers, to reduce as much as possible the number of hadron showers from the background.

Because the large overlap between the muon and hadron distributions in gamma and proton-showers, it is shown that the muon poorness, by itself, is not sufficient to select primary photons with a sufficient precision (2). The more satisfactory answer is given adding the hadron fluctuations (3) which is only possible for experiments with a sufficiently large calorimeter.

This is why, it is important to define quite new and independent criteria able to pick up $\gamma$-showers generated by primary photons with UHE energies.

2 Method

Because, in $\gamma$-showers, muons are produced very deep in the earth atmosphere, it is interesting to define a new selection criterion of such showers based on their longitudinal development. As well known, information on the longitudinal development of EAS can be obtained analysing the Cerenkov flux or the fluorescence light emitted during the shower development. However, as mentioned in the introduction, such possibilities are not available for UHE. An answer to the problem can be obtain using the EAS muon component and more precisely the Time and Track method. Indeed, Linsley (4) proposed an idea to use muon track and time information simultaneously for the determination of the individual muon production heights. We developed this idea defining the Time-Track-Complementarity (5) named as TTC-method in the following. Because time and track data seemed to be relatively independent for the fixed production height, they where proposed to be used complementary to improve the accuracy of the muon production height determination. The advantage of our work (5), in comparison with the previous ones is the simultaneous and complementary use of the muon time and track information and the shift towards higher muon energies of about a few GeV, where deviation of their trajectories from the straight lines is less and individual determination of muon production height becomes principally possible. More precisely, the muon production height is estimated by two ways, from the time measurements, $z_\mu^{\text{time}}$ and from the muon angles and coordinates in the experimental plane, $z_\mu^{\text{track}}$. To take into account not only the accuracy of the $z_\mu^{\text{time}}$ and $z_\mu^{\text{track}}$ determination, but also their correlation and systematic shifts from the true value $z_\mu^{MC}$ (known from Monte Carlo simulations), we performed a new muon depth estimation $z_\mu^{TTC} = f(z_\mu^{\text{time}}, z_\mu^{\text{track}})$. Comparison made at the mountain altitude and for muons with $E_\mu \geq 5$ GeV gave no shift between $z_\mu^{TTC}$ and the known exact value $z_\mu^{MC}$. For example (2), we show on figure 2, the dependences of $z_\mu^{MC} - \Delta(z_\mu^{TTC})$ and $z_\mu^{MC} - \sigma(z_\mu^{TTC})$ where
\[ \Delta(z^{TTC}) = z^{TTC} - z^{MC} \]

\( z^{TTC} \) is the muon production depth determined by the TTC-method, 
\( z^{MC} \) is the exact muon production depth obtained from the Monte Carlo simulation, 
\( \sigma(z^{TTC}) \) is, as usual, the relative standard deviation of \( z^{TTC} \).

These results are for showers generated by primary protons with zenith angle \( \theta \leq 30^\circ \), energy \( E_0 = 10^6 \) GeV and for muons registrated at 220-230 m from the shower axis at 700 g.cm\(^{-2}\) depth.

3 Selection of \( \gamma \)-showers

\( \gamma \)-showers are not only muon poor showers, they have a specific structure too. Indeed, because of the smallness of the photoproduction cross-section for intermediate energies, \( \sigma_{\gamma p}/\sigma_{\gamma \rightarrow e^+e^-} \approx 10^{-3} \), the largest number of muons are produced only when the number of photons is sufficiently important, i.e. deep in the atmosphere and from \( \gamma \)-quanta with low energies. For example, in cascades generated by primary photons with the fixed energy \( E_{0,\gamma} = 5 \times 10^5 \) GeV, the average energy of muons with energy larger than 5 GeV is only 50 GeV (2) and are produced mainly in the range 400 - 600 g.cm\(^{-2}\). This last remark is important because it means that the distributions of the muon production heigh, \( z_{\mu} \), in hadron showers and in \( \gamma \)-showers have to be quite different. This effect is drown in figure 3 on which we have drown the distribution of \(< z_{\mu}^{TTC} >\) in proton-EAS and in showers generated by primary photons with the same primary energy. Here, \(< z_{\mu}^{TTC} >\) is the average muon production heigh determined using the TTC-method (5), taking into account all muons \((E_{\mu} \geq 5\) \( \) GeV).
GeV) in each showers collected between 110 and 120m from the shower axis. These two distributions are normalised to the unity.

Figure 2 shows that, in each individual shower, the average depth of muon production $<z_{\mu}^{TTC}>$ could be a good parameter able to select $\gamma$-showers from the background of hadronic EAS. Let us notice that, contrary to the $\gamma$-showers selection based on the muon number distributions (2), there is no full overlap between the $<z_{\mu}^{TTC}>$-distributions in proton and gamma-showers. Of course, taking into account the intensities of the primary photons and protons such as $I_\gamma (\geq 4.8 \times 10^5 \text{ GeV})/I_p (\geq 8.7 \times 10^5 \text{ GeV}) = 3.75 \times 10^{-4}$ and picking up showers such as $<z_{\mu}^{TTC}>\geq <z_{\mu}^{TTC}>_{\text{threshold}}$, the collected EAS will be more spoiled by proton-EAS. As example, we selected showers such as $<z_{\mu}^{TTC}> \geq 520 \text{ g.cm}^{-2}$, ($<z_{\mu}^{TTC}>_{\text{threshold}} = 520 \text{ g.cm}^{-2}$). Then, among all collected EAS, 72% are $\gamma$-showers and 28% generated by protons. This result is good. However, many $\gamma$-showers do not satisfy the condition selection: only 29% of the cosmic gamma radiation are collected.

### 4 Conclusion

Using the Time Track Complementarity (TTC-method) to analyse the longitudinal development of the muon component in EAS, we determine the distribution of the muon average production heigh, $<z_{\mu}^{TTC}>$, in showers generated by primaries with the same energy. Because the specificity of the showers generated by primary photons, we determine a threshold value $<z_{\mu}^{TTC}>_{\text{threshold}}$ and pick up showers such as $<z_{\mu}^{TTC}> \geq <z_{\mu}^{TTC}>_{\text{threshold}}$. Then for primaries with energy $E_0 = $ and with $<z_{\mu}^{TTC}>_{\text{threshold}} = 520 \text{ g.cm}^{-2}$, among the selected EAS 72% are $\gamma$-showers and 29% of the primary cosmic gamma radiation are collected.
This work is only a first approach of the method. It is possible to improve these results making the proposed criterion more selective. For example, adding a second criterion based on the proportion of muons generated above a depth which has to be determined.

References
Consequences of the existence of the infrared background in addition to the microwave background for the future high energy \(\gamma\)-rays experiments

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Abstract

We show that the attenuation of the gamma ray flux from extragalactic sources due to the blackbody background in addition to the infrared background attenuation, bring to the necessity to lower as much as possible the threshold of the future high energy \(\gamma\)-rays detectors.

1 The blackbody background attenuation

It is well known that the gamma ray fluxes from high energy sources can lose photons from the interaction with the blackbody background through the process \(\gamma\gamma \rightarrow e^+e^-\). The electrons then lose the source direction due to the interstellar magnetic field. The cross section of the process is [1]

\[
\sigma_{\gamma\gamma} = \frac{\pi r_e^2}{2} (1 - v^2) \left\{ (3 - v^4) \ln \left( \frac{1 + v}{1 - v} \right) - 2v(2 - v^2) \right\}
\]

where \(r_e\) is the classical radius of the electron and

\[v = \sqrt{1 - \frac{4m_e^2}{2\omega_1\omega_2(1 - \cos \vartheta)}}\]

\(\omega_1\) and \(\omega_2\) are respectively the energies of the blackbody spectrum and the high energies gamma ray and \(\vartheta\) is their angle of incidence.

Because the blackbody spectrum is isotropic, we can integrate in \(d\Omega = 2\pi \sin \vartheta \, d\vartheta\) with the normalization \(1/(4\pi)\), then the ratio between the flux \(I(L)\) at a distance \(L\) from the source and the initial flux \(I\) can be written as:

\[
\frac{I}{I_0} = \exp(-k_{\gamma} \cdot L)
\]

where \(k_{\gamma}\) is the absorption coefficient

\[
k_{\gamma} = \frac{1}{2} \int_0^\infty \int_0^{\pi} \frac{dn_{\gamma}}{d\omega_1} \sigma_{\gamma\gamma} \sin \vartheta \, d\vartheta \, d\omega_1
\]

and \(dn_{\gamma}/d\omega_1\) is the Plank black body distribution

\[
dn_{\gamma}/d\omega_1 = \frac{1}{\hbar^3 c^3 \pi^2 \exp(\omega_1/kT) - 1}
\]

The minimum angle \(\vartheta^*\) depends from the photon energy because the energy in the center of mass must be

\[\sqrt{2\omega_1\omega_2(1 - \cos \vartheta)} \geq 2m_e\]

In fig.1 is shown \(I/I_0\) obtained from eq.1 for \(kT=2.726\) for three different distances
2 The Infrared radiation field

Observational determinations of the extragalactic infrared background are plagued by the difficulty of separating the true extragalactic component from Galactic radiation and instrumental background. The observational determinations are general upper limits which lie above theoretical estimates. Figure 2 shows reasonable upper and lower limit on the infrared background. The solid curve corresponds to the maximum contribution from normal galaxies [3] the dotted curve is the minimum contribution chosen to include the estimation of Tyson [4](cross points) and of Yoshii and Takahara [5](open circle). The observed upper limits are from IRAS experiment [6] and by [7]. With these limits one can calculate [2] the degree of absorption for objects at red shift of $z \sim 1$ and $z \sim 0.03$, the distance of Markarian 421, shown in Figures 3 and 4. For a $z \sim 1$ object the possible transmission of 100 GeV photons is between 36% (upper limit) and 67% (lower limit) at 500 GeV the transmission falls to less then 1%. In fig.5 it is shown the sum of the infrared and black-body background.

The previous argument indicates that the future ground experiments will greatly benefit by a threshold as low as possible. The region between 100 GeV and 1TeV is doubly interesting, first because it cannot be reached by satellite experiments and second because by measuring the change in the slope of the spectra from $1/E^2$, one can have an indirect measurement of the extragalactic infrared background.

To lower the threshold as much as possible two conditions must be fulfilled. One is to make an extensive air shower detector which is active on all the area covered, like in the Argo project, the other is to reduce the atmospheric thickness.

Figure 6 shows the number of electrons with energies > 1.5 MeV in a shower in function of the traversed radiation length in air for different primary energy and figure 7 shows the relation between the height and the radiation length traversed. It can be seen that, if one requires at least 300 electrons as trigger at 4000 m of altitudes ($17 X_0$) one can have a threshold of 200 GeV (perhaps less with some heavy converter in front of the detector for the conversion of the γ-rays).

References

Figure 1: The absorption of the $\gamma$-ray flux due to the black-body background.

Figure 2: Estimation of the extragalactic infrared background.
Figure 3: The absorption of the $\gamma$-ray flux for objects at redshift of $z \sim 1$ and $z \sim 0.03$ due to the infrared background. The solid and dotted curves are the upper and lower limit due to the indetermination in the knowledge of the spectrum.

Figure 4: The absorption of the $\gamma$-ray flux as in figure 2 but for a different energy interval.
Figure 5: The absorption of the γ-ray flux for objects at redshift of $z \sim 1$ and $z \sim 0.03$ due to the sum of the infrared and black-body background.
Figure 6: The number of electrons in a shower in function of the traversed radiation length in air for different primary energy.

Figure 7: The relation between the height and the radiation length traversed.
Detection of small size air showers at high altitude: the expected performances of an RPC's carpet

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Abstract

The detection of small size air showers initiated by photons of a few hundreds GeV is of great importance for extragalactic gamma-ray astronomy. The performances - triggering efficiency and pointing accuracy - of a full coverage RPC's carpet (as proposed for the ARGO detector) operating at high altitude have been calculated.

Introduction

The ARGO detector was proposed [1] to operate with high sensitivity in the energy range $5 - 100\, TeV$, a region marginally accessible to the traditional techniques (Cerenkov telescope and E.A.S. arrays). The design of the detector is very simple: it consists of a layer ($\sim 95\%$ of active area) of Resistive Plate Counters covering a $\sim 10^2$ area and providing a detailed space-time picture of the shower front with fine granularity and $< 1.5\, ns$ time resolution (the performances of the RPC's are presented in an accompanying paper at this Symposium). The site originally proposed to locate ARGO was in Italy at an altitude of 1200 m above sea level. This location was chosen as that one realizing a good compromise among the scientific, technical and economical requirements. This choice determines an energy threshold
of a few TeV. However, recent results from EGRET (G.R.O.) concerning both the observation of high energy gamma rays from several AGN [2] - one of them, Mrk421, observed also at TeV energies by Whipple [3] - and the detection of a gamma-ray burst with a spectrum extending up to 10 GeV [4], prompt the need of ground-based detectors operating in the energy range from 100 GeV to 10 TeV and free of the traditional limitations of the Cerenkov technology. Such a detector could bridge the energy region between GeV and TeV accessible, respectively, to satellite equipments and Cerenkov or E.A.S. apparatus. Since the ARGO operating at high altitude could meet these requirements, calculations have been started to estimate the efficiency and the pointing accuracy of this detector at an elevation of 4300 m a.s.l. (corresponding to the site of the ASγ array in Tibet) for small size showers initiated by low energy (< 1 TeV) gamma rays.

Simulation of electromagnetic showers

The EPAS code [5] is used for the simulation of electromagnetic air showers initiated by gamma-rays. Photons with energies of $10^2 \div 10^3$ GeV are injected at 20° zenith angle from the top of the atmosphere and propagate up to a vertical depth of 606 g/cm². Both electrons and photons with energy $\geq 1$ MeV are recorded at the sampling level. The dependence of mean size $\overline{N}_e, \overline{N}_\gamma$ on the primary energy and size distributions for 500 GeV showers are shown in Fig. 1 and Fig. 2, respectively. Fig. 3 shows the pattern of electrons (a) and photons (b) on a plane normal to the primary photon direction, for a 500 GeV shower. About 50% of the electrons is concentrated in a circle of ~$\sqrt{N}$ radius. Photons are spread farther from the shower core than the electrons, so that only about 25% of them is inside a similar circle. Nevertheless, since the $\gamma$-component is about 7 times more abundant than electrons, the conversion of low energy photons could be exploited to increase the number of charged particles. Moreover, converter of appropriate thickness is expected to
improve the charged particle time profile, the effect being due to the removal of low energy particles which exhibit large time fluctuations respect to the shower front. The effect of a lead converter 1 cm thick on 500 GeV showers has been evaluated processing the shower particles by means of the EGS4 code [6]. In Fig. 4 the size distribution of electrons inside a circle of 50 m radius with (a) and without (b) the converter are compared. The average size is increased of a factor 1.9. Likewise, the integral time distributions of electrons at distances $20 \div 30$ m from the shower core are compared in Fig. 5. The spread in arrival time delay is clearly reduced.

**Experimental set-up**

An RPC's carpet of $120 \times 120$ m$^2$ has been considered with a 95% active area. Moreover a 95% efficiency has been take into account. Each RPC ($1 \times 2$ m$^2$) is equipped with a read-out system of 3 cm wide, 50 cm long strips. Signals from the strips are OR-ed in order to get the time of the first particle hitting each $50 \times 50$ cm$^2$ 'pad'. This time is smeared out with the detector response and assigned to a conventional particle hitting the center of the pad. The detector response is described by folding the 'shower time' to a gaussian with $\sigma = 1$ ns (the typical RPC time resolution) and then adding the transit time in the strip (up to 2.5 ns depending on the crossing point). Accidental signals are simulated by sampling hits from a Poisson distribution with $m = 10$, randomly distributed on the whole area in a time window of 500 ns. Pseudo-experimental time patterns obtained in this way are compared to the time patterns of the shower electrons in Fig. 6. Signals from $50 \times 50$ cm$^2$ pads are OR-ed again to define a 'logic pads' $1 \times 1$ m$^2$ wide. The information from these 'logic pads' can be easily managed for triggering purpose. Preliminary results concerning efficiency and angular resolution can be summarized as follows:
Efficiency

N shower events have been simulated uniformly distributed over an area of $100 \times 100 \, m^2$ inside the detector area. We define the efficiency for internal events as the ratio $n/F$, being $n$ the number of showers satisfying the trigger conditions. A very simple trigger logic has been considered: the whole carpet is subdivided in $4 \times 4 \, m^2$ logic sub-units and a threefold coincidence ($\tau = 500 \, ns$) of these units is required, each sub-unit having at least two $1 \, m^2$ logic pads fired in a narrow temporal window ($\tau = 50 \, ns$). Furthermore, a minimum number $N_p$ of fired pads is required. This logic can be easily carried out and exploits the low noise and the time properties of the RPC's to keep the frequency of spurious triggers at a level of $\leq 1 \, Hz$. The efficiency as a function of the energy for $N_p = 20, 30$ is shown in Fig. 7. Only a marginal gain is obtained with $0.5 \, cm$ of lead converter, while no gain is found by simulating the effect of $1 \, cm$ of lead. A straightforward explanation is that the pair production by photon interaction is 'seen' by the $1 \, m^2$ 'logic pad' as an unique particle, so that the number of charged particles gained by the conversion effect does not exceed the lost of low energy electrons absorbed in the converter.

Angular resolution

An iterative procedure is adopted to reject spurious times due either to accidental hits (on average 10 in 500 ns) or to extreme time fluctuations of shower particles, and to take into account the shape of the shower front. This procedure consists of the following steps:

(i) location of the core position from the center-of-gravity of the hits ($\sigma_x \simeq \sigma_y \sim 2m$) plane fit to hits at core distance $R < 30 \, m$;

(ii) rejection of out-lying times by means of a $4\sigma$ cut ($\simeq 10 \, ns$) to the distribution of time residuals, and cone-like fit by fitting a conical shape to the survived times. This step is repeated applying a cut to a $3\sigma$ level. No weights are used. As a result, $\sim 20\%$ of times are rejected.

This procedure is rather fast because makes use only of analytic formulae without
requiring any information about shower features. The conicity parameter $\alpha$ is determined by data itself as well as the time offset and the direction cosines. The angular spread in the reconstructed arrival direction is shown in Fig. 8 for 500 GeV showers, $N_p > 20$, and 1 cm thick lead converter. The opening angle $\psi(70\%)$ including 70% of events is about 0.60°. In the energy range we have explored (300 $\div$ 700 GeV) the angular resolution depends essentially on the number of hits as shown in Fig. 9 where the opening angle $\psi(70\%)$ is plotted as a function of the number $N_p$ of fired pads. The horizontal bars indicate the bin size. Results not significantly different are obtained with 0.5 cm of lead. For comparison, the dependence of $\psi(70\%)$ on $N_p$ in the case of no shielding is also reported. Thus, the use of the converter allows one to improve the angular resolution of a factor two at least. On the contrary, present results show that no substantial gain is obtained at the triggering level. A systematic study will be carried out by considering also the use of an iron converter.

Conclusions

Preliminary calculations indicate that an RPC’s carpet operating at high altitude could achieve excellent performances in detecting air showers initiated by photons of energy $\geq$ 300 GeV. At this energy the minimum detectable integral flux at 4$\sigma$ level in 1 yr of data taking is expected to be about $6 \cdot 10^{-11} \cdot \frac{(\psi(70\%))}{0.6°} \cdot \frac{1}{Q} \, \text{cm}^{-2} \, \text{s}^{-1}$, comparable to fluxes expected from extragalactic sources. Here $Q$ is a rejection factor resulting from the capability of discriminating photon/hadron induced showers ($Q = \frac{N_\gamma}{\sqrt{N_B}}$, $N_\gamma, N_B =$ fraction of $\gamma, h$ showers, respectively, retained after the selection). Since at these energies the muon content can not be exploit (as envisaged in the original ARGO proposal) to select electromagnetic cascades against the hadron induced ones, this capability is essentially related to differences in the space-time pattern. Work is in progress to identify peculiar features allowing one to distinguish $\gamma$-showers from background showers initiated by cosmic ray hadrons.
References


Figure Captions

Fig. 1: The average size $\overline{N_e}, \overline{N_\gamma}$ as a function of the photon energy.

Fig. 2: Size distribution of electrons (a) and photons (b) for showers initiated by 500 GeV $\gamma$-rays.

Fig. 3: The pattern of electrons (a) and photons (b) in a 500 GeV shower [$N_e = 111$, $N_\gamma = 751$].

Fig. 4: Size distribution of electrons inside a circle of 50 m radius with (a) and without (b) 1 cm Pb converter [$E = 500 GeV$].

Fig. 5: Integral time distribution of electrons at distances $20 \div 30$ m from the shower core with and without 1 cm Pb converter.

Fig. 6: Time distribution of the electron component of 500 GeV showers as a function of the core distance ($0 \div 10$ m, $20 \div 30$ m, $40 \div 50$ m from the top). The distribution on the right side are obtained after folding with the detector response.

Fig. 7: The triggering efficiency as a function of the primary photon energy.

Fig. 8: Distribution of the space angle $\psi$ between the input direction and the reconstructed one.

Fig. 9: The opening angle $\psi(70\%)$ as a function of the number of fired pads.
Fig. 1

Fig. 2

Fig. 3
Fig. 4

Fig. 5
USE OF RESISTIVE PLATE CHAMBERS FOR THE DETECTION OF EXTENSIVE AIR SHOWERS

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Abstract
The potentialities of the Resistive Plate Chamber (RPC) in the detection of Extensive Air Showers (EAS) are analysed. Preliminary experimental results concerning a small full coverage test array are presented.

1 Introduction
The study of EAS was carried out so far by using large scintillator arrays as detector. The high time resolution of the scintillator coupled to photomultipliers allows indeed to measure the primary direction, typically with 1 deg error, from the relative delay of the signals detected by different counters of
the array. This technique, in spite of the considerable cost of the scintillator, is appropriate as far as the coverage ratio, defined as the sensitive area over the total area covered by the array is $\ll 1$. On the other hand, an efficient detection of low energy EAS demands high coverage arrays due to the small number of particles in the shower.

Gaseous detectors are more suitable than the scintillator for high or full coverage arrays: they are by far less expensive and allow a much larger segmentation which can be obtained just by a convenient choice of the read out electrodes. Their time resolution can be made comparable to that of the scintillator provided that the field acting in the gas is the uniform field generated by two parallel electrode plates rather than the more usual one produced by a charged wire.

The RPC [1], sketched in fig. 1, is a gaseous detector working with a field of about 5 KV/mm generated by two parallel plates of a plastic phenolic material with a volume resistivity ranging in the interval $10^{10} - 10^{12} \Omega \cdot cm$. The 2 mm gas gap is filled with a mixture of Argon-Butane in the ratio 60/40 in volume and a small amount (3-5%) of freon. The electrode plates are coated, on the external sides, with thin graphite layers connected to high voltage and ground respectively. Due to their high surface resistivity, about 100 $K \Omega / \square$, these graphite electrodes are transparent to the transient of electrical discharges generated inside the gas thus allowing the capacitive read-out, through virtually grounded pads which are fixed or simply pressed on the detector walls. A PVC-Polythene film 0.3 mm thick, glued on the graphite is used to insulate the high voltage electrodes from the read-out pads. Construction details are visible in fig 2.

The RPCs are usually operated in the streamer mode. Recently a lower gas amplification mode has also been successfully tested for high counting rate applications [2]. The electrons freed in the gas by an ionizing particle produce the avalanche and the streamer within a very short time and with minimal fluctuations. The discharge is quenched by a twofold mechanism based both on the high electrode plates resistivity and the UV photon absorption of the gas organic component which prevents secondary discharges due to the gas photoionisation. The quenching due to the resistivity can be understood by comparing two characteristic time constants of the system: the discharge duration which has been measured and is about 10 ns and the electrode plate relaxation time given by the product of the resistivity and the dielectric constant which is of the order of 10 ms. Due to the large factor,
about $10^6$, between these time constants the electrodes behave like insulators during the discharge thus insuring the quenching. RPCs have been tested in a very wide range of different working conditions using both cosmic rays [3] and accelerator beams [4].

2 Temperature and pressure test

The EAS physics requires usually to operate the detector in mountain sites where the environment conditions, particularly those related to the temperature and the pressure, are different and more severe than in a normal laboratory.

Specific tests concerning the response of RPCs in different conditions of temperature and pressure are in course. We present here preliminary results.

The tests are carried out on two chambers of area 2x2 m². Each chamber consists of two RPC modules 2x1 m² coupled along the 2 m side and read-out by 2 m long and 3 cm wide aluminium strips running parallel to the 2 m side. These strips work as transmission lines where the induced signal propagates without losses of amplitude and time information, apart for a systematic delay of 5 ns/m, up to the ends. Here the line is terminated on 50 Ω and connected to the frontend electronics which is mounted on boards situated at both sides of the module. Each board contains 16 frontend channels that can be serially read out and a single fast OR output which is optimised for time measurements, as the input to output delay is the same for all the 16 ORed channels.

The two test chambers were mounted vertically, 30 cm apart, into a closed hut where the temperature could be controlled in the range 0-30 C with an accuracy of 1 C. The hut was placed aside of the MINI [3] telescope as shown in fig 3.

The telescope, at room temperature, is equipped with fourteen chambers identical to those already described and also mounted vertically so that the horizontal cosmic muons selected and tracked by the telescope could be used to test the performance of the chambers inside the hut.

Fig 4 shows the counting rate per unit surface of the test chambers vs the operating voltage for different temperatures. An exponential rise of the rate at high voltages is observed which is more evident at high temperature. This is mostly due to the noise produced by the spacers which are used to
keep the plates parallel to one another.

The detection efficiency vs operating voltage is shown in fig 5a for different temperatures. A plateau is reached at 95% efficiency. Most of the 5% inefficiency is due to the dead areas of the spacers and seals as well as to the uncovered area between the two RPC modules.

Comparison among different curves in fig 5a shows that the same efficiency is reached at higher voltage for a lower temperature. This is well explained as an effect of the temperature on the gas density: at lower temperature the density is higher and this is equivalent to a larger gas gap which requires a higher operating voltage. If this effect is accounted for by renormalising the voltage scale with the factor \( T/T_0 \), where \( T \) is the actual temperature and \( T_0 = 293 \text{ K} \) is the standard room temperature, all the points fit on the same curve as is shown in in fig 5b.

Muons reconstructed in MINI as going in the direction from the test chambers towards the telescope, were used to measure the time of flight between the test chambers. The mean time \( (t_1 + t_2)/2 \) between the arrival times of the signal at the opposite ends of the strip was used to correct for the systematic delay due to the propagation time of the signal along the strip.

The time of flight distribution at 30 C and 9100 Volt is shown in fig 6. It is characterized by a sharp peak of 2.0 ns FWHM and two non gaussian tails that have been demonstrated to be due to trajectories crossing one of the chambers near a spacer.

The experimental conditions, with respect to previously published data [3], are different in the following points: higher operating voltage (1.6 KV inside the plateau instead of 1.0 KV), higher frontend threshold (100 mV instead of 50 mV) and small differences in the construction procedure concerning the graphite layer which, in this case, was removed at the spacers position.

Fig 7 shows the delay (7a) and the time resolution (7b) of the test chambers vs the operating voltage.

Pressure tests are in progress. The detection efficiency vs operating voltage is shown in fig 8a for two different pressures: 1000 and 500 mbar. The operating voltage scales with respect to the pressure in good agreement with the rule \( E/p = \text{constant} \) as is shown in fig 8b.
3 The RPC test array

A 30 m² RPC array is under test at the University of Roma 2. The array consists of 15 RPC modules of area 1x2 m² grouped in 5 lines or "corridors" of 1x6 m² as shown in fig 9 and in the photograph of fig 10.

Each station of the array, according to the lay out shown in fig. 11, is composed of a RPC module, 128 read out alluminium strips of size 3x50 cm², two grounded alluminium foils that shield both faces of the detector, two plastic foam plates 1 and 2 cm thick used as spacers and a 15 mm thick photon converter of iron subdivided in plates of 20x20 and 20x50 cm². All these elements are not fixed but just superposed to one another and held together by the weigt of the iron converter which is also used as a basement for the fixation of the frontend boards.

Each station is read out by 8 boards symmetrically disposed along the 2 m sides of the RPC module and each board is connected to 16 strips 50 cm long running along the 1 m side of the module. The strips are terminated at 50 Ω only at the end connected to the board; the opposite end is left open. The fast OR of the board which has been already described in the previous section, gives a single timing signal for a portion of detector of size 50x50 cm². The details of the shower pattern inside this area are given by the 16 strips that are serially read out at any trigger occurrence.

We present here preliminary results concerning single corridors of the array. A dedicated electronics which will handle all the signals of the 120 boards at the same time will be ready in the next future.

A single corridor of 1x6 m² is subdivided in 12 regions of size 1x0.5 m² by using the OR of pairs of opposite boards (see fig 9). EAS are selected by a trigger condition requiring the coincidence of all the regions of the corridor. TDCs are used to measure the arrival time of the signals of each region.

The plot of the time delay vs position is given in fig. 12a,b,c for three events. The best linear fit of the experimental points is also shown in fig 12. The slope of the straigt line fitting the data gives the direction of the shower.

The angular distribution of 200 recorded EAS is shown in fig 13.
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FIGURE CAPTIONS

Fig. 1- Sketch of a RPC

Fig. 2- Photograph showing construction details of a RPC

Fig. 3- Sketch of the test chambers and of the MINI telescope

Fig. 4- Counting rate per unit surface of the test chambers vs operating voltage for different temperatures

Fig. 5a- Detection efficiency vs operating voltage for different temperatures

Fig. 5b- Same as in fig. 5a but with the voltage scale renormalized by the factor \( T/T_0 \) where \( T \) is the actual temperature and \( T_0 = 293 \text{ K} \) is the standard room temperature.

Fig. 6- Time of flight distribution between the test chambers at 30 C and 9100 V

Fig. 7a- Time delay of the test chambers vs operating voltage for different temperatures. The delay is measured with respect to the MINI telescope kept at room temperature and fixed voltage.
Fig. 7b- Time resolution vs operating voltage for different temperatures

Fig. 8a- Detection efficiency vs operating voltage for two different pressures at 20°C

Fig. 8b- Operating voltage for 50% efficiency vs pressure

Fig. 9- Sketch of the test array for the detection of EAS

Fig. 10- Photograph showing details of the array

Fig. 11- Lay out of a station of the array

Fig. 12- Space-time pattern of three showers detected by the array, giving position and timing of the detected hits. The line represents the best fit of the points

Fig. 13- Angular distribution of the detected showers
Resistive electrode plates (phenolic polymers $\rho = 10^{11} \pm 1 \, \Omega \times \text{cm}$)

P.V.C. spacers

Pick-up x-strips

Graphite painted electrodes

GAS Argon / n-Butane - 60/40
Freon 3-5%

Insulating film

Pick-up y-strips

High Voltage $+8 \, \text{KV}$

$\sim 100 \, \text{K} \Omega / \square$

Fig. 1
Fig 3
Fig 5a
Figure 5b
T = 30°C
HV = 9100 V

T.O.F. F.W.H.M. = 2 ns
Single R.P.C \( \sigma = 600 \) ps

Fig 6
Fig 7a
$$\frac{FWHM}{2.36\sqrt{2}}$$

Figure 7.6
Fig 8a

Efficiency (%)

P = 500 mb
T = 20°C

P = 1000 mb
T = 20°C

HV (Volt)

810
Fig 8 b
Fig 12
Water Čerenkov Detectors at High Altitude for High Energy Gamma-Ray Astronomy

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Abstract

We will show an expected performance of 3 types of water Čerenkov detectors at an altitude of 4300 m a.s.l. to detect gamma-rays with an energy greater than about 300 GeV by a simulation. Energy threshold of this detector for detectable primary gamma-rays will be lowered one to two orders of magnitudes compared with the present scintillation detector array. Astrophysics such as gamma-ray bursts could be performed using this detector.

1. Introduction

The Tibet air shower array[1] at an altitude of 4300 m can observe air showers initiated by gamma rays at 10 TeV region which is the lowest energy observable by array type detector at the northern hemisphere. Water Čerenkov detectors set at the same altitude will be able to decrease the observable energy threshold to nearly a few hundred GeV[2,3]. This type of detector has an advantage to observe the sky continuously all the time compared with detectors to observe air Čerenkov light using mirrors.

One of the interesting physics by the water Čerenkov detectors will be the study of the gamma-ray bursts(GRBs). In spite of the existence of a lot of observations for the GRBs, origins of the GRBs are almost not solved yet. The EGRET detector on board the Compton GRO satellite observed the energy spectra of the gamma-ray bursts up to about 100 MeV. [4] If we can observe the energy spectra of the gamma-ray bursts at several hundred GeV using water Čerenkov detectors, it will help us a lot to resolve their origin.

In this paper, we show some performance such as detection efficiency of gamma rays for three types of water Čerenkov detectors and angular resolution of the detector.
2. Method of simulation

We assumed the following three types of water Čerenkov detectors at an altitude of 4300 m.

a) Water pool with an area of 50m×50 m and a depth of 1.5m. PMT's are arranged in the pool with a 17×17 matrix form with a spacing of 3m (Fig. 1).

b) An array of 121 water boxes each of which has an area of 2m×2m and a depth of 1.5m and arranged with a grid spacing of 7.5 m.

c) Similar to the array b), but with the spacing of 15m (Fig. 2).

Figure 1: Schematic view of the water Čerenkov pool (type a).

Figure 2: Water Čerenkov array of type (b) (solid square) with scintillation counter array (open square) of the Tibet AS-\(\gamma\) experiment.

The EGS4 code[5] is used for the simulation of electromagnetic air showers which is initiated by gamma rays. Geomagnetic field is taken into account. Altitude of the water surface is assumed to be 4300 m a.s.l. and a distance from the water surfaces to the PMT's are assumed to be 1.5 m. PMT's with a diameter of 8 inches are assumed to
be used for all of the cases. Gamma rays are vertically injected from the top of the atmosphere to the center of the detectors. Response of the PMT is not taken into account.

3. Results of simulation

Detection efficiencies of the three types of the detectors for various trigger conditions are obtained and shown in Fig. 3. Four types of trigger conditions are assumed in this simulation, where, for example, any4(\(\geq 2\) p.e.) means at least any 4 of all PMT's detected number of photoelectrons larger than one. The type (a) detector has of course the best efficiency such as about 50\% for a condition of any10(\(\geq 2\) p.e.) even at low energies around 250 GeV among them. The type (b) detector with 7.5 m spacing has the efficiency of 50\% at energies around 700 GeV and the type (c) detector with 15 m spacing has the efficiency of 50\% at energies around 1.3 TeV.

Figure 3: Detection efficiency as a function of energy for three types of water Čerenkov detectors.

Angular resolution of the type (a) is obtained to be about 1 degree at around 300 GeV and gets better as the energy increases. The resolution for the type (b) is about 1 degree at around 1 TeV for the trigger condition of any10(\(\geq 2\) p.e.).

4. Discussion and summary

Number of electron component is about 7 times larger than the photon component at 4300 m a.s.l. for air showers initiated by gamma rays at energies around several hundred GeV. The water Čerenkov detector has an advantage to convert almost all photon component to electrons in the water[5]. This fact resuls the observable energy
threshold of the water Čerenkov detector becomes much lower than that of a detector such as the plastic scintillation counter having the same area.

We have tested the feasibility of this kind of detector using a water tank with a diameter of 2.2 m and a depth of 2 m in which we put a PMT with 20 inch diameter and 5 scintillation counters around it to detect air showers at sea level in a campus of Konan university. We got a correlation between number of photoelectrons from the 20" PMT by the Čerenkov light generated in the water tank and number of shower particles detected by the scintillators. A distribution of Čerenkov light output by muons are also obtained by using coincidence counters installed at the top and the bottom of the tank.

We are going to construct a test module of water Čerenkov detector which has a water pool with an area of 7m×3m and a depth of 2m in which we will put 6 PMT's with a diameter of 8 inches at Mt. Norikura at an altitude of 2780m a.s.l.. We will put 6 scintillation counters with an area of 0.5 m² around this pool to determine directions and energies of air showers. By this experiment we will examine the feasibility to make the water Čerenkov detectors and determine parameters for the simulation.

We expect to make water Čerenkov detector at Yangbajing in Tibet in near future combining with the Tibet II air shower array to observe air showers initiated by gamma rays or nuclei in wide energy region.

References

MONTE CARLO SIMULATION OF A SCINTILLATING OPTICAL FIBER CALORIMETER

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Abstract

A scintillating optical fiber calorimeter (SOFCAL) is being developed by NASA/Marshall Space Flight Center for use in balloon-borne experiments to study the spectrum of high-energy cosmic rays and gamma rays. SOFCAL will not saturate for long exposures and the calorimeter will be helpful for the study of primary cosmic-ray nuclei energies from 100 GeV to 1,000 TeV. For a given incident particle and energy, computer simulations of electromagnetic cascades allow computation of energy deposited in different regions of the calorimeter. For these initial simulations, a 5-cm x 5-cm x 7-cm calorimeter was used. Each subsection contained a 0.4-cm thick lead plate or two 0.2-cm lead plates and two layers of optical fibers, 90° to each other. The 100 fibers in a layer were 0.5-mm thick with a square cross-section. For incident gamma ray energies of 0.5 to 1.5 TeV, the energy deposited in each layer of fibers was computed. Due to the limited dynamic range of the imaging electronics, a window for the energy deposition in the fibers is explored to determine the best measure of energy deposition ($E_y$) in the calorimeter. Funding was provided by the NASA/University Joint Venture (JOVE) Program.

1 Introduction

The Monte Carlo method in GEANT was used to simulate the photon and electron events in the Scintillating Optical Fiber Calorimeter (SOFCAL), which is under development at NASA/Marshall Space Flight Center for future applications in cosmic ray and gamma ray measurements.

Emulsion chambers employing calorimeters have been used for direct measurements of cosmic-ray composition (protons through Fe) between $10^{12}$ and $10^{15}$ eV using balloon-borne emulsion chambers [1], [2], [3], [4], [5], [6], [7]. The typical emulsion chamber [4] is composed of four parts: (1) a charge-determination module, (2) a target module with $-0.2$ vertical interaction mean free paths for protons, (3) a spacer module, and (4) an emulsion calorimeter module with about fourteen vertical radiation lengths. The simulations described here are for a scintillation optical fiber counterpart to the calorimeter section in the emulsion chamber.
The part of the primary energy going into gamma-rays, \( \Sigma E_\gamma \), is the parameter most easily related to the primary cosmic ray spectrum in emulsion chamber experiments. The ability to measure energies of electron-photon cascades is one of the most important functions of the calorimeter. The photons originating from an interaction will develop individual electromagnetic cascades in the calorimeter. For these simulations, a calorimeter module with ten vertical radiation lengths of Pb was used. In one geometrical configuration, each subsection of the calorimeter consisted of a 4-mm lead block, 100 fibers (0.5-mm thick) in the x-direction and 100 fibers (0.5-mm thick) in the y-direction. In these initial simulations, this lead and optical fiber combination was repeated fourteen times.

2 The Monte Carlo Program for SOFCAL Simulations (SOFCALS)

The Monte Carlo simulations which used GEANT3 were done on DEC 5000 workstations. The process of optimization requires frequent design changes, so users should be able to change the geometry easily. The time required to modify GEANT programs containing geometry information about the detector can be enormous. Therefore a subroutine was developed to read in the geometrical configuration from a separate file in an ASCII format. This subroutine reads not only detector setup, but also other parameters needed for the simulation, such as tracking medium parameters.

Energy deposition is calculated from the lowest level geometry. Total energy deposition is integrated using step functions. When a threshold is imposed due to limitations in the electronic read out devices, then the measured energy is less than the energy actually deposited in each fiber. The program SOFCALS has interactive routines which are called to draw the trajectories of an individual gamma ray event.

3 Results

Fig. 1 illustrates the shower of electrons and photons produced by an incoming gamma ray with incident energy of 0.1 TeV in the SOFCAL detector. In these simulations, the incident gamma ray lies along the z-axis which is normal to the plane of each lead plate and layer of fibers. The typical detector (emulsion chamber [4]) has a "target section" and "calorimeter section" designed for measuring produced charged
particles and gamma rays, respectively. The target section includes many layers of nuclear emulsion plates to measure the charge of the incident particle and the emission angles of the produced charged particles with high accuracy (0.01 mrad). The calorimeter includes layers of nuclear emulsion and X-ray film among lead plates to measure the electron distributions from the electromagnetic cascades initiated by gamma rays from π^0 decay. The calorimeter is used to measure the spectrum of energy deposition ∑E_i, from which the primary energy spectrum is derived [4].

For the simulations, the angular distribution and energy distribution of gamma rays from each π^0 decay is needed. Isospin symmetry is assumed so the number of π^0s which decay into pairs of gamma rays is about half that of the charged π mesons.

For 1 TeV gamma rays and 100 events, Fig. 2 shows the energy deposited within each adjacent layer (#12) of x- and y-fibers. The energy transition curve in Fig. 3 shows the total energy deposited within each x-layer of fibers as a function of distance through the detector SOFCAL. The incident particle is a gamma-ray with energies of 0.5, 1.0, and 1.5 TeV. The three curves are based on ten events each.

4 Discussion

In these simulations of gamma rays incident on the SOFCAL detector, the energy transition curves show the energy deposited in each layer of optical fibers. These curves have been determined for gamma rays from 10 MeV to 1.5 TeV. Within single layers of fibers, the energy deposited in each fiber has been computed and plotted. GEANT has the advantage that it is relatively easy to modify the geometry of the detector. Simulations were done for a second geometrical configuration with 2-mm lead sheet, x-layer of fibers, 2-mm lead sheet, and y-layer of fibers in each subsection.

The dynamic range is one limitation of the output image intensifier CCD electronics. Typical devices are limited to a dynamic range of approximately 256. For example, if the threshold energy is set to 1 MeV, then the highest energy which can be measured is only 256 MeV. Due to this limitation, a specific threshold and window may be needed to optimize the measurements. For these initial simulations of SOFCAL, a dynamic range of 100 was used. In Fig. 4, a threshold of 2 MeV appears to be optimal. Fig. 5 and Fig. 6 show the energy transition curve for a 0.5- to 50-MeV
window and 5- to 500-MeV window, respectively. When compared with the energy transition curve in Fig. 3, for which no threshold has been imposed, these figures show that a 2- to 200-MeV window differentiates between gamma ray energies from 0.5 to 1.5 TeV better than other windows. For simulations of the primary cosmic rays, calculations must be performed with event generators, such as FRITIOF, to predict the distributions in $\Sigma E_\gamma$ and then use GEANT for associated optimum "window" settings.

Fig. 3. The energy transition curve.  
Fig. 4. The threshold is 2 MeV.  
Fig. 5. The threshold is 0.5 MeV.  
Fig. 6. The threshold is 5 MeV.

References

The GILDA mission:
a new technique for a gamma-ray telescope
in the energy range 20 MeV - 100 GeV

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Abstract

In this article a new technique for the realization of a high energy gamma-ray
telescope is presented, based on the adoption of silicon strip detectors and lead
scintillating fibers. The simulated performances of such an instrument (GILDA)
are significatively better than those of EGRET, the last successful experiment
of a high energy gamma-ray telescope, launched on the CGRO satellite, though
having less volume and weight.

1 Introduction

The high energy gamma-ray astrophysics has greatly developed in these last few
years because of the results of the experiment EGRET[1], on the Compton Gamma
Ray Observatory. The satellite observations have brought more detailed data about
the well known gamma-ray sources, but also the discovery of new ones, both galactic
and extragalactic, especially Active Galactic Nuclei and gamma-ray bursts. Never­
theless, the emission mechanisms of these sources are still not clear, so it is of crucial
importance the investigation of the high energy component of the cosmic gamma
radiation with a telescope working in a energy interval broader than EGRET.

The most serious problem affecting the EGRET telescope is the decrease of the
detection efficiency at high energies, due to the use of antioccidence counters placed
around the detector. Since at energies greater than 1 GeV the number of secondaries
produced in an electromagnetic shower is relevant (more than 100), the probability
of having a back scattered particle on the antioccidence counters, inhibiting in this
way the acquisition trigger, becomes quite high, reaching the value of 70% for a 30
GeV gamma.

Another drawback of the EGRET instrument is provided by the spark chambers.
They need periodic substitution of the filling gas to work and this requirement
brings weight and duration time problems for a space experiment. Moreover, they
have quite a long dead time, especially related to the typical length of transient
phenomena like the gamma ray bursts. Finally, the track resolution of such detectors
is not better than few millimeters. All these problems can be overcome with the
adoption of silicon strips detectors.

2 The GILDA apparatus

The core of the GILDA telescope is a modified space version of the silicon calorimeter
presently used in the Wizard balloon flights program, to be installed on a future
version of the Resource-01 satellite, scheduled to fly at the beginning of the next millennium. This detector is a fine-grained imaging electromagnetic calorimeter conceived for the Wizard experiment to investigate, in a planned space mission, the antimatter component of the primary cosmic radiation [2].

Detectors based on the silicon technology have many advantages for space applications: no gas refilling system or high voltages, no need of photomultipliers (low consumption), short dead time, possibility of self triggering. During the project phase, the calorimeter has been extensively studied with Monte Carlo simulations, and a prototype, containing 20 XY samplings of silicon wafers with strips 3.6 mm wide interleaved with 19 showering tungsten planes (for a total of 9.5 X₀), has already been built and tested at the CERN Proton Synchrotron (PS) [3]. Five planes (50 × 50 cm²) have already flown in a balloon experiment from the NASA base at Fort Sumner (New Mexico) in September 1993; another Si-W calorimeter with 8 planes is ready for a second flight in Lynn Lake (Canada), scheduled in July 1994.

The basic element of the GILDA telescope is a 6 × 6 cm² module composed by two Si detectors, each with a thickness of 380 µm, mounted back to back with perpendicular strips to give the X and Y coordinates (figure 1). In this experiment, two different strips widths are considered. For the 3.6 mm strips, each module contains 16 strips, while for the 125 µm ones it is possible to arrange 500 strips in each wafer (figure 2). The detectors are held in a special package which, when patched to form large surfaces, allows a minimal dead area for the sampling planes of the calorimeter. All the used materials are approved by NASA for space applications.

The principal constraints are imposed by the satellite in terms of volume, weight and available electric power. The free volume on the satellite is a cylinder 110 cm diameter and 70 cm in height, the available mass and electric power are respectively 700 kg and 350 W.

The baseline configuration of GILDA has a height of 40.8 cm, an area of 50 × 50 cm² and a total showering length of 10 X₀ (radiation lengths). A suitable arrangement of the electronics coupled to the calorimeter and of the anticoincidence system allows to match the 110 cm diameter of the available cylindrical volume. In the volume under the detector, the remaining digital electronics, interfaces and services can be located.

The stratigraphy of the instrument is shown in figure 3. The γ detector can be separated into two sections: the converter (or tracker) and the absorber. The first twenty planes form the converter zone, in which the silicon layers, made of 125 µm strips, are separated by tungsten plates of thickness 0.07 X₀. The distance between two contiguous planes is 1.0 cm. In each plane, 4000 silicon strips per view allow a very precise measurement of the direction of the incoming gamma ray. The granularity of the silicon and the thickness of the tungsten have been decided by detailed Monte Carlo studies and hardware developments and they represent the compromise between number of necessary electronic channels, distance between planes, power consumption (1.5 mW/ch), efficiency and angular resolution.

The last ten planes E₁...E₁₀, constituting the absorber, are composed of 3.6 mm silicon strips and separated by layers of active scintillating lead fibers, 1 X₀ total thickness. Between the converter and the absorber, an aluminum plate of 0.2 X₀ is placed in order to reduce the back scattering of particles from the bottom of the calorimeter. Each silicon plane is 1.6 cm far from the following.

The structure of the scintillating fibers is shown in figure 4. It has been built embedding polystyrene fibers emitting in the blue, 1 mm of diameter, between plastic
deformations of lead foils 0.5 mm thick. Fibers are glued to the foils and run parallel to each other with a pitch of 1.35 mm. The overall structure has a fiber:lead:glue volume ratio of 48:42:10 and a sampling fraction of ~14% for a minimum ionizing particle; moreover, it has a density of ~5 g cm\(^{-3}\) and a \(X_0\) of ~1.5 cm. This means that, in one radiation length, ten lead foils are interleaved with the same number of fibers. Prototypes have already been extensively tested [4],[5] with accelerator beams, showing that the lead scintillating fibers calorimeter has an energy resolution for \(\gamma\) of the order of \(5\%/\sqrt{E(GeV)}\) for total containment. The solution of adopting these fibers is particularly attractive because HPK has developed compact PM's (PMT R5600 series) reduced to the same dimensions as a solid state detector and housed in a robust metal package 15 mm in diameter and 10 mm in length, while maintaining the same performances, high sensitivity and high speed as a conventional PM. The very low mass and the power consumption of the PMT R5600 (~100 mW) allow the use of the large number of PM needed for a fast trigger.

The configuration is completed with a plastic anticoincidence scintillator \(A_c\) (3 cm thick) around the converter zone of the calorimeter, and with two fibers scintillators (without the lead), one, \(E_{o1}\), after the first seven planes (that is after 0.49 \(X_0\)) and the other, \(E_{o2}\), after fourteen planes from the top of the detector. The introduction of the first one allows to obtain a threshold for gamma ray detection of 25 MeV.

2.1 Trigger

Two different triggers are adopted, for the low and high energy regions respectively:

- \(\overline{A_c} \cdot (E_{o1} \cdot OR \cdot E_{o2})\), up to 1 GeV.
- for high energy, to avoid the same problems as EGRET, we do not use the anticoincidence scintillators. The trigger is constituted by the OR between \(E_{o1} \oplus E_{o2}\), with the request of having at least two of the following conditions for the energy deposited in the first five planes of the absorber:

\[
E_2 > E_1, \\
E_3 > E_2, \\
E_4 > E_3, \\
E_5 > E_4,
\]

to impose a shower behaviour for an entering particle. In this case, the elimination of crossing charged particles (like \(\mu\)) and of particles inducing hadronic showers is realized on board with the aid of neural networks; several algorithms of pattern recognition, in fact, based on neural networks, have been developed by the WiZard collaboration with great success [6],[7].

3 Analysis method

For the simulation of gamma rays in the GILDA calorimeter we used the Geant 3.15 code. As a result of a number of optimizations, the energy threshold has been fixed at 10 keV; this means that GEANT follows a secondary particle until its energy is above or equal this value, then it drops it.
During the tests made at Cern with the prototype of the WiZard calorimeter, it has been possible to check the reliability of the Monte Carlo simulations, based on the Geant code, in reproducing real events. An excellent agreement between real and simulated data has been observed, as confirmed by figures 5 and 6. In figure 5 the total energy released in the calorimeter, obtained adding the signal of each silicon strip for both the views, as a function of the incoming gamma energy for both real data and Monte Carlo simulations, is showed, while in figure 6 the longitudinal development of a typical electromagnetic shower, induced by a 6 GeV electron, again for real and Monte Carlo events, is presented. The curve is obtained taking the value of the transversal energy deposit in each plane, for a sample of 2000 events, for the whole length of the prototype.

The calorimeter responses have been studied for gammas at energies of 20 MeV, 100 MeV, 500 MeV, 1 GeV, 10 GeV, 50 GeV, 90 GeV, with a statistical error of ~ 2.2 %. Photons hit the calorimeter orthogonally, and in the center of the first plane. Each layer of scintillating lead fiber has been simulated interleaving, for 10 times, 0.5 mm of lead with 1 mm of polystyrene, for a total of 1.5 cm of thickness (~ 1 X₀).

For each sensitive volume, a cut of 0.5 mip (minimum ionizing particle) on the energy released has been imposed, since our aim was to reproduce the experimental situation in which it is necessary to eliminate the noise of the electronics from the analysis; this implies that the following thresholds in energy are present:

- 70 KeV for each silicon strip (380 µm thick)
- 100 KeV for each layer of polystyrene (1 mm thick)
- 3 MeV for the anticoincidence plastic scintillator A_c (3 cm thick)

The γ energy is linearly related to the sum of the energies deposited in each lead scintillating fiber and in the X and Y silicon strips. The statistical fluctuations of this sum have been taken as an error and define the energy resolution of our apparatus.

To reconstruct the gamma incidence angle in our calorimeter, we developed an algorithm of track reconstruction, based on an iterative process. The track is identified with the axis of the shower. In fact, since the secondaries produced in an e.m. shower are more than 100 for gammas with energies greater than 1 GeV, their distribution is almost symmetric around the direction of the primary photon. The axis is determined by a linear iterative interpolation of the barycentres x_c of the transversal energy deposit of the shower in each plane:

\[ x_c = \Delta \sum_i (i - 0.5) E_i / \sum_i E_i \]  (1)

where \( \Delta \) is the strip width and \( E_i \) is the energy deposited in the i-th strip (-0.5 because we simulated a beam hitting in the center of the silicon strip). The algorithm develops in the following steps:

1. it operates a linear fit of the barycentres of the transversal energy deposit in all the hit planes in the absorber (second half of the calorimeter), determining in this way a direction;
2. from this direction an area is extrapolated, with a fixed radius \( r \), for the first three hit planes of the tracker, and in this area it evaluates the barycentres. In this way, the process excludes the strips hit by back scattered particles;

3. with these three barycentres it determines a new direction, and the iterative process begins;

4. the track just evaluated will individuate an area in the following plane where it calculates a new barycentre;

5. with these four barycentres, the algorithm evaluates a new direction, and the process comes back to point 4.

The process stops when a direction converges, within a chosen error (10 mrad for us), with the previous one, or when the number of iterations overcomes the value of 20 (the number of planes in the tracker). To be significative, a trajectory must be determined by at least four points. Since in the first two planes of the detector the showering material (tungsten) is absent (see figure 3), we can use them as a secondary anticoincidence system for charged particles; in fact, if one of these two planes gives a signal, within one Moliere Radius, along the direction just determined, the particle is eliminated being recognized as charged. In conclusion, the gamma direction is given only by the tracker planes, where the granularity is very high, but the information of the absorber is preliminary used to eliminate from the fit tracks in the initial part of the detector due to back scattered secondaries. The reconstructed angles distribution, whose sigma furnishes the GILDA angular resolution, is dominated by multiple scattering up to energies of \( \sim 1 \) GeV and by the geometry of the Si planes at higher energies, and by the fluctuations in the shower developing.

4 Results

The energy resolution is shown in table 1 and in figure 7; its deterioration for high energies is related to the longitudinal leakage of the shower. For comparison, the relative contributions of the silicon detectors and the lead scintillating fibers are presented in tables 2 and 3 and in figure 1.

In conclusion, the total energy resolution of GILDA calorimeter is around \( \sim 6\% / \sqrt{E(\text{GeV})} \), that is the combination of \( \sim 18\% / \sqrt{E(\text{GeV})} \) of the silicon strips and \( \sim 10\% / \sqrt{E(\text{GeV})} \) of the lead fibers, as far as the longitudinal leakage of the shower is negligible \( \leq 1 \) GeV). Finally in figure 8 a comparison between GILDA and EGRET energy resolutions is presented. Apart from very low energies (below 100 MeV), our telescope performances are better as compared with those of EGRET, even in the region where leakage is dominant.

In table 4 and in figure 9 the trigger efficiency and the total efficiency of GILDA are shown. The second one takes into account the loss of good events due to the track recognition algorithm previously described. It is easy to verify that the EGRET problems of efficiency for high energy gamma rays have been overcome.

The results of the angular resolution are plotted in figure 10 together with the EGRET ones. Our pointing capacity comes out to be better than that of EGRET in all the energetic spectrum considered.

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\(^1\) We chose the Moliere Radius of our calorimeter (a radius in which 90% of the transversal development of the shower is contained), again evaluated by the simulations.
The GILDA absorber can also measure the direction of the gamma that escapes materialization in the tracker with a larger solid angle and full efficiency; for these photons the angle is measured by reconstructing the shower direction in the absorber.

Finally, in table 5 we report some geometrical characteristics of our calorimeter, compared with EGRET.

5 Conclusions

Our simulations have shown that the GILDA instrument is able to reach significatively better performances than the experiment EGRET on the CGRO, though having less area and weight; the main characteristics that make this telescope more efficient are:

- the use of silicon strips instead of spark chambers as main device for reconstructing the gamma's trajectory; in this way, we avoid the problem of gas refilling, high voltages and dead time (silicon strips have lower dead time than gas detectors). Moreover, we can reach a resolution of the order of a hundred of microns, instead of few millimeters;

- the elimination of the anticoincidence counters for the high energy trigger, so that an efficiency of 70% up to 100 GeV can be reached.

- the constitution of a whole calorimeter with 10 X₀, formed by scintillating lead fibers, instead of the 8 X₀'s of the EGRET instrument;

- the elimination of TOF, with the consequential increase of the acceptance and decrease of the energetic detection threshold (25 MeV for GILDA and 35 for EGRET); again, the pattern recognition algorithms will substitute, off line, the TOF system, recognizing an upward going particle from a downward.

An important point is that the modularity of our calorimeter consents to easily change his lateral dimensions (at least in the range 6 cm ÷ 200 cm) to tune the area, in an advanced project phase, to the maximum value permitted by the total weight of the payload. Of course, the collected statistics increases widening the area.

References

### Table 1: Total energy resolution for GILDA telescope.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$E$ deposited (MeV)</th>
<th>$\sigma(E)$ (MeV)</th>
<th>Resolution (%)</th>
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<tr>
<td>100</td>
<td>18.70</td>
<td>3.28</td>
<td>17.5</td>
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<tr>
<td>500</td>
<td>101.4</td>
<td>7.41</td>
<td>7.3</td>
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<td>1000</td>
<td>200.0</td>
<td>13.69</td>
<td>6.8</td>
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<td>10000</td>
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<tr>
<td>50000</td>
<td>7123.1</td>
<td>924.4</td>
<td>13.0</td>
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### Table 2: Silicon detectors energy resolution.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$E$ dep. in Si-D (MeV)</th>
<th>$\sigma(E)$ (MeV)</th>
<th>Resolution (%)</th>
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<tr>
<td>100</td>
<td>4.68</td>
<td>2.14</td>
<td>45.8</td>
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<td>500</td>
<td>12.17</td>
<td>3.66</td>
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<td>1000</td>
<td>20.47</td>
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<tr>
<td>10000</td>
<td>149.1</td>
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<td>50000</td>
<td>603.0</td>
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### Table 3: Fibers detectors energy resolution.

<table>
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<th>Energy (MeV)</th>
<th>$E$ dep. in fibers (MeV)</th>
<th>$\sigma(E)$ (MeV)</th>
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<td>50000</td>
<td>6476.1</td>
<td>877.2</td>
<td>13.5</td>
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### Table 4: Efficiency for GILDA telescope; the first column presents the trigger efficiency only, while the second considers the trigger plus the analysis.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Trigger efficiency(%)</th>
<th>Trigger + analysis efficiency(%)</th>
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<tr>
<td>100</td>
<td>48.9</td>
<td>14.6</td>
</tr>
<tr>
<td>500</td>
<td>57.1</td>
<td>31.6</td>
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<tr>
<td>1000</td>
<td>55.9</td>
<td>48.5</td>
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<tr>
<td>10000</td>
<td>68.3</td>
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</tr>
<tr>
<td>50000</td>
<td>78.4</td>
<td>77.1</td>
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### Table 5: Some of the principal characteristics of GILDA telescope compared with those of EGRET.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>EGRET</th>
<th>GILDA</th>
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<tr>
<td>Effective area (area × efficiency)</td>
<td>0.16 m²</td>
<td>0.14 m² (500 MeV)</td>
</tr>
<tr>
<td></td>
<td>0.12 m²</td>
<td>0.13 m² (1 GeV)</td>
</tr>
<tr>
<td></td>
<td>0.07 m²</td>
<td>0.17 m² (10 GeV)</td>
</tr>
<tr>
<td>Solid angle</td>
<td>0.6 sr</td>
<td>0.92 sr</td>
</tr>
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<td>Point source sensitivity (ph cm⁻² s⁻¹)</td>
<td>5.4 × 10⁻⁸</td>
<td>6.45 × 10⁻⁹ (0.1 GeV)</td>
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<tr>
<td></td>
<td>1.2 × 10⁻⁸</td>
<td>7.23 × 10⁻¹⁰ (1 GeV)</td>
</tr>
<tr>
<td></td>
<td>2.1 × 10⁻⁸</td>
<td>3.60 × 10⁻¹⁰ (10 GeV)</td>
</tr>
<tr>
<td>Volume</td>
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<td>0.102 m³</td>
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<tr>
<td>Mass</td>
<td>1830 kg</td>
<td>700 kg</td>
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<tr>
<td>Power</td>
<td>190 W</td>
<td>250 W</td>
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</table>
Particle flux

Tungsten plate

x strip detectors

to x readout

y strip detectors

to y readout

Figure 1: The silicon wafer, main element of the WiZard calorimeter.

Figure 2: The 125 micron silicon strips.
Figure 3: The stratigraphy of the GILDA detector.

- 3 cm plastic scintillator
- X-Y SiD Strip 0.125 mm
- Distance between Si planes = 1 cm
- Tungsten 0.07 X₀
- Scintillating fibers E₁, E₂
- Al 0.2 X₀
- Scintillating fibers + Pb 1 X₀
- X-Y SiD Strip 3.6 mm
- Distance between Si planes = 1.6 cm
Figure 4: Structure of the lead scintillating fibers.

Figure 5: Energy linearity of the prototype of the WiZard calorimeter; real data (triangles), MC data (bullets).

Figure 6: Longitudinal development of an electromagnetic shower for the prototype of the WiZard calorimeter; real data (triangles), MC data (bullets).
Figure 7: Simulated behaviour of GILDA energy resolution as a function of energy for lead fibers (squares), silicon strips (triangles) and total (sum of the two: bullets).

Figure 8: Simulated GILDA energy resolution, compared with EGRET.
Figure 9: GILDA efficiency, before and after the analysis.

Figure 10: Simulated GILDA angular resolution, compared with EGRET.
The Research on Tibet Air Transparency and VHE Cosmic Ray Astronomy

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Abstract:

The level atmospheric transparency of Yangbajing was studied by us for one year with laser and computer, in the same time, we have also researched the vertical atmospheric transparency of Yangbajing using solar radiator, therefore, total date of atmospheric transparency in Yanbajing is presented in each month and govern a academic background further observation of VHE Cosmic Ray Astronomy in Yangbajing.

Key words;
Laser technology; Computer automatic collection date; Air transparency; Solar radiator; VHE Cosmic Ray Astronomy.

1 The level atmospheric transparency date of Yangbajing.
1.1 Experiment method
The experiment method is shown in fig below.

1.2 Weak coefficients

The weak coefficients is defined by formula \( I = I_0 e^{-\alpha L} \), in generally, \( \alpha \) is weak coefficients, \( I_0 \) and \( I \) is emission photon intensity and Collecting intensity, respectively, \( L \) is atmospheric distance.

1.3 Theoretical analysis

Collecting data by Computer is Voltage of PMT and transistor, respectively. Before everytimes detecting, the equipment will be calibrated by us for two hours, therefore the instrument constant will be presented through calibration. After laser through atmosphere, the Voltage of PMT is

\[
V_1 = \eta_1 I_1 = \eta_1 I_0 e^{-\alpha L_1}
\]

the Voltage of transistor is

\[
V_2 = \eta_2 I_2 = \eta_2 I_0 e^{-\alpha L_2}
\]

In order to calculate \( \alpha \), formula (1) is divided formula (2):

\[
\frac{V_1}{V_2} = \frac{\eta_1 I_0 e^{-\alpha L_1}}{\eta_2 I_0 e^{-\alpha L_2}} = Ce^{-\alpha(L_2 - L_1)}
\]

\[
\alpha = \frac{\ln \left( \frac{V_1}{V_2} C \right)}{(L_2 - L_1)}
\]

In formula (3), \( V_1 \) and \( V_2 \) is shown in computer. \( C \) is instrument constant. \( L_1 \) and \( L_2 \) is atmosphere distance, \( \eta_1 \) and \( \eta_2 \) is the transfer coefficient between photon and electron of PMT and transistor, respectively.
1. 4 The level atmospheric transparency of Yangbajing

The experiment results indicate that the level atmospheric transparency in Yangbajing is very large after using method above given to have detected one year.

The average value of months is shown as follows.

<table>
<thead>
<tr>
<th>months</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>weak coefficients</td>
<td>3.5%</td>
<td>5.8%</td>
<td>6.2%</td>
<td>5.8%</td>
<td>5.4%</td>
<td>5.2%</td>
<td>5.2%</td>
<td>5.0%</td>
<td>4.9%</td>
<td>4.5%</td>
<td>4.0%</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

These are weak coefficients that the distance is 2 kms, it is converted the distance which photon intensity is weaked to 1/e, therefore the average value of months is shown as follows:

<table>
<thead>
<tr>
<th>months</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lkm</td>
<td>20</td>
<td>12.5</td>
<td>11.6</td>
<td>12.5</td>
<td>13.1</td>
<td>13.4</td>
<td>13.4</td>
<td>14</td>
<td>14.8</td>
<td>15</td>
<td>17.2</td>
<td>19.2</td>
</tr>
</tbody>
</table>

The same experiment method is adopted in Hefei city of Hanhwei provience in China, the average value of months is shown as follows:

<table>
<thead>
<tr>
<th>months</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lkm</td>
<td>3.5</td>
<td>3.8</td>
<td>3.6</td>
<td>4.2</td>
<td>5.7</td>
<td>5.9</td>
<td>6.0</td>
<td>5.7</td>
<td>5.4</td>
<td>5.3</td>
<td>4.9</td>
<td>3.7</td>
</tr>
</tbody>
</table>

It is obviously that the atmospheric transparency in Yangbajing is much better than Hefei.

1. 5 The night background of Yangbajing

We have also studied the night background of Yangbajing using PMT and High Voltage Power as well as Digital Voltage Monitor for one year, the experiment results in shown as follows:
2 The vertical transparency in Yangbajing

We have detected the vertical transparency in Yangbajing using solar radiator for one month in accordance with Bier law.

In a clear condition, multi-wavelegth solar radiator will be taken at sun for detecting, the Bier law under clear weather conditions is

\[ F(\lambda, z) = F_0(\lambda) \exp[-zt(\lambda)m(z) + \int nId[\lambda, z, A(\lambda), B(\lambda) d\lambda]] \] (4)

In general, \( F(\lambda, z) \) and \( F_0(\lambda) \) is solar radiation flux which solar radiator is collected at distance of zenith \( z \) and outside atmosphere, \( t(\lambda) \) is atmospheric optics depth, \( m(z) \) is atmospheric mass.

If solar radiator has only a small angle of view, for example, the angle of view is \( 1^\circ30' \) or \( 1^\circ \), the formula (4) can be turned into:

\[ F(\lambda, z) = F_0(\lambda) \exp[-zt(\lambda)m(z)] \] \hspace{1cm} (5)

if \( t(\lambda) \) and sensitivity of solar radiator is not chargable during the detecting time, In \( F(\lambda, z) \) and \( m(z) \) is linear relationship.

We use the data of June 15 to July 15 for calculation and the vertical transparency in Yangbajing is 14.9 Kms which photon intensity is weakened to \( \frac{1}{e} \).

3 Conclusion

Detecting VHE Cosmic Gamma-ray at surface of earth is base on atmospheric Cerenkov radiation with EAS atmospheric Cerenkov light producted by VHE gamma photon is similar to the element character of EAS atmospheric Cerenkov light producted by charged—particial which
energy is equite to VHE gamma photon is near VHE gamma photons.

(1). The direction of Cerenkov light elemently maintain the direction of origin particlial and arrive at ground with developing about \(10^4\) m\(^2\) or more scale range; (2). It weak a very litter after through atmospheric layer is seen one kind of arriving the ground EAS throughout componet; (3). The EAS atmospheric Cerenkov light photons density is well-distributed and its intensity is approach direct proportion with origin particle energy; (4). The ascend time of Cerenkov light pulse and sustained time is about 2ns and 10ns, respectively. These character make a possibility to detected VHE cosmic gamma rays at ground, but the energy of atmospheric Cerenkov light is very weak, it is only about lev, furthermore the photons density arriving ground is also 30 photons/m\(^3\), therefore the observatory condition is demanded in a high mountain and atmosphere transparency district in order to remedy a defect of small area; the elevation of Yangbajing is 4310m and the atmospheric transparency is very well enough to carry out studying VHE Cosmic Gamma-rays Physics.

For example, if we take a time from 21:00~6:00 as observatory time, the season of observation Cerenkov light in Yangbajing is shown as follow:

<table>
<thead>
<tr>
<th>Object</th>
<th>Throughout day</th>
<th>Effective time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg x-3</td>
<td>15.99hr</td>
<td>7.27hr/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>middle of June to middle of October</td>
</tr>
<tr>
<td>Her x-1</td>
<td>15.23hr</td>
<td>7.17hr/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>early of April to middle of August</td>
</tr>
<tr>
<td>Crab nebula</td>
<td>13.79hr</td>
<td>6.62hr/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>middle of November to early of March</td>
</tr>
<tr>
<td>Geminga</td>
<td>13.45hr</td>
<td>6.38hr/day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>early of November to middle of March</td>
</tr>
</tbody>
</table>
Throughout day 7.20hr

effective time 0/day

early of October to middle of April

To sum up, the night background and atmospheric transparency as well as the effective time for candidate celestial is very well, therefore we think that the experiment of studying VHE cosmic gamma ray astronomy in Yangbajing will have important academic prospect.

Acknowledgments

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References


Search for Antimatter in Space with a New Type of Permanent Magnet and Precision Spectrometer

The AMS Collaboration

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Abstract

We discuss a simple magnetic spectrometer to be installed on a satellite or space station. The purpose of this spectrometer is to search for primordial antimatter to the level of antimatter/matter $\sim 10^{-9}$, improving the existing limits obtained with balloon flights by a factor of $10^4$ to $10^5$. The design of the spectrometer is based on an iron-free, Nd-Fe-B permanent magnet, scintillation counters, drift tubes, silicon or Time Projection Chambers. Different design options are discussed. Typically, the spectrometer has a weight of two tons and an acceptance of $1 \text{ m}^2 \text{sr}$. The availability of the new Nd-Fe-B material makes it possible for the first time to put a magnet into space economically and reliably.
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Introduction

The existence of antimatter was first proposed by P.A.M. Dirac in the early 1930's(1) from simple relativistic quantum mechanical considerations. It was clear from Dirac's argument that all the particles in the world should also have corresponding anti-particles as he stated in the conclusion of his Nobel Lecture: "If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods".

Following the discovery of positrons by Carl D. Anderson (2) and antiprotons by Owen Chamberlain and Emilio Segre (3), we now know that every elementary particle has its anti-particle, every quark has its anti-quark and in accelerator, anti-protons and anti-neutrons indeed form anti-deuterons(4).

According to the current understanding of the Big Bang, at the very beginning of the universe there should have been the same amount of matter and antimatter. It is indeed a great mystery that antimatter such as anti-helium and anti-carbon have not been observed in space. There are now theoretical speculations based on baryon number non-conservation and/or breakdown of time reversal invariance (5) to explain the absence of antimatter. It is important to note that the observed magnitude of breakdown of time reversal invariance and the upper limit of the baryon number non-conservation cannot explain the observed upper limit of absence of antimatter in space. In the last four decades, there have been many discoveries in astro particle physics with satellites and telescopes and ground based antennas(6) (7) (8). There has never been an experiment with a magnet in space and therefore our experimental knowledge of antimatter is exceedingly limited.

(1) P.A.M. Dirac "Theory of electrons and positrons", Nobel Lecture, Dec.12, 1933.
(6) See for example the Nobel Lecture in 1974 by Ryle, Sir Martin and A. Hewish on pulsars.
(7) A.A. Penzias and R. W. Wilson, Nobel Lecture 1978 on cosmic microwave background radiations.
Several balloon experiments and one satellite experiment\(^{(9)}\) have shown that the upper limit of antimatter to matter ratio is currently at the level of \( \sim 10^{-4} \) as shown in Fig.1.

Fig.1 Current status of searches for antimatter in the cosmic rays

The construction of the B factory to understand time reversal is an indirect approach to trace the absence of antimatter and in the past there have been efforts to put in space superconducting magnets \(^{(10)}\) as well as a small permanent magnet \(^{(11)}\). A more fundamental approach is to directly search for the amount of antimatter in galaxies with a large sensitive magnetic spectrometer in space.

With the recent rapid advancement of permanent magnet technologies and the abundance of high quality permanent magnet material (Nd-Fe-B) as well as the development of precision instrumentation in high energy physics, we present here a simple spectrometer in space, with a large permanent magnet to search for antimatter in the universe down to the level of antimatter-matter ratio of \( \sim 10^{-10} \) i.e. a factor \( 10^4 \) to \( 10^5 \) improvement over earlier efforts.


\(^{(11)}\) P. Spillantini and others "Russian-Italian Mission Program in Astroparticle physics " November 1993.
Chapter 1 Permanent Magnet for Astrophysics Research

A) Introduction

The presence of high energy product magnet materials (Nd-Fe-B is the representative) makes possible the replacement of direct-current exciting magnetic fields by permanent magnetic fields (12). In certain cases such as MRI-CT where superconducting magnets were traditionally used, permanent magnets could also be used in low field strength range. Neither power supply nor cooling system are necessary for the working of the permanent magnet. The structure of the permanent magnet is compact and rigid and its operation convenient. No maintenance is necessary in most cases.

Both theoretical and applied researches on permanent magnet have greatly progressed since the eighties. This can be shown by the following:

1. By using the permanent magnetic materials now available, it is possible to design a magnet with a field strength as high as 4T in a disk-shaped cavity of 2.5 cm diameter. Moreover, with the aid of mechanical drive, the magnetic flux density in the working space can be continuously adjusted from 0 to 4.0T if necessary.

2. It is possible to construct a magnet for the MRI-CT with large working space and very high homogeneity (see Fig.2).

3. It is possible to construct magnets with complicated shapes such as helical magnets (Fig.3).

4. It is possible to design magnets without using any iron material and with very low leakage flux outside the working space as well as low gross weight.

(12) Zhou Rongzhong, Xia Pingchou, "A permanent magnet for MRI-CT, Proceedings of Beijing International Symposium, October 19-21, 1988, Beijing China
- Klaus Halbach "Strong rare earth cobalt quadrupoles" IEEE production on nuclear science, Vol.NS-26, No.3, June 1979
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- E. Potenziani, J.P. Clarke, H.A. Leupold "The production of laminar fields with permanent magnets" J Appl. Phys. 61 (8), 15 April 1987
Fig. 2: Second generation of permanent magnet for MRI-CT built by the Institute of Electrical Engineering, C.A.S., China. Field strength: 0.3T, bore: 46.85 cm, homogeneity of magnetic field within a sphere of 30 cm diameter: ±20 ppm, gross weight: 9.6 t made with Nd-Fe-B (completed in February 1994).

<table>
<thead>
<tr>
<th>Bases</th>
<th>Ideal structure</th>
<th>Actual structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>d</td>
<td>g</td>
</tr>
<tr>
<td>b</td>
<td>e</td>
<td>h</td>
</tr>
<tr>
<td>c</td>
<td>f</td>
<td>i</td>
</tr>
</tbody>
</table>

Fig. 3 (a, b, c) Three-twister structure bases; (d, e, f) respective ideal twister structures; (g, h, i) respected approximations to the ideals. The heavy arrows show the magnetic field direction in the working space. The small arrows show the constituent magnet orientations.
Such progress with respect to permanent magnetic material and magnet technology described above indicates that it is now time to consider the application of a permanent magnet on a space station or satellite.

Reference (10) presents the design of the Astromag which was proposed for use on a space station and had a superconducting magnet at its core. The structure of the superconducting magnet is very complicated and its operation is not convenient. As for its construction, the size of the coil is rather large and the coil needs rigid support. The magnet has to be equipped with a power supply in space. Dewar and cryogenic equipment are also needed to maintain the low temperature required by the coils. The annual loss of energy stored in the magnet must be kept very low so as to ensure long term effective working conditions. At any fault of the magnet, it is necessary to quench it promptly. The power supply and cryogenic equipment must be launched by a rocket into space together with the magnet.

In comparison with the superconducting magnet, the permanent magnet has many advantages. Its structure is compact and rigid and neither Dewar nor power supply or cryogenic equipment are necessary. Provided that the magnet structure can endure the vibration during the launching period, and that the environment temperature can be kept suitable, the magnet can work indefinitely.

To design a large acceptance (-m²sr) permanent magnet with strong analysing power (BL² = 0.15Tm²) for antimatter study in space, we must make the following considerations:

a) The magnet will be launched into space and hence its weight must be as low as possible.

b) To avoid the yaw and pitch caused by the interaction of the magnet with the earth magnetic field, or in other words to ease the burden of the satellite altitude control system, there should be compensating facilities on the magnet so that the overall magnetic dipole moment of the magnet is minimum.

We present here the principles for the above mentioned magnet design:

1. An iron-free structure to reduce the weight.
2. Except at the two ends, the magnet should have minimum leakage flux.
3. A uniform field.

The specific weight of iron is rather large and iron is not a flux source itself. With an iron-free structure, the effective parts of the magnet consist totally of Nd-Fe-B, which has a specific weight of 7.4t/m³ and is the flux source itself. This reduces the gross weight of the magnet. The design of the magnet with roughly no leakage flux will raise the utilisation factor of the magnetic material and a uniform field in the working space can make full use of the working space. All of these will reduce the weight of the magnet further. Hence, it is a reasonable approach to design the magnet according to the three principles stated above.
The magnetic dipole moment of the magnet must be very small. This is especially true for a magnet working on satellite.

B) Iron-free Magnet Structure

The commonly known structures of iron-free hollow cylindrical dipole magnets are of three types (Fig.4).

![Fig.4 Iron-free hollow dipole magnet](image)

Among them, (a) is less commonly used, (c) is most famous and is called "magic ring". In practical applications, it is usually designed in the following shape (Fig.5).

![Fig.5 : Practical structure of "magic ring"](image)

(b) is called yokeless magnet of square cross-section and its magnet structure form has many prospects for practical applications. For the purpose of our design, both (b) and (c) of Fig.4 may be our choice of magnet structure. Both of them satisfy the basic three design principles. We present these two designs below:
1. Magic Ring

The 'magic ring' is a Hollow Cylindrical Flux Source (HCFS). An HCFS is a cylindrical permanent magnet shell with its magnetization vector constant in magnitude and oriented according to the formula:

\[ \alpha = 2\phi + \pi / 2 \]

where \( \phi \) is the angular cylindrical coordinate. Such a distribution gives an interior field of:

\[ B = B_r \ell n \left( r_2 / r_1 \right) \]

where \( B_r \) is the residual magnetic flux density of the ring and \( r_1 \) and \( r_2 \) are its inner and outer radius respectively. The figure below shows the field distribution at the cross-section of the center of the magnet (Fig.6).

Fig.6  Magnetic field distribution at cross-section of center of the magnet

In practice, it is not possible to make it vary continuously, so its value is made to change abruptly by \( 4\pi / N \) between adjacent wedge-shaped sections of equal size and uniform magnetization. \( N \) is the number of such segments into which the ring is divided.
The field suffers surprisingly little from the approximation by segmentation. For example, if the ring is divided into 16 segments, it still produces a magnetic field of over 97% of that produced by a continuous ring. The figure below shows the field distribution at the center of the magnet, when the magnet is composed of 8 segments (see Fig.7).

Fig.7  Field distribution at the cross-section of the center of 'magic ring' with 8 segments

Below are the parameters of the 16 segment 'magic ring' which are to be used in our proposed magnet:

- **Window area**: \( s = 0.5 \text{m}^2 \)
- **Inner radius**: \( r_1 = 0.399 \text{m} \)
- **Length of magnet \( L \)**: \( : \quad B L^2 > 0.15 \text{Tm}^2, \quad : \quad L = \sqrt{0.15/B} \)
- **Weight of magnet (effective part)**: \( W = 7.4 \times \pi (r_2^2 - r_1^2) \times L \)
- **Angle view**: \( 2 \tan^{-1} r_1/L \)
- **Residual magnetic field of permanent magnet material**: \( B_r = 1.3 \text{T} \)
Table 1 shows the relation of flux density versus weight (1)

<table>
<thead>
<tr>
<th>Flux density B T</th>
<th>Inner radius r1 m</th>
<th>Outer radius r2 m</th>
<th>Length L m</th>
<th>Weight W t</th>
<th>Acceptance m²sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0343</td>
<td>0.399</td>
<td>0.41</td>
<td>2.09</td>
<td>0.433</td>
<td>0.054</td>
</tr>
<tr>
<td>0.0647</td>
<td>0.399</td>
<td>0.42</td>
<td>1.52</td>
<td>0.607</td>
<td>0.099</td>
</tr>
<tr>
<td>0.0943</td>
<td>0.399</td>
<td>0.43</td>
<td>1.26</td>
<td>0.755</td>
<td>0.14</td>
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<tr>
<td>0.123</td>
<td>0.399</td>
<td>0.44</td>
<td>1.1</td>
<td>0.879</td>
<td>0.18</td>
</tr>
<tr>
<td>0.151</td>
<td>0.399</td>
<td>0.45</td>
<td>0.99</td>
<td>0.996</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 1: Relation of flux density vs. weight and acceptance
When the window area of the magnet is changed to 1m², the corresponding data are shown below (Table 2).

<table>
<thead>
<tr>
<th>Flux density B T</th>
<th>Inner radius r1 m</th>
<th>Outer radius r2 m</th>
<th>Length L m</th>
<th>Weight W t</th>
<th>Acceptance m²sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0134</td>
<td>0.564</td>
<td>0.57</td>
<td>3.35</td>
<td>0.53</td>
<td>0.084</td>
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<tr>
<td>0.0353</td>
<td>0.564</td>
<td>0.58</td>
<td>2.06</td>
<td>0.876</td>
<td>0.21</td>
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<tr>
<td>0.0568</td>
<td>0.564</td>
<td>0.59</td>
<td>1.63</td>
<td>1.137</td>
<td>0.33</td>
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<tr>
<td>0.0800</td>
<td>0.564</td>
<td>0.60</td>
<td>1.37</td>
<td>1.334</td>
<td>0.44</td>
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<tr>
<td>0.0989</td>
<td>0.564</td>
<td>0.61</td>
<td>1.23</td>
<td>1.544</td>
<td>0.53</td>
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<tr>
<td>0.119</td>
<td>0.564</td>
<td>0.62</td>
<td>1.12</td>
<td>1.726</td>
<td>0.61</td>
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<td>0.140</td>
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<td>0.63</td>
<td>1.04</td>
<td>1.905</td>
<td>0.69</td>
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<tr>
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<td>0.635</td>
<td>1.09</td>
<td>1.978</td>
<td>0.73</td>
</tr>
<tr>
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<td>0.564</td>
<td>0.64</td>
<td>0.9</td>
<td>2.063</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 2: Relation of flux density vs. weight and acceptance
From Tables 1 and 2 one can see that with the window area kept constant and under the same constraint of $BL^2 = 0.15 \text{ Tm}^2$, the choice of a smaller B and a longer length L can considerably reduce the weight of the magnet. But this will obviously reduce the acceptance.

Comparing Table 1 and 2, one can see that with the same values of B, the weight of the two magnets with smaller window area is approximately equivalent to the weight of one magnet with larger window area. But the acceptance of a large magnet is much larger than that of two smaller magnets together.
2. Yokeless magnet with square cross-section

This is another type of iron-free structure of magnet. (see Fig. 8)

When the inner hollow is a square in shape and satisfies the condition

\[ b = \left( \sqrt{2} - 1 \right) / 2 \times a \]

there is no flux outside the magnet and the flux density within the working space of the magnet is homogeneous, the value is:

\[ B = B_r \left( \sqrt{2} - 1 \right) / \sqrt{2} = 0.2929 B_r \]

where \( B_r \) is the residual magnetic flux density of the permanent magnetic material.

The magnetic field distribution is shown below:

Assuming \( B_r = 1.3 \text{T} \), then \( B = 0.38 \text{T} \), to fulfill the condition of \( BL^2 = 0.15 \text{Tm}^2 \), \( L \) will be 0.628m. If we assume a window area of 0.5m², then the weight of the effective part of the magnet will be 2.32t. If the window area is 1m², then the weight will be 4.65t.
It is obvious that the magnet is too heavy. The trial calculation shows that with the prerequisite to fulfill the constraint of $BL^2 = 0.15Tm^2$, the decrease of $B$ will reduce the weight of the magnet even though $L$ will increase.

Under this condition, the relation of $b = \left(\sqrt{2} - 1\right)/2 \times a$ will not be maintained, i.e. $b$ will be greatly reduced and very small flux will leak outside the magnet. But the effect is negligible.

There is no simple or obvious analytical relation between the flux density in the working space and the dimension of the magnet. In this case, the field distributions at three different values of $b$ with window area of $0.5m^2$ and $1m^2$ respectively are obtained by numerical calculation then the length $L$ and the weight of the effective part of the magnet are calculated, satisfying the equation $BL^2 = 0.15Tm^2$. The results are listed below:

<table>
<thead>
<tr>
<th>Window area 0.5m²</th>
<th>Thickness of magnet wall</th>
<th>Flux density B (G)</th>
<th>Length of magnet L (cm)</th>
<th>Weight of magnet W (kg)</th>
<th>Acceptance $\Omega (m^2sr)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$ (cm)</td>
<td>$L_2$ (cm)</td>
<td>$d_1$ (cm)</td>
<td>$d_2$ (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100.0</td>
<td>50.0</td>
<td>1.0</td>
<td>1.0</td>
<td>310</td>
<td>220</td>
</tr>
<tr>
<td>100.0</td>
<td>50.0</td>
<td>3.0</td>
<td>3.0</td>
<td>905</td>
<td>129</td>
</tr>
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<td>100.0</td>
<td>50.0</td>
<td>3.5</td>
<td>3.5</td>
<td>1049</td>
<td>120</td>
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<tr>
<td>100.0</td>
<td>50.0</td>
<td>5.0</td>
<td>5.0</td>
<td>1470</td>
<td>101</td>
</tr>
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<td>2.5</td>
<td>961</td>
<td>125</td>
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<td>90.9</td>
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<td>94.5</td>
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<tr>
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<td>70.7</td>
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<td>1.0</td>
<td>310</td>
<td>229</td>
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Table 3a: Relation of flux density, weight and acceptance of the magnet with window area of 0.5m².
<table>
<thead>
<tr>
<th>Window area</th>
<th>Thickness of magnet wall</th>
<th>Flux density</th>
<th>Length of magnet</th>
<th>Weight of magnet</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L₁ (cm)</td>
<td>L₂ (cm)</td>
<td>d₁ (cm)</td>
<td>d₂ (cm)</td>
<td>B (G)</td>
<td>L (cm)</td>
</tr>
<tr>
<td>100.0</td>
<td>100.0</td>
<td>8.0</td>
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<td>1687</td>
<td>94.3</td>
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<td>3.5</td>
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<td>3.5</td>
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<td>141</td>
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<td>650</td>
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<td>110</td>
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<td>6.0</td>
<td>4.5</td>
<td>1335</td>
<td>106</td>
</tr>
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<td>85.0</td>
<td>6.5</td>
<td>4.0</td>
<td>1267</td>
<td>109</td>
</tr>
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<td>85.0</td>
<td>7.0</td>
<td>5.0</td>
<td>1435</td>
<td>112</td>
</tr>
<tr>
<td>118.8</td>
<td>85.0</td>
<td>6.5</td>
<td>4.5</td>
<td>1352</td>
<td>105</td>
</tr>
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<td>5.0</td>
<td>1599</td>
<td>96.8</td>
</tr>
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<td>9.5</td>
<td>4.0</td>
<td>1825</td>
<td>90.6</td>
</tr>
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<td>4.0</td>
<td>1713</td>
<td>93.6</td>
</tr>
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<td>4.0</td>
<td>1680</td>
<td>94.5</td>
</tr>
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<td>9.0</td>
<td>4.2</td>
<td>1751</td>
<td>92.6</td>
</tr>
<tr>
<td>118.8</td>
<td>85.0</td>
<td>9.0</td>
<td>5.0</td>
<td>1775</td>
<td>91.9</td>
</tr>
</tbody>
</table>

Table 3b: Relation of flux density, weight and acceptance of the magnet with window area of 1.0 m²

C) Magnetic Dipole Moment

The magnetic dipole moment usually belongs to a single magnet regardless of which one is adopted, whether 'magic ring' or yokeless magnet. From the point of view of qualitative analysis, one can see from Fig.6 that the magnetic field in the 'magic ring' is similar to the field produced by the current rings.

The yokeless magnet can be treated in the same way at the qualitative analysis stage. Thus a pair of magnets shown in (a) of Fig.10 can be treated in a similar way as a pair of coils shown in (b) of Fig.10 when the magnetic dipole moment produced by the magnet is qualitatively analyzed. This is the same as for the arrangement of two superconducting coils in Astromag, hence the net magnetic dipole moment will be very small.

Fig.10: Dipole moment of parallel magnet pair with reverse polarities
From physical requirements, two magnets can be overlapped on each other. Then, the situation would be shown in Fig.11:

**Fig.11 :** Dipole moment of overlapped magnets with reverse polarities

The arrangement shown in Fig.11 has a large quadrupole moment; this will make the altitude control of a satellite more difficult.

In case of a single magnet working in space, its dipole moment needs specific compensation. Theoretically, it is possible to construct a compensation system made of Nd-Fe-B near the single magnet so as to compensate the dipole moment of the magnet (see Fig.12). But this requires a total of about 300 kg of Nd-Fe-B.

**Fig.12 :** Schematic to eliminate the dipole moment of the permanent magnet

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D) **Structure Problems**

The mechanical parameters of Nd-Fe-B material are shown below in Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.3 - 7.5 g/cm³</td>
</tr>
<tr>
<td>Viker's hardness</td>
<td>530</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>80 kg/mm²</td>
</tr>
<tr>
<td></td>
<td>(for gray cast iron 40-110 kg/mm²)</td>
</tr>
<tr>
<td>Bending strength</td>
<td>24 kg/mm²</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>$1.7 \times 10^4$ kg/mm²</td>
</tr>
<tr>
<td></td>
<td>(for cast steel $1.75 \times 10^4$ kg/mm²)</td>
</tr>
</tbody>
</table>

Table 4: Mechanical parameters of Nd-Fe-B material

One can see from the above table that the mechanical performances of Nd-Fe-B are roughly equivalent to that of cast iron and cast steel; its compressive strength especially is quite satisfactory. As for the design of the magnet structure, it is possible to subject all the Nd-Fe-B parts composing the magnet to a compressive state both at normal operation or at the rocket launching period, while the compressive stress would not exceed the safety limit. A high strength aluminium alloy is used as structural material so as to reduce its weight. Fig.13 shows a possible structure of magnet.

![Fig.13 : Structure of magnet](image_url)

Up to now, there exists electric motors made of Nd-Fe-B material which have been launched into space with rockets and are working reliably there. The structure design is
essentially the weight design. It must be optimized so as to achieve structural elements with a minimum weight while still ensuring a rigid and stable structure.

Conclusion

The permanent magnet is simpler than the superconducting magnet with regard to its structure and operation and it is possible to use a permanent magnet rather than a superconducting magnet. The weight of a permanent magnet, compared to that of a superconducting magnet, while adding the weight of cryogenic and power supply systems, is nearly the same.
Chapter 2  An Antimatter Spectrometer

A)  Design considerations

To search for antimatter in space with a sensitivity of $10^4$ to $10^5$ better than the current limits, the following must be taken into consideration:

1. Large acceptance and strong analyzing power:
   The magnet must have a large acceptance (≈1.0 m$^2$sr) and strong analyzing power ($BL^2 = 0.15$ Tm$^2$).

2. Minimum magnetic flux leakage and magnetic dipole:
   The magnetic flux leakage must be minimized and the magnetic dipole must be $-0$.
   After detailed studies, we have selected the following magnet configurations as candidates for the spectrometer:
   
   a) Two identical magnets with opposite field as shown in Fig.14a. This design provides a minimum combined weight of 1.934t and has the important advantage of a nearly zero magnetic dipole moment. It has the additional important advantage that, in case of failure of an instrument in one of the magnets, the other magnetic spectrometer can still function independently. The combined acceptance is: $0.45$ m$^2$sr.

![Diagram of two magnets with opposite fields and dimensions](image)

**Total weight = 1.934 t**

*Fig.14a:* Two identical magnets with opposite field and large acceptance
b) Two magnets, one on top of the other, as shown in Fig.14b. This system has a large analyzing power of $BL^2 = 0.6Tm^2$, a solid angle of $0.07m^2sr$ and weight of 1.934 t. For comparison, the proposed LISA detector on the superconducting magnet Astromag has an acceptance of $0.031 m^2sr$. The weight of the magnet is 2.4t and average $BL^2 = 1Tm^2$.

![Diagram of two magnets](image)

**Total weight = 1.934 t**

**Fig.14b**: Two magnets on top of one another, with large $BL^2$ arrangement

c) One permanent magnet with two small correcting permanent magnets mounted on both sides of the magnet as shown in Fig.15. The distance between the small permanent magnet and the main magnet is adjustable to ensure the dipole moment $I \times A = 0$. This arrangement has the advantage of a rather large acceptance of $0.8 m^2sr$. 362
3. Background considerations:

There are two sources of backgrounds. The first one is downward atomic nuclei which will enter into the detector with a yield shown in Table 5.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Yield (10^10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>10^10</td>
</tr>
<tr>
<td>C</td>
<td>2 x 10^8</td>
</tr>
<tr>
<td>Al</td>
<td>0.5 x 10^7</td>
</tr>
<tr>
<td>Fe</td>
<td>0.7 x 10^7</td>
</tr>
</tbody>
</table>

Table 5: Yield of nuclei in 1 m^2sr in 3 years at kinetic energy > 0.5 GeV/Nuclear in the polar orbit.

As seen from Table 5, there are 10^{10} helium entering into the spectrometer. Therefore a 10^5 improvement in our current limit implies that we need to reach an antimatter rejection of 10^{-10} or smaller.

The second source of backgrounds is upward moving nuclei due to the earth magnetic field. The amount of upward moving particles has recently been measured on the PBAR and SMILII balloon experiments (13) as shown in Fig.16.

Fig. 16: Relative numbers of upward moving and downward moving cosmic ray particles for two balloon flight in Northern Canada at 40 km altitude

Since an upward carbon nuclei passing through a magnetic spectrometer will have the same trajectory as a downward moving anti-carbon nuclei, this upward moving background must be rejected with the ratio \( \geq 10^{10} \).

4) Past experience:

To design a spectrometer with an \( \frac{\text{antimatter}}{\text{matter}} \) rejection of \( 10^{-10} \), it is worthwhile to recall the history in the discovery of anti-deuterons in 1965 \(^4\). The spectrometer is reproduced in Fig. 17. The most important feature which enables this spectrometer to reach a rejection of \( \frac{D^-}{\pi^-} = 10^{-10} \) is that the negative particles were repeatedly measured with counters \( S_1 \ldots S_{10} \) so that large angle nuclear scattering from any of the counters would be swept away and would not follow the trajectory defined by the 10 counters. In addition, the anti-counters \( A_1 \ldots A_3 \) kept the beam clean from scattering of particles off the face of the magnet. This arrangement enabled one to make many independent time of flight measurements to determine the velocity of the negative particles. An independent measurement of velocity was also proposed with a Fitch counter. The
information of the momentum and velocity determined the mass of anti-deuterons. Fig.18 shows the correlation of time of flight spectrum between two sets of counters.


Fig.18 : Correlation of time of flight spectrum between two sets of counters
At \( p = 5 \) GeV/c, the \( \frac{D^-}{\pi^-} = (2.0 \pm 0.5) \times 10^{-8} \) based on 21 events is shown in Fig.18.

Similarly at 9.0 GeV/c, the yield is \( (1\pm1) \times 10^{-10} \).

B) The antimatter spectrometer

Fig.19 is the design of the antimatter spectrometer based on the above considerations. The magnet can be either the two-magnet options shown in Fig.14a and Fig.14b or the one-magnet option (with two additional compensating permanent magnets) shown in Fig.15. The spectrometer has the following unique properties:

1) The magnet system will weigh \( = 2 \) t.
2) The thin drift tubes DT will measure the incident and exit angles of nuclei and thus determine the ratio \( P \) (momentum) / \( Q \) (charge).
3) The magnetic volume is filled with a Time Projection Chamber (TPC) with extremely thin gas of \( \text{Ne : CH}_4 = 80:20 \) and with a radiation length of 381 m. The TPC will provide 100 measurements of the trajectory in the magnetic field and 100 measurements of \( \frac{dE}{dx} \). Thus the TPC will provide an independent measurement of \( P/Q \) and the measurement of \( |Q| \).

Following a 20 years' investigation of wire chamber systems by U. Becker et al. \(^{(14)}\) including the development of high-rate multi-wire proportional chambers, the invention of straw tubes, the development of large area drift chambers and the development of extra-high precision large area drift chambers, we are investigating the most suitable gas for this TPC - including the possible use of \( \text{He : CH}_4 = 80:20 \) which is extremelly light and has a radiation length of 2178m.

4) The scintillators (Si) will provide time of flight measurements and yet another independent measurement of \( |Q| \) by pulse height.

---

- U. Becker et al., "Gain and sparkproofness of drift chamber gases" MIT-LNS report #181.
5) The veto counters Ai will reject sprays from neutrons and protons on the magnet which produce secondary particles and thus confuse the time of flight measurements.

![Diagram of the antimatter spectrometer](image)

- **P**: permanent magnets and supporting structure
- **DT**: Thin drift tubes
- **TPC**: Time projection chamber, 100 measurements of $\frac{dE}{dx}$ (charge) and coordinates
- **Si**: scintillators for time of flight and $\frac{dE}{dx}$ (charge)
- **Ai**: veto scintillators

Fig.19: Side view of the antimatter spectrometer

The principle of this system is very similar to the 1965 anti-deuteron spectrometer but with much more redundancy.

The TPC used in this spectrometer will operate in a low field of ~2 kG. Fig.20 illustrates the measurement principles of the TPC and Fig.21 shows the schematics of the design of the Multi-Wire Proportional Chambers (MWPC) with pads measuring x direction with an accuracy of 125µm and sense wires measuring the y coordinates (150µm) and $\frac{dE}{dx}$. The z coordinate (400µm) will be measured by drift time $z = V_D \times t$ from the sense wires. Also shown in Fig.21 is the design of a field cage.
Fig. 20: TPC measurement principle

- X measures $p_\perp$ by interpolating pads
- Y by wire #
- Z by drift time $z = V_0 \cdot t$
MPWC \((x, y)\)

- Gating grid
- Potential grid
- Sense/Field wires
- Pads on G10

Pads measure: \(x\) by charge distribution
Sense wires: \(y\), and \(dE/dx\)
Field wires: decouple, calibration

**Field cage**

- .5 mm Al
- Al honeycomb 12 mm
- .5 mm Al
- 2 mm Mylar
- .75 mm Kapton
- \(2 \times 30 \mu m\) Cu
- electrodes
- Drift Region

Fig. 21: Schematic for the MPWC and field cage design

Alternatively, we can fill the magnet with a special precision muon chamber which provides a 140\(\mu m\) accuracy. The wires are made out of 30\(\mu m\) W-Ru. There will be a total of \(\sim 1000\) wires grouped into 10 rows and thus each track will be measured 110 times.

In Table 6, we present the scintillation counter sizes for both one-magnet and two-magnet options. Table 7 summarizes the power consumption for the two options.

<table>
<thead>
<tr>
<th>Counter</th>
<th>Size cm(^2)</th>
<th>Counters</th>
<th>PMT's</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veto</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>100 x 94</td>
<td>8</td>
<td>64</td>
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<tr>
<td>A2</td>
<td>120 x 128</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>TOF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1 = S4</td>
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<td>96</td>
</tr>
<tr>
<td>S1' = S4'</td>
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<tr>
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**Table 6(a):** Scintillation counters: one-magnet option

369
<table>
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<tr>
<th>Counter</th>
<th>Size cm²</th>
<th>Counters</th>
<th>PMT's</th>
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</thead>
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<tr>
<td>A1</td>
<td>(60, 82) x 94</td>
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</tr>
<tr>
<td>A2</td>
<td>(75, 102) x 128</td>
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<td>112</td>
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<tr>
<td>TOF:</td>
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<td></td>
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<td>14 x (75, 102)</td>
<td>32</td>
<td>128</td>
</tr>
<tr>
<td>S2 = S3</td>
<td>82 x 58</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>80</td>
<td>444</td>
</tr>
</tbody>
</table>

Table 6 (b): Scintillation counters: two-magnet option

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Channels</th>
<th>Power per channel</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One-magnet</td>
<td>Two-magnets</td>
<td></td>
</tr>
<tr>
<td>Scint-PMT's</td>
<td>384</td>
<td>444</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100mW/PMT + 400W / readout channel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drift Tubes</td>
<td>6212</td>
<td>9680</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3mW/preamp + 27mW/TDC</td>
<td>186W</td>
<td></td>
</tr>
<tr>
<td>TPC pads</td>
<td>11,700</td>
<td>19,500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3mW/preamp + 0.1x20mW/ADC</td>
<td>59W</td>
<td></td>
</tr>
<tr>
<td>TPC wires</td>
<td>75</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3mW/preamp + 47mW / TDC +ADC</td>
<td>4W</td>
<td></td>
</tr>
<tr>
<td>TPC HV</td>
<td>5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>TPC gas</td>
<td>50</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Upper level processing</td>
<td>50 W</td>
<td>100 W</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>546 W</td>
<td>827 W</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Power consumption
Chapter 3 Spectrometer Performance

In this chapter, we present the performances of the proposed spectrometer. These performances are valid for both the one-magnet and the two-magnet designs.

A) Momentum resolution

We present here the expected momentum resolution of the TPC for a nucleon with a momentum of 10 GeV/c.

Coordinate resolution:

\[
\sigma_x = \frac{300\mu}{\sqrt{6}} = 125\mu, \quad \mu (\text{particle})
\]
\[
\sigma_y = 50\mu, \quad \sigma_z = 400\mu, \quad \mu (\text{particle})
\]

Momentum resolution:

\[
\frac{\Delta p_T}{p_T} = \sqrt{\frac{720}{(N-2)N(N+1)(N+2)}} \frac{\sigma_T}{L^2} \frac{10 \text{ GeV}}{QP}
\]

\[
\frac{\Delta p_T}{p_T} = 7.4\% \text{ at } 10 \text{ GeV/c}
\]

N is Number of measurements; L is Length of measurements

B) Rejection of accidentals

Fig. 22 illustrates the various accidentals (protons and neutrons) that may enter into the spectrometer through the side of the magnet and produce secondary particles (neutrons and protons) which may cause confusion in the time of flight signals in the scintillator (S1...S4).

We present here the calculation of the rejection of accidentals in Table 8.

<table>
<thead>
<tr>
<th>Rejection of accidentals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Anti-counter A1 rejects charged particles</td>
</tr>
<tr>
<td>2) Anti-counter A2 rejects charged particles produced in the magnet by neutral particles</td>
</tr>
<tr>
<td>3) Upward carbon will be rejected from time of flight difference between S1-S4 (anti carbon) and S4-S1 (carbon) of 10ns at 10 GeV/nucleon</td>
</tr>
<tr>
<td>a) Albedo probability &lt; 10^{-3}</td>
</tr>
<tr>
<td>b) Probability of accidental in 10 ns = 10,000 protons x 10 ns = 10^{-4}</td>
</tr>
<tr>
<td>c) Probability of not detecting accidental = fraction of detector as &quot;cracks&quot; &lt; 10^{-5}</td>
</tr>
</tbody>
</table>

Background < 10^{-3} \times 10^{-4} \times 10^{-5} = 10^{-12}

Table 8: Rejection of accidentals
C) Rejection of Albedo

The earth magnetic field sweeps nuclei upward into the magnetic spectrometer. Upward carbon nuclei have the same trajectory as downward anti-nuclei and this albedo must be rejected. Fig.23 illustrates this situation and Table 9 presents our estimates of the rejection power of albedo carbon.

<table>
<thead>
<tr>
<th>Rejection of Albedo carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Albedo fraction is $&lt; 10^{-3}$</td>
</tr>
<tr>
<td>2) One pair of scintillators : Probability of mistaking &quot;up&quot; for &quot;down&quot; = $10^{-5}$</td>
</tr>
<tr>
<td>3) Two pairs of scintillators : Probability of mistaking &quot;up&quot; for &quot;down&quot; = $10^{-10}$</td>
</tr>
</tbody>
</table>

Background $< 10^{-13}$

Table 9 : Rejection of Albedo carbon
The most important background comes from large angle single scattering illustrated in Fig.24 where carbon nuclei entering into the spectrometer and scattering with gas in the TPC at point Z with a sufficiently large angle make it appear as a trajectory of anti-carbon. Table 10 presents the principle of rejection of large angle single scattering.

### Rejection of large angle single scattering

1. By DT measuring incident and exit angles
2. By matching tracks L1 with L2 with a total of 100 measurements requiring L1 and L2 to form a continuous curve in both bending and non-bending planes
3. By requiring the momentum (P1) to determine from L1 and L2 (P2) to be equal
4. By detecting nuclear knock-outs (n)

Monte-Carlo results: \[
\frac{\text{anticarbon}}{\text{carbon}} = 10^{-10}
\]

Table 10: Rejection of large angle single scattering
The studies were carried out with full GEANT detector simulation and full event reconstruction. The cosmic ray carbon spectrum was used to simulate the particle source. We generated the events with the kinetic energy from 1 GeV/amu to 100 GeV/amu. The tracking resolution is assumed to be 125µm per wire with a total of 100 wires. The non-bending plane tracking is done using thin-wall drift tube chambers located on the top and bottom of the magnet with 150 µm resolution per wire and with the TPC. These chambers will measure 28(top) + 28(bottom) points of the trajectory coordinate in non-bending plane in addition to 100 measurements in the TPC.

Based on experience with anti-proton search experiment (15), we used a $\chi^2$ variable to control the fitting quality. $\chi^2$ is defined as:

$$\chi^2 = \frac{\sum_i (\text{fitting residual}^2)_i}{N_{\text{total}} - M_{\text{parameter}}}$$

where $N_{\text{total}}$ is the number of measured data points and $M_{\text{parameter}}$ is the number of fitting parameters.

We also require that the bending sign redundancy be determined by fitting the tracks using the first \((L_1\) of Fig.24) and the second part of the chamber \((L_2\) of Fig.24). We require that the bending direction must be consistent with the global fitting and the top-chamber region and bottom-chamber region fittings. The following cuts have been used to reject the background:

1. Rigidity < 25 GeV/c, which corresponds to the kinetic energy of 11.5 GeV/amu for a carbon (rigidity is defined as momentum/charge, \(P/Q\), where \(P\) is determined from fitting, and \(Q\) is determined by the scintillator pulse height).
2. \(\chi^2\) of the global momentum fitting < 2.5.
3. Global fitting consistency with the top- and bottom-chamber separate fittings.

In addition, the nuclear knock outs \((n\) in Fig.24) will be detected and our Monte-Carlo results show that we obtain \(\frac{\text{anti-carbon}}{\text{carbon}} = 10^{-10}\).
Chapter 4  Silicon antimatter spectrometer in space

Following the discussions in Chapters 1, 2 and 3, it is obvious that gas detectors in the magnet are not the only choice. Gas detectors have the advantages of having few channels and minimum multi-scattering. Excellent results can also be obtained with other detectors, in particular with high precision double sided silicon microstrip detectors, widely used in tracking applications.

Following many years of R&D by R. Battiston et al.,(16) including the development of 35 cm long, self-supporting double sided silicon ladders having a very small radiation length (0.4% X₀/layer) and the successful installation of the very precise L3 Silicon Micro-vertex Detector (SMD) which has reached a coordinate resolution of σ = 7µm over a surface of 0.3m². Independently, R. Orava's group has developed many silicon sensor configurations(17) and, together with L3 physicists, a large silicon detector has also been studied (18).

A multilayer double-sided silicon antimatter spectrometer has the following characteristics:

a)  Ease of operation without the need of gas supplies or cryogenics.

b)  An order of magnitude better coordinate resolution:

It gives a set of very precise two dimensional coordinates (7µm in the bending plane and 10µm in the non-bending plane for Z = 1 particle, improving for higher Z), allowing multiple precise measurements of the track direction inside the spectrometer.

---

(16) - R. Battiston et al., The SMD Study Group "Proposal for a Silicon Microvertex Detector for L3" CERN-LEPC 91-5, LEPC4-Add.1, April 1991.
- R. Battiston et al., "Test beam results from the prototype L3 Silicon Microvertex Detector" DESY/93-159 and INFN/AE-93-21 to be published in NIM.

(17) - M. Huhhtinen et al., "Single sided stereo angle silicon strip detector" (1993)
- I. Hietanen et al., "Ion-implanted silicon detectors processed on a 100 mm wafer", Nucl. Instr. and Methods A301 (1991) 116-120.

c) It gives multiple very precise measurements of the particle charge Q (each about 1% at 
Z = 1, improving with higher Z). These measurements can be compared with the 
independent measurements of Q done with scintillators.

With double-sided silicon detectors, both x and y coordinates can be obtained from 
the same layer, thus minimizing the multiple and nuclear scattering contributions to the 
measurement error. This is an essential feature in hunting antiparticles with a very high 
rejection power against the particles scattered in the detector material.

In Fig.25a, we present a design based on the magnet configuration of Fig.15, replacing 
the TPC and the drift tubes with five layers of double-sided silicon detectors. Note that the 
five layers can be equally spaced in the magnet with very similar rejection power.

In this arrangement, two 50 cm silicon self-supporting ladders are mechanically joined 
forming a 100 cm long bridge (see Fig.25b). Five silicon planes are assembled on an 
independent mechanical support to be inserted inside the permanent magnet. At the center of 
the magnet, the ladders are supported by a membrane connecting the five silicon planes and 
fixed to the spectrometer mechanical structure. In order to fully exploit the magnet 
acceptance, the readout electronics, located at the bridge ends, is surface mounted on hybrids 
forming a 90° angle with the bridge through a microlitographed flexible kapton fanout.

In order to reach the highest accuracy, the double-sided silicon sensors will have a 25 
micron strip pitch in the bending direction and will be read out every 50 microns. In this 
configuration, with a \( \frac{\text{Signal}}{\text{Noise}} = \frac{S}{N} = 16 \), we have measured 7\( \mu \) detector resolution with Z = 1 
minimum ionizing particles. The readout pitch in the non-bending direction will be 20\( \mu \) 
where we have measured a 14\( \mu \) resolution with an \( \frac{S}{N} \) of 16. By using very low noise 
integrated electronics capable of driving large input capacitances (19) and a new readout 
scheme, we expect to improve these resolutions reaching an \( \frac{S}{N} > 20 \) with 50 cm long ladders. 
Recent measurements(20) show that this value of \( \frac{S}{N} \) corresponds to a resolution < 5 \( \mu \) in the 
bending direction and < 10 \( \mu \) in the non-bending direction. We are currently testing the 
construction and the performances of these long ladders.

(19) O. Toker et al., "VIKING, a CMOS low noise monolithic 128 channel front end for Si-strip detector 
(20) L. Bosisio, private communication.
Antimatter spectrometer using silicon as detector

P : permanent magnet with supporting structure
SC : Double sided silicon detector resolution (7 µ)
and $\frac{dE}{dx}$ (charge) measurements
Si : scintillators for time a flight and $\frac{dE}{dx}$ (charge)
Ai : veto scintillators

Fig. 25a: Antimatter spectrometer using silicon as detector
Double sided Si sensors self supporting ladder

mid-bridge supporting carbon fiber membrane

Fig.25b: Conceptual design of a double-sided silicon half bridge (ladder) with carbon fiber stiffeners

Table 10 shows the main parameters of this version of the silicon spectrometer. We refer to the two options as shown in Fig.14b (one magnet) and Fig.14a (two magnets).

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Channels</th>
<th>Power per channel mW</th>
<th>Total W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sci-counters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One magnet</td>
<td>Two magnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon spectrometer :</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Planes</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>- Ladders</td>
<td>250</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>- Bridges</td>
<td>125</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>- Wafers / ladder</td>
<td>7</td>
<td>7 &lt;-&gt;9</td>
<td></td>
</tr>
<tr>
<td>- Readout channels / ladder</td>
<td>1536</td>
<td>1536</td>
<td></td>
</tr>
<tr>
<td>- Total readout channels</td>
<td>384000</td>
<td>322560</td>
<td>1.5</td>
</tr>
<tr>
<td>- Mux factor</td>
<td>3840</td>
<td>3840</td>
<td></td>
</tr>
<tr>
<td>- FADC</td>
<td>100</td>
<td>84</td>
<td>300</td>
</tr>
<tr>
<td>HV</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Total Power (W)</td>
<td>878</td>
<td>973</td>
<td></td>
</tr>
</tbody>
</table>

Table 10

Our Monte-Carlo study on the search for anti-helium shows that this arrangement can easily reach a rejection \( \text{Anti He} < 10^{-10} \) up to 40 GeV/N.
Chapter 5 Summary

The permanent magnet cost is about $\frac{1}{1000}$ of the superconducting magnet and could be constructed in six months' time. Following the discussions in the previous chapters, we present a few detector configurations:

1. **Option 1**

One large single magnet with two correcting small magnets to ensure that $B$ (earth) x $(I \times A) = 0$. This detector is made of drift tubes and TPC. This design has the advantage of having a large acceptance of $= 0.8 \, \text{m}^2 \text{sr}$ (see Fig.26).

![Antimatter spectrometer: Option 1](image-url)
2. **Option 2**

Two identical magnets with opposite field to eliminate the torque, each with independent TPC and drift tubes. The acceptance of each system is $0.23 \text{ m}^2\text{sr}$, This design has the advantage that if one of the systems is not functional in space, the other one can still collect data (see Fig. 27).

![Diagram of the Antimatter spectrometer: Option 2](image)

**Fig. 27:** Antimatter spectrometer: Option 2
3. **Option 3**

In this option, we replace the drift tubes and the TPC of option 1 with double-sided silicon detector. This option has the advantage of having a large solid angle \(= 0.8 \, \text{m}^2\text{sr}\) and also, with the use of silicon, of not having any gas system to be concerned about (see Fig.28).

![Diagram of Antimatter Spectrometer: Option 3](image)

**Fig.28:** Antimatter spectrometer: Option 3
4. **Option 4**

This is the same option as option 2 but with silicon replacing the drift tubes and the TPC (see Fig.29).

![Diagram of silicon option with two magnets on top of each other]

**Fig.29:** Silicon option with two magnets on top of each other

Table 11 compares the merits of the various options proposed together with Astromag (LISA) option\(^{(20)}\). As seen from this table, the permanent magnet, together with the simple detector offers unique advantages over superconducting magnet designs, both in providing large acceptance and in reducing the cost.

\[^{(20)}\] P. Spillantini: Private communication.
<table>
<thead>
<tr>
<th>Weight (tons)</th>
<th>Acceptance (m²sr)</th>
<th>Magnet cost (M$)</th>
<th>Detector</th>
<th>Power (W)</th>
<th>BL² (kGm²)</th>
<th>rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>2.15</td>
<td>0.80</td>
<td>&lt; 1.0</td>
<td>TPC</td>
<td>500</td>
<td>1.5</td>
</tr>
<tr>
<td>Option 2</td>
<td>1.934</td>
<td>0.45</td>
<td>&lt; 1.0</td>
<td>TPC</td>
<td>730</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>(2 x 0.967)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option 3</td>
<td>2.15</td>
<td>0.80</td>
<td>&lt; 1.0</td>
<td>Silicon</td>
<td>770</td>
<td>1.5</td>
</tr>
<tr>
<td>Option 4</td>
<td>2.0</td>
<td>0.06</td>
<td>&lt; 1.0</td>
<td>Silicon</td>
<td>770</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>(2 x 1.00)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comparison</td>
<td>2.4</td>
<td>0.03</td>
<td>~ 200 M$</td>
<td></td>
<td>400</td>
<td>~ 10</td>
</tr>
<tr>
<td>with Astromag (LISA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 11: Comparison of typical magnet options.

Fig. 30 shows the sensitivity of this experiment compared with the existing limits.

As seen, our detector can improve the existing limits by $10^4$-$10^5$ and, at the same time, precisely measure the abundance of atomic nuclei (as shown in Table 5).
Fig.30: Current limits and sensitivity of this experiment for antimatter

In addition to the search for antimatter, our detector could be easily modified (particularly for options 2 and 4) to explore the search of $\bar{p}$ and $e^+$.  

The $\bar{p}$ and $e^+$ are "tracers" of the movement of the cosmic ray particles through the interstellar medium in the galaxy. The protons originate from sources which may or may not be the same as the sources of helium and the heavier nuclei and their propagation history may be different from that of the heavier nuclei. This is one of the fundamental outstanding questions in high energy astrophysics.

The observation of antimatter is of fundamental importance to our understanding of the origin of the universe.
Multi muon event tracking with Neural Network algorithms

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Abstract

Automatic tracking of multitrack events in underground apparatus based on least square fits presents difficulties increasing with the multiplicity. Traditional algorithms, based on chi-square fit, seem to be unable to deal with muon bundles having more than eight tracks, so that visual inspection needs to supplement the automatic recognition. In a different approach we consider the track reconstruction task as an optimization problem and we use an Hopfield-like (fully connected) analog Neural Network to find a collectively computed solution. Given a set on N points and M=N(N-1)/2 segments between these points, our goal is to find the K segments corresponding to a set of tracks, where each track is a continuous, nonbifurcating and as more as possible straight line. In order to speed up the convergence of the network, an Hough transform derived method is applied in the initialization step.

The performance of this new tracking algorithm has been tested, using a Monte Carlo track generator, versus the following experimental parameters: number of tracks, signal to noise ratio, efficiency (points in a track) and accuracy in the point position. Experimental results are given in terms of distribution of efficiency (number of track correctly detected with respect to the total number of generated tracks) and contamination (number of false track with respect to the total number of detected tracks) as a function of muon bundles multiplicity. The neural network algorithm is very efficient for high track multiplicities and it is therefore a useful tool to improve the global performance of the track recognition in underground detectors.
1 Introduction

For a large area underground detector of the present generation, tracking of mu-bundles with high multiplicity is a real problem. Some general consideration on the track finding can be done:

1) traditional tracking algorithms, based on chi-square fit, show performances decreasing with the multiplicity;
2) a global approach is needed since all points enter in the algorithm on the same base - optimization problem;
3) the optimization problem is \textit{NP-complete} and the computation time for exploring all possibilities grows like \( N! \).

Nowadays algorithm based on Neural Networks (NN) offer both a computing solution intrinsically \textit{collective} and a high degree of parallelism.

2 Recurrent Network

2.1 The Hopfield Network

In this paper a recurrent associative NN architecture based on a Hopfield network is taken into account. It consists of \( N \) binary neurons \( V_i(t) = \pm 1 \) fully connected by means of the synaptic strengths matrix \( T_{ij} \).

The dynamics of the system is given by [1, 2]:

\[
V_i(t+1) = \text{Sign} \left( \sum_{j} T_{ij} V_j(t) \right),
\]

where a stable state (attractor) of the network:

\[
V_i(t+1) = (V_i(t))
\]

is reached in a minimum of the Energy function:

\[
E(t) = -\frac{1}{2} \sum_{ij} T_{ij} V_i(t)V_j(t)
\]

In the case of the track finding, the neuron \( V_{ik} \) corresponds to the segment between the signals \( i \) and \( k \) and is equal to unity if the segment \( i \rightarrow j \) is part of a track.
2.2 Experimental constraints

The goal of the algorithm is, given $N$ signals (and $N(N-1)$ possible segments), to draw the maximum number of tracks [3, 4, 5] continuous, nonbifurcating and smooth. At the aim, the following generalized Energy function has been introduced

$$E = -\frac{1}{2} \left( \sum_{ijkl} (T_{ijkl} - C_{ijkl}) V_{ij} V_{kl} - D \right)$$

by imposing the following constraints (see figure 1):

1) the continuity, i.e. excitatory connections only between neurons (segments) sharing a point:

$$T_{ijkl} = \delta_{jk} T_{ijkl}$$

2) and the track smoothness: i.e. short segments with small relative angles should be favoured:

$$T_{ijkl} = \delta_{jk} \frac{\cos \theta_{ij,kl}}{(d_{ij} + d_{kl})^n}$$

3) nonbifurcating tracks: i.e. each point should be associated to only one track:

$$C_{ijkl} \propto \delta_{ik}(1 - \delta_{jl}) + \delta_{jl}(1 - \delta_{ik})$$

4) the total number of activated neurons is not greater than $(N-1)$ where $N$ is the number of input points - global inhibition:

$$D \propto \sum_{ij} (V_{ij} - N)^2$$

With these conditions a NN track finding algorithm has been coded and the performance has been evaluated on simulated data.

3 Test Results

A Montecarlo-based Track Generator has been developed in order to check the performances of the neural tracking algorithm. The following parameters has been considered:

- $\mu$ multiplicity ($M_\mu$) (number of tracks to be identified);
- noise to signal ratio ($N/S$) (number of track points with respect to out of track points);
efficiency \( \epsilon \) (average number of points in a track);

- accuracy \( \delta_p \) in the point position;

- minimal \( d_T \) inter track distance.

The NN here proposed has been studied in the following specific range:

\[
2 \leq M_\mu \leq 22 \\
0.1 \leq N/S \leq 0.5 \\
0.68 \leq \epsilon \leq 0.98
\]

at a fixed \( \delta_p = 3 cm \) and \( d_T = 2 \delta_p \).

For each event 100 MonteCarlo histories have been considered and the results are analyzed in terms of the following mean values:

- reconstruction efficiency: number of track correctly detected with respect to the total number of generated tracks;

- reconstruction contamination: number of false track with respect to the total number of detected tracks;

versus the muon bundle multiplicity.

In order to speed up the convergence of the network and to avoid false tracks, the constraint of parallelism among reconstructed tracks has been reinforced using a Hough transform derived technique for neurons initialization. Starting neurons values \( \{ V_{ij}(t = 0) \} \) have been chosen ad hoc:

\[
V_{ij}(t = 0) \propto \left[ \frac{(\theta_{ij} - \theta_0^*)}{d_{ij}} \right]^{2n}
\]

where \( \theta_0^* = \text{max} \) in the frequency distribution of the input \( \theta_{ij} \).

Figures 2 to 5 give the results obtained testing the algorithm on simulated data. Figure 6 shows an example of a typical reconstruction of a 20 prongs multi-\( \mu \) event with an electronic efficiency of 80\% and a noise of 50\%.

4 Conclusions

In this paper a Neural Network track finding algorithm for multi-\( \mu \) events in underground large area detectors has been developed and tested. Its performance appear particularly good with:
- high track reconstruction efficiency:
  - performance nearly independent of muon multiplicity;
  - performance nearly independent of signal to noise ratio;
  - dependence on electronic efficiency;

- very low reconstruction contamination:
  - contamination nearly independent of $\mu$ multiplicity at low $N/S$;
  - contamination independent of electronic efficiency;
  - strong correlation between contamination and total number of input points.

The neural network algorithm here developed is very efficient for high track multiplicities and it is therefore a useful tool to improve the global performance of the track recognition in underground detectors.
References


Figure Captions

Fig. 1. Experimental constraints: (a) continuity, (b) nonbiforcatng tracks.

Fig. 2. Network reconstruction efficiency versus noise.

Fig. 3. Network reconstruction versus electronic efficiency.

Fig. 4. Track contamination versus noise.

Fig. 5. Track contamination versus electronic efficiency.

Fig. 6. Reconstruction of a 20 prongs multi-µ event, with 80% electronic efficiency and 50% noise hits added; (a) input pattern, (b) network reconstruction.
\[ T_{ijkl} = \delta_{jk} T_{ijkl} \]

\[ C_{ijkl} \propto \delta_{ik}(1 - \delta_{jl}) + \delta_{jl}(1 - \delta_{ik}) \]
NET RECONSTR. EFFICIENCY vs. NOISE

Reconstruction Efficiency

Noise/Signal Ratio

- = 0.1
Δ = 0.3
○ = 0.5

* Total of 6600 simulated events

FIG 2
NET RECONSTR. EFFICIENCY vs. ELECTRONIC EFFICIENCY

Simulated Electronic Efficiency:
- ◇ = 65%
- □ = 75%
- △ = 85%
- ★ = 98%

* Total of 8800 simulated events
TRACK CONTAMINATION vs. NOISE

* Total of 6600 simulated events

Noise/Signal Ratio:
- $\bullet = 0.1$
- $\triangle = 0.3$
- $\ast = 0.5$

Figure 4
TRACK CONTAMINATION vs. ELECTRONIC EFFICIENCY

Electron Efficiency:
- = 65%
- = 75%
- = 85%
* = 98%

* Total of 8800 simulated events
THE POSSIBILITY TO IMPROVE EFFICIENCY OF ANALYZING COSMIC RAYS WITH HELP OF NEURAL NETWORK METHOD

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Abstract

In this work, we demonstrate the feasibility of applying artificial neural network (ANN) in analysis of the cosmic ray data. Even though our neural network is very simplified but an obvious success manifests after a "training" process with only 14 samples generated by a Monte-Carlo program, the neural network has learned to recognize the incoming cosmic particle with high efficiency, then a few test samples are fed in and correctly recognized by the trained system. Further improvements of usage of ANN are discussed.

I. Introduction.

In recent years the non-accelerator physics has regained attention of both experimentalists and theorists of high energy physics, just because of its advantages which cannot be substituted by accelerator experiments. Especially, as the long-expected SSC project was turned down and the LHC probably will not be functioning in this century, if one hopes to study high energy processes or very massive particles, a rich source comes from the universe, namely, observation of cosmic rays will be important for exploring fundamental

1 This work is partially supported by the national Natural Science Foundation of China
processes and discovering new physics.

The cosmic rays not only can give us information about the universe, such as the supernova explosion, extra high-energy radiation etc., but also provide us with knowledge on new physics and heavy particles (Higgs, perhaps) which are not to be produced at the present accelerators. In history, studies on cosmic rays have indeed given people valuable knowledge about the mysterious universe and particle physics, in 1932, Anderson identified positron predicted by Dirac in cloudy chamber and in 1987, the data of Supernova 1987 A [1] suggested possible neutrino mass and mixing. Recently, a restudy of the event observed at the Yunnan mountain observatory in 1972 suggests, it may be an event that a supersymmetric particle–neutralino bombarded on a proton to produce a π–, a proton and a chargino which is heavy [2].

Since the information from the cosmic rays can be used to study the dark matter, fundamental physical principles and new particles, people have great interests in the it, so serious analysis on the data of cosmic rays becomes more and more necessary.

In fact, one of our interests is to investigate new physics and new particles from cosmic rays, to serve this purpose, we have to single out such events from the majority of regular cosmic events, but unfortunately, the events which correspond to new physics are very few, therefore one needs to carefully pick up some peculiar findings among a flood of junks and then a careful analysis will be carried out to determine if an unknown physical phenomenon is involved. This is exactly similar to getting rid of background in collider physics.

There are many ways to observe cosmic rays and among them the detectors built up at high altitude mountains are an important means, where individual detectors which can measure the total number, charge and energies and arrival time of the received particles, are arranged to make arrays. The signals received by the detectors should be synthesized and a reconstruction (if possible) can tell us what kind of cosmic particle (charge, mass and momentum) comes from the universe to visit us.

However, on the way from the outspace to the earth detector, the cosmic ray particle travels a long distance and interacts with the atmosphere atoms and also decays into lighter particles. During this long journey, radiation of photons, bremsstrahlung, l+ℓ−-pair production and the scattering of secondary particles all occur and finally a huge amount of particles emerge. The number of particles received by the detector must be very large.
During the long journey many particles are lost due to scattering with atmosphere, and because of the fluctuation of atmosphere molecular distribution the reaction kinematics turns out to be very complicated and furthermore, the detector arrays are not continuous, so it is impossible to detect all produced particles on the earth. Besides, due to the measurement error of the calorimeter, even energies and charges of the particles which finally arrive at the detectors cannot be measured accurately. Therefore, tracing-back to determine characteristics of the cosmic particle from the obtained data on earth is hard, at least a simple sum of the energies and charges is not that of the cosmic particle. This motivates us to employ the artificial intelligence system – neural network in analysis of the messy cosmic ray data.

In the following section we briefly introduce the extensive air showers (EAS) characteristics and then in the third section, we discuss the back propagation (BP) algorithm for the neural network which we employ in this work and other concerning problems. In the last section we present the learning results of the neural network and we give a detailed discussion on possible further improvements of this approach. Finally a conclusion is drawn.

II. The general EAS characteristics.

An extensive air shower (EAS) is a cascade of particles produced in the atmosphere by a single cosmic ray of sufficiently high energy that a coherent flux of cascade particles is observable at detectors on the earth [3].

Basically, the majority of cosmic particles are electrons (positrons), photons and regular mesons, if the dark matter consists mainly of supersymmetric particles, the cosmic rays would include a great amount of neutralinos, but their interaction with the regular matter is very weak, the observable events are still rather rare.

The cosmic particle comes into the atmosphere and may undergo many fundamental processes, such as the Coulomb scattering, bremsstrahlung, Compton scattering, $e^+e^-$ ($\mu^+\mu^-$, $\tau^+\tau^-$)–pair production etc.

Many secondary particles are produced in these elementary processes and finally makes a cascade of enormous number of leptons, photons and even hadrons which eventually arrive at our detectors. Even though these basic interactions are studied thoroughly in field theory and proved by accelerator experiments, scattering processes with atoms and
molecule of the atmosphere are very complicated. First there are too many collisions, pair-productions, photoproductions and decays, and furthermore the atmosphere molecular distribution is not uniform but obeys complicated laws. Moreover, the fluctuation of the distribution is by no means negligible. All these phenomena have been studied for many decades.

If one only needs to study the statistical behavior of cosmic particles or a regular fluctuation of the cosmic rays in order to understand the source of radiation in the universe, many statistical models and computer programs have been established and results consistent with observation are obtained.

However, to investigate a single peculiar event which may lead to discovery of new physics demands a reconstruction of the event and precise identification of the cosmic particle, its charge, mass energy and momentum etc. Doing so, the most important job is to identify the regular cosmic particles which are involved in majority of events. But, as aforementioned, the complicated evolution process of EAS not only produces great amount of particles, but also makes their distribution on the earth very messy. To identify the original cosmic particle and determine its energy and momentum is a very difficult analysis of the data recorded by the detectors. Therefore it is necessary to establish a reliable and efficient system which can distinguish the peculiar events from the regular ones, depending on the interests of research.

The artificial neural network is just such an artificial intelligence system which manifests incomparable effectiveness in many aspects, especially the pattern recognition. It has been proved that the neural network method is powerful in analyzing data obtained in high energy experiments and emulsion experiments. This method definitely can gain wide applications in cosmic ray analysis.

III. The Artificial Neural Network

The neural network model has been discussed by many authors who are working in various fields. There are many ways to construct neural networks, each approach has its own advantages and disadvantages. In this work we employ a simple neural network structure and the back propagation (BP) algorithm.

Generally, there are $M$ layers of neurons, $N(m) (m \leq M)$ is the number of neurons at the $m$-th layer, and $S_j(m)$ and $O_j(m)$ are input and output signals of the $j$-th neuron at
this layer, and
\[ S_j(m) = \sum_{i=1}^{N(m-1)} W_{ji}O_i(m-1), \]  
(1)
where \( W_{ji} \) is the synapse connecting neuron \((j,m)\) and neuron \((i,m-1)\). The transformation is a sigmoid function as
\[ O_j(m) = f(S_j(m) - \theta_j(m)) \]  
(2)
and
\[ f(x) = \frac{1}{1+e^{-x}}, \]  
(3)
where the threshold \( \theta_j(m) \) is a numerical function which can be adjusted.

Denoting \( O_p \) as the actual output of the network, the mean-square error energy function \( E \) is defined as
\[ E_p = \sum_{n=1}^{N(M)} (Y_{pn} - O_{pn})^2, \]  
(4)
where \( P \) is the total number of samples to be learned, \( Y_{pn} \) is the desired output, so \( E \) characterizes a deviation of the actual output with the desired one. Minimizing \( E \) will be our goal for training the network.

The weights \( W_{ji} \)'s are updated as
\[ \Delta W_{ji}(m) = -\frac{\partial E}{\partial W_{ji}(m)} \cdot \Delta = \sum_{p=1}^{P} \delta_{jn}(m)O_{pi}(m) \cdot \Delta, \]  
(6)
where \( \Delta W_{ji} \) is the change in the weight vector at each time step, \( \Delta \) is a step parameter and the threshold \( \theta_{pi} \) has an expression similar to (6).

\[ \delta_{ji}(m) = (Y_{pj} - O_{pj})f'(S_{pj}(M) - \theta_{pj}(M)) \]  
(7)
\[ f'(S_{pj}(m) - \theta_{pj}(m)) = \sum_{n=1}^{N(m+1)} W_{ji}(m+1)\delta_{jn}(m+1) \]  
(8)
This is a back propagation process, namely, an error occurring at the last layer will be propagated back to the preceding layers. To minimize \( E \) means to change the weight vectors according to our learning process described in eq.(6).
The convergence of the BP model has been discussed by some authors. The advantage of this model is a fast learning process with a limited amount of training samples. This model has been applied to many fields.

Now we give our neural network the training samples generated by a Monte-Carlo program which simulated the real cosmic ray events caused by photon and electron. For simplicity, we let the cosmic ray be normally incident into the atmosphere.

We choose the simplest setting for the neural network, namely we only have two layers. The first layer receives signals from the detectors as inputs. In our case, we suppose that there are $7 \times 7 = 49$ detectors, of size $16 \times 16m^2$ which covers $112 \times 112 m^2$ area. Of course, this is far away from the practical situation while nobody can build up such large detectors at present, but at this primary investigation stage, we try to use the most simplified toy model to demonstrate feasibility of this method. Two typical Monte-Carlo simulation diagrams caused by photon and electron are shown in Fig.1. Generally, there are more than 300 particles produced, but only less than 50 particles fall in the detection area. With most particles missing detectors, we still want to use the obtained information to identify the original particle. It is exactly what we require the neural network to do.

We assume that each detector can record the total energy, photon number and number of charged particles which arrive at this detector. Therefore, totally, we have $49 \times 3 = 147$ pieces of information to deal with, so we set 147 neurons at the first layer.

The inputs would be converted to outputs of the first layer neurons with the sigmoid function as the transformation and then transferred to the next layer through the interconnection $W_{ji}$. At the second layer which is also the last one, there are two neurons, since we only require to output the identity of the cosmic particle which is characterized by its charge and the energy of the incoming particle. In our case, output of one neuron is "1" or "0", "1" corresponds to electron, whereas "0" to photon. Another neuron can give information on the energy of the incoming cosmic particle. Obviously, in our model only photon and electron exist, in practice, as other particles, proton, neutron, mesons etc. are under consideration, one needs to increase number of neurons of the output layer to achieve more information.

Totally, we generate 12 events for the training, among them 9 are electron events (corresponding to "expected charge" 0.9) and 3 are photon events (to "expected charge" 0.1). Now in the following table we show the learning results for the 12 events. In this model,
there is a threshold $\theta$ in eq.(2), so the standard values are 0.1 for photon and 0.9 for electron. The input energies, charges and output energies and charges are listed below.

<table>
<thead>
<tr>
<th>sample</th>
<th>No. of produced particles</th>
<th>No. of recorded particles</th>
<th>expected output energy</th>
<th>real output energy</th>
<th>expected output charge</th>
<th>real output charge</th>
<th>particle type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49</td>
<td>7</td>
<td>0.1000</td>
<td>0.1057</td>
<td>0.90</td>
<td>0.89</td>
<td>electron</td>
</tr>
<tr>
<td>2</td>
<td>83</td>
<td>12</td>
<td>0.2455</td>
<td>0.2371</td>
<td>0.90</td>
<td>0.91</td>
<td>electron</td>
</tr>
<tr>
<td>3</td>
<td>101</td>
<td>15</td>
<td>0.3182</td>
<td>0.3410</td>
<td>0.90</td>
<td>0.88</td>
<td>electron</td>
</tr>
<tr>
<td>4</td>
<td>122</td>
<td>16</td>
<td>0.3910</td>
<td>0.3790</td>
<td>0.90</td>
<td>0.91</td>
<td>electron</td>
</tr>
<tr>
<td>5</td>
<td>144</td>
<td>21</td>
<td>0.4636</td>
<td>0.4605</td>
<td>0.90</td>
<td>0.90</td>
<td>electron</td>
</tr>
<tr>
<td>6</td>
<td>165</td>
<td>24</td>
<td>0.5364</td>
<td>0.5308</td>
<td>0.90</td>
<td>0.91</td>
<td>electron</td>
</tr>
<tr>
<td>7</td>
<td>190</td>
<td>27</td>
<td>0.6091</td>
<td>0.6141</td>
<td>0.90</td>
<td>0.89</td>
<td>electron</td>
</tr>
<tr>
<td>8</td>
<td>215</td>
<td>39</td>
<td>0.6818</td>
<td>0.6818</td>
<td>0.90</td>
<td>0.90</td>
<td>electron</td>
</tr>
<tr>
<td>9</td>
<td>240</td>
<td>34</td>
<td>0.9745</td>
<td>0.9746</td>
<td>0.90</td>
<td>0.90</td>
<td>electron</td>
</tr>
<tr>
<td>10</td>
<td>257</td>
<td>42</td>
<td>0.318</td>
<td>0.319</td>
<td>0.10</td>
<td>0.10</td>
<td>photon</td>
</tr>
<tr>
<td>11</td>
<td>87</td>
<td>16</td>
<td>0.404</td>
<td>0.460</td>
<td>0.10</td>
<td>0.10</td>
<td>photon</td>
</tr>
<tr>
<td>12</td>
<td>365</td>
<td>49</td>
<td>0.5364</td>
<td>0.5365</td>
<td>0.10</td>
<td>0.10</td>
<td>photon</td>
</tr>
</tbody>
</table>

Table 1.

In our calculations, for convenience the input and output energies are normalized by a formula to a dimensionless value as

$$E_i = \frac{(E(i) - E_{\min}) \times 0.8}{E_{\max} - E_{\min}} + 0.1,$$

where $E(i)$ are the real value of the i-th sample and $E_i$ is the dimensionless energy, $E_{\max}$ and $E_{\min}$ are the maximum and minimum values of the samples. In practice, the expected energy and expected charge are the energy and charge of the cosmic particle which is normally incident into the atmosphere and other data, for example the number of produced particles (secondary particles) and the number of particles recorded by the detectors are generated by our Monte-Carlo program. It is noted that even the large fraction of produced particles do not reach the detectors, our neural network still can recognize the original cosmic particle (energy and charge).

From these results, we can notice that the learning is successful, 100% events are recognized.

Then several test samples which are also generated by the Monte-Carlo program are fed into the system, we identify all the cosmic particles right and the energy estimation is
consistent with the real energy of the incoming particle within error of less than 20%, so
the result is completely positive, the recognition efficiency is satisfactory, even though the
energy restoration does not fully meet our requirements. This deviation can be reduced
to a tolerable scale as we improve the neural network and we will discuss it in some detail
next section. Two test samples and the recognition results are shown in Table 2.

<table>
<thead>
<tr>
<th>sample</th>
<th>expected output energy</th>
<th>real output energy</th>
<th>expected output charge</th>
<th>real output charge</th>
<th>particle type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.39</td>
<td>0.32</td>
<td>0.9</td>
<td>0.87</td>
<td>electron</td>
</tr>
<tr>
<td>2</td>
<td>0.39</td>
<td>0.28</td>
<td>0.1</td>
<td>0.17</td>
<td>photon</td>
</tr>
</tbody>
</table>

Table 2.

Since the charges of photon and electron are very apart, it is easy to distinguish them,
in fact, if the real outputs are less than 0.3 or larger than 0.6, they can be undoubtedly
identified as photon and electron. Our results listed in Table 2, clearly confirm a success
of the particle type identification.

IV. Discussions and conclusion

In this work, we demonstrate that the neural network-artificial intelligence system can
be introduced to help improving efficiency of analyzing the cosmic ray data. It is not
surprising if one knows how successful applications of neural network have been in many
fields.

Of course the present work is very rough, but it is to show feasibility of applying neural
network and is the first paper in a systematic series of work. In here, we assume that the
cosmic particles only can be photon or electron, their energies cover a not very wide range,
normally incident into the atmosphere, meanwhile the size of detector is larger than the
real one that makes collection of data easier, the data are also different from the practical.
Even though there are so many approximations, the success of training process and tests
claims that the neural network method can play an important role for analyzing data.

Minsky and Papert showed that a two-layer perceptron (or linear network) cannot
make successful learning for a complicated XOR logic problem [7]. In fact, the neural
network learning process is to establish an interconnection weight matrix among layers
for \( W_{ji} \) to minimize \( E \) (in eq. (3)). If the learning process is successful, a reasonable group of \( W_{ji} \) would be obtained, then the system can be put into action. The XOR problem raises an equation group where some relations may be contradictory to each other, therefore there is no solution for \( W_{ji} \) in general, in other words, the neural network system learning fails. It has been proved that once the number of layers is increased the number of contradictory relations is reduced, therefore in principle, a system with infinite layers resolves the complex mapping problem.

As a matter of fact, our two-layer neural network is only a perceptron, since these a few events simulated by Monte Carlo for training and test are not to have very bad behavior and there are no other localized extremes in the evaluation function of \( E \), the learning is successful. But for a practical situation, problem will be much more complicated and XOR problem may occur. Thus an intermediate layer is necessary.

We have tried to include an intermediate layer with two neurons and found that the identification quality is obviously improved and detecting accuracy increases. No doubt, more layers mean that training process would be prolonged and computer CPU time increases, then more money and manpower should be put in. How many layers are most appropriate is an open question and worth more discussions.

Our conclusion is that the artificial neural network is applicable in analyzing the cosmic ray data, our simplified structure is set only for a demonstration of the usage of ANN. The success of learning and testing confirms the feasibility and usefulness for improving the analyzing efficiency.

Our model for cosmic rays is as simple as the ANN system, in the later work, we need to include proton, pion, neutrinos and other particles with a wider energy range. The Monte-Carlo outputs can simulate real cases which are detected by a practical set, for example, the array in Tibet.

Meanwhile, the ANN system, training method should be improved either. Anyhow, the whole project is a long and difficult one, our recent work is just beginning and preliminary, but it indicates that this research is worthwhile for cosmic ray studies.

Acknowledgments. We would like to thank Chang-quan Shen and Gui-ru Jing for their great help about the physics of cosmic rays and creative suggestions. We especially appreciate that Jing kindly lends her Monte-Carlo program for generating cosmic ray events.
1. INTRODUCTION.

In the central nervous system of all vertebrate animals and human beings continuously arrive signals, characterizing the surrounding conditions. There, these signals are elaborated and analysed in such a way that the information they are bringing becomes more understandable, more useful, and in many cases more indispensable. After a period long enough, the nervous system not only identifies distinctly the signal series, but begins to foresee their following configurations.

The Artificial Neural Network (ANN) is a mathematical model created in an attempt to simulate these processes. The programs supporting that model are autoadjustable during the computations. The internal program parameters change after any iteration, so the results we are looking for could be obtained with better accuracy.

2. ARCHITECTURE OF THE ANN MODEL.

The basic ANN model is always connected with a special structure generally named "architecture of the model". A simplified ANN architecture, which we assume is similar to one neuron, is shown on Fig.1.

![Fig. 1.](attachment:fig1.png)
Here box 1. is the input layer. Box 2. is generally called "hidden layer". Box 3. is the output layer.

The points in the boxes are called "nodes". \( x_i \) are the input nodes, \( z_k \) are the output nodes. \( y_j \) and \( z_k \) (capital letters) are the "in" nodes of the corresponding layer, where \( y_j \) and \( z_k \) are the "out" nodes. The "out" nodes of the last layer are the output nodes.

The activation of every \( y_j \) node could be made from every one of the \( x_i \) nodes. The resultant activation could be presented as:

\[
Y_j = \sum_{i=1}^{\text{max}} W_{ij} x_i.
\]  

(1)

It is accepted that the values of the matrix members \( W_{ij} \) are within the interval \(-1 \leq W_{ij} \leq 1\).

Analogically for the connections between \( y_j \) and \( z_k \) we have:

\[
Z_k = \sum_{j=1}^{\text{max}} W_{jk} Y_j,
\]

(2)

where \(-1 \leq W_{jk} \leq 1\).

Specially on Fig. 1. \( i_{\text{max.}} = 2 \) \((i=1, 2)\) and \( k_{\text{max.}} = 1 \) \((k=1)\).

The activations in the boxes are not intercrossing, so:

\[
y_j = f(Y_j) \quad \text{and} \quad Z_k = f(Z_k).
\]

(3)

(4)

We define the functions \( f(Y) \) and \( f(Z) \) to be:

1. Limited in the closed interval \( 0 \leq f(y) \leq 1 \) and \( 0 \leq f(z) \leq 1 \).
2. Nonlinear.
3. Monotone.

Generally for such a function is chosen:

\[
f(Y_j) = (1 - \exp(-Y_j))^{-1}
\]

(5)

and very often \( f(Z_k) \) is presented with the same function:

\[
f(Z_k) = (1 - \exp(-Z_k))^{-1}.
\]

(6)
3. **FORWARD PROPAGATION.**

Let us have a series of measured data

\[ p_t \quad (t = 1, 2, 3, \ldots t_{\text{max}}) . \]  

(7)

We could present them as a series of values

\[ a_t \quad (t = 1, 2, 3, \ldots t_{\text{max}}) . \]  

(8)

where \( a_0 = a_t = 1 \), using for example a simple constant \( c \)

\[ a_t = cp_t \]  

(9)

Let us apply \( a_1 \) to the node \( x_1 \) and \( a_2 \) to the node \( x_2 \). The propagation of these activations from the left to the right part of the architecture, when the computations (1), (2), (3), and (4) are executed, we call forward propagation. To be completed the first forward propagation the values of \( W_{ij} \) and \( W_{jk} \) have to be known. Because we do not know them we simply choose any arbitrary values in the interval \(-1, +1\).

The result of this first forward propagation \( b_1 \) appears on the output \( z_k \). This result obviously depends on the choice of \( W_{ij} \) and \( W_{jk} \).

4. **COMPARISON.**

If we should like to predict the third value \( a_3 \) of our series from the two previous values \( a_1 \) and \( a_2 \) we have to compare the output value \( b_1 \) with \( a_3 \), constructing for example the difference:

\[ E_1 = (b_1 - a_3)^2 \]  

(10)

Then we try to change the values of \( W_{ij} \) and \( W_{jk} \) in such a way that in the next iteration hopefully

\[ E_2 < E_1 \]  

(11)
5. BACKWARD PROPAGATION.

We could do that using the Backpropagation network (BPN)
(See for example [1]). So we construct:

\[ \Delta w_{jk} = - \frac{dE}{dw_{jk}} \]  \hspace{1cm} (12)

Using the chain rule of calculus we have:

\[ \frac{dE}{dw_{jk}} = \frac{dE}{db_1} \frac{db_1}{dZ_k} \frac{dZ_k}{dw_{jk}} \]  \hspace{1cm} (13)

We could easily obtain from (10), (6), and (2)

\[ \frac{dE}{db_1} = 2(b_1 - a_3); \hspace{0.5cm} \frac{db_1}{dZ_k} = z_k(1 - z_k); \hspace{0.5cm} \frac{dZ_k}{dw_{jk}} = y_j. \]  \hspace{1cm} (14)

So we have:

\[ \Delta w_{ij} = - \frac{dE}{dw_{ij}} = - 2(b_1 - a_3)z_k(1 - z_k)y_j. \]  \hspace{1cm} (15)

Farther we have to calculate:

\[ \Delta w_{ij} = - \frac{dE}{dw_{ij}}. \]  \hspace{1cm} (16)

Using the same rule, we have:

\[ \frac{dE}{dw_{ij}} = \frac{dE}{dy_j} \frac{dy_j}{dY_i} \frac{dY_i}{dZ_k} \frac{dZ_k}{dw_{jk}} \]  \hspace{1cm} (17)

where again

\[ \frac{dy_j}{dY_i} = y_j(1 - y_j); \hspace{0.5cm} \frac{dY_i}{dW_{ij}} = x_i. \]  \hspace{1cm} (18)

And finally:

\[ \Delta w_{ij} = - \frac{dE}{dw_{ij}} = 2(b_1 - a_3)z_k(1 - z_k)Y_j(1 - y_j)y_jx_i. \]  \hspace{1cm} (19)

We use the value \( \Delta w_{jk} \) (15) and the value \( \Delta w_{ij} \) (19) to "improve" our arbitrary chosen values.
\[(\mathbf{w}_{ij})_{t=2} = (\mathbf{w}_{ij})_{t=1} + \eta (\Delta \mathbf{w}_{ij})_{t=1} \quad (20)\]

and

\[(\mathbf{w}_{jk})_{t=2} = (\mathbf{w}_{jk})_{t=1} + \eta (\Delta \mathbf{w}_{jk})_{t=1} \quad (21)\]

The coefficient \(\eta\) introduced here is called "learning rate". Very often it is accepted that

\[\eta = 1 \quad (22)\]

With the calculation of (20) and (21) the backward propagation cycle is finished.

6. TRAINING.

The next iteration begins with a new forward propagation when \(a_2\) is applied on \(x_1\) and \(a_3\) on \(x_2\) and the "improved" values \((\mathbf{w}_{ij})_{t=2}, (\mathbf{w}_{jk})_{t=2}\) are used.

The calculations continue forward and backward till the whole chain of measured values is used and the cycle when \(a_t\) is applied on \(x_2\) is just finished.

Generally that is not the end. The whole procedure has to be repeated \(n\) times till the differences \(\varepsilon_{tn}\) converge to a small enough value. Often \(n\) is greater than 10 000 or even 100 000.

The repetition of this procedure is called "training of the program". When our program is well trained, then hopefully we could say that applying \(a_{t\text{ max}}\) on \(x_2\) and using the last calculated values of \(\mathbf{w}_{ij}\) and \(\mathbf{w}_{jk}\) we could accept with certain probability the value \(b\) on the output as a predicted value of the unmeasured yet value of \(a(t_{\text{max}} + 1)\). We could go even farther, applying \(a(t_{\text{max}} + 1)\) on \(x_2\) we could accept the value on the output as a predicted value of the next unmeasured value \(a(t_{\text{max}} + 2)\) and so on. But in this case the predictability decreases with every step.

7. POSSIBILITIES OF ANN.

The method described above could be used in different
The architecture could be changed. The quantity of the nodes in the layers could be varied, secondary hidden layers could be introduced, the sequence of the measured values application could be altered.

One of the most interesting advantages of this method is the possibility to use several simultaneously measured values of different interconnected physically series:

\[ a_t; c_t; g_t; \ldots \quad (t = 1, 2, 3, \ldots t_{\text{max}}) \] (23)

Sometimes the highest predictability in one of these series could be obtained introducing all the other series of measured values. If, for example we use the appropriate architecture, shown on Fig. 2. we could apply:

\[ a_1 \text{ to } x_1; a_2 \text{ to } x_2; a_3 \text{ to } x_3; \]
\[ c_1 \text{ to } x_4; c_2 \text{ to } x_5; c_3 \text{ to } x_6; \]
\[ g_1 \text{ to } x_7; g_2 \text{ to } x_8; g_3 \text{ to } x_9. \]

Of course there are a lot of possible combinations, and to choose the most appropriate from them is not an easy task.

\[ \text{Fig. 2.} \]

Here:
\[ i_{\text{max}} = 9; j_{\text{max}} = 9 \]
\[ k_{\text{max}} = 3; v_{\text{max}} = 1. \]
For simplicity only the connections \( W_{ij}, j=1 \)
\( W_{jk}, k=1 \) and \( W_{kv} \) are shown.
The coefficients of the matrices $W_{ij}$, $W_{jk}$, $W_{kv}$ obtained at the end of all the iterations could be taken as an analogue of the correlation coefficients, but we always have to have in mind that the interconnections are treated nonlinearly when ANN is used.

The time shift between the values of the input series could be also estimated, activating for example $x_1$ with $a_t$; $x_4$ with $c_{t+\tau}$; $x_7$ with $\Theta_{t+\tau}$ and correspondingly the other input nodes presented on Fig. 2:

Changing the shift time $\tau$ we could possibly obtain maximum predictability.

8. APPLICATIONS.

The ANN is a method applicable practically everywhere if reliable forecasts are necessary, if interconnections between series of measured parameters have to be estimated, if the usual time delay between these parameters have to be determined.

Technology, engineering, industry, finance, economy, health prognosis, sport competitions, insurance and many others are the areas in which the use of ANN gave unexpected profit [2]. Of course many special ANN programs are developed for many specific areas. Their possibilities for variations offer up to 8000 nodes and several hidden layers. With the use of accelerated hardware or multiprocessor computers up to 3000 propagations per second are achieved [3].

The physicists who always were the first to apply and to use any achievement in the programming and in the computation were obviously late with the application of the ANN. May be that was because the real physical processes were deeply hidden behind the hidden layers and many additional, sometimes very sophisticated methods had to be applied separately to extract the real physical meaning from the obtained mathematical interconnections.

But gradually the meteorologists using ANN began to improve their forecasts. The heliophysicists began to predict better the Sun activity. Very interesting attempts were made using the ANN to distinguish chaotic processes from the accompanying noise [4].
The interconnections between cosmic ray intensity changes with the changes in solar plasma fluxes and the connected with them heliophysical, heliospherical, geomagnetical, ionospherical, geophysical, and meteorological phenomena are well investigated. It looks like that could be a very fruitful area for ANN application.

The expectation to make predictions are rather encouraging, specially for the magnetic storm appearance. But to find the most reliable minimum of the input data quantity and simultaneously to obtain maximum predictability is a rather difficult work which now is in progress.

10. REFERENCES.
Possibility of $H^0 \rightarrow \tau^+\tau^-$ Search at LHC by Neural Network*

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Abstract

Based on PYTHIA5.6 simulation, the possibility of Higgs boson search in intermediate mass range through $H^0 \rightarrow \tau^+\tau^- \rightarrow \epsilon \mu \chi$ channel is studied by feed-forward neural network method. It shows that the $\epsilon \mu$ events from $t\bar{t}$, $W^+W^-$ or Drell-Yan and $H^0$ can be seperated with quite satisfactory efficiency. also neural network (NN) can be used to reconstruct invariant mass of the resonance particle with large missing energy in decayed final states, so that by such a approach this channel may play an active role in intermediate mass Higgs boson search, especially at high luminosity run with the existence of pile-up effect.

1 Introduction

Higgs particle search will be the most important task of future LHC pp collider to reveal the origin of spontaneously breaking symmetry mechanism of standard model, if the coming LEP$\Pi$ will not find this particle. As standard model can not give a prediction of Higgs mass, if it lies in the intermediate mass range, i.e. $80 GeV < M_H < 140 GeV$, it is commonly convinced by Monte Carlo simulation studies that the only favorable searching channel is $H^0 \rightarrow \gamma \gamma$. Because of the large Drell-Yan, $t\bar{t}$ and $W^+W^-$ background, the selection of $H^0 \rightarrow \tau^+\tau^- \rightarrow \epsilon \mu \chi$ signal events is difficult by conventional discriminant method, also because of the large missing energy, in order to be able to reconstrcut its mass, the machine can only be run at low luminosity to avoid the pile-up effect, in this case since lorentz boost

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the final neutrino pair and charged lepton form $\tau$ are almost at the same direction, so the charged lepton direction can be taken as the $\tau$'s. From following formula the neutrino pair transverse momentum $p_T^{\nu_1}$ and $p_T^{\nu_2}$ from each $\tau$ can be calculated,

$$p_T^{\nu_1} \cdot \vec{u}_{T_1} + p_T^{\nu_2} \cdot \vec{u}_{T_2} = \vec{p}_T^{\text{miss}}$$

(1)

with $\vec{p}_T^{\text{miss}}$ being the total transverse momentum loss of pp collision, $\vec{u}_{T_1}$ and $\vec{u}_{T_2}$ the unit transverse momentum vector of charged leptons, then $\tau$'s energy and finally Higgs mass can be reconstructed. Solution of equation 1 requires the acolinearity of $\vec{u}_{T_1}$ and $\vec{u}_{T_2}$, i.e. $|\cos(\phi_e - \phi_\mu)|$ cut is needed to select Higgs with big transverse momentum, therefore the event rate is decreased[1,2,3]. So far the simulation results for this channel are pessimistic.

Recent years NN has shown a great power in pattern recognition and is widely successfully used in high energy physics data analysis, see for example [4-9]. Here based on PYTHIA5.6[10] simulation, as a phenomenological study, a feed-forward NN is designed to identify the $e\mu$ events from different processes, quite satisfactory selection efficiency and background rejection is reached. This kind of NN can also be used for mass reconstruction of resonance particle with large missing energy, by this method the Higgs mass for this channel is correctly reconstructed at high luminosity with pile-up effect existing, which has particular importance for using this channel to search Higgs particle in the intermediate mass range.

2 Monte Carlo Simulation

e$\mu\nu$ events from different processes, $H^0 \rightarrow \tau^+\tau^-$, Drell-yan, $t\bar{t}$ and $W^+W^-$ are produced by PYTHIA5.6 generator, EHLQ1($\Lambda = 200MeV$) structure function is taken. Assuming the detector rapidity coverage range is $|\eta| < 3$ and it can precisely measure the momentum of $e$ and $\mu$ track with 100% efficiency, as putting a 10GeV/c lower limit cut on the transverse momentum of final state $e$ and $\mu$ tracks. Some other parameters and assumptions are as following:

- Electromagnetic calorimeter: resolution is taken as $\sigma/E = 0.15/\sqrt{E} + 0.01$.
- Hadron calorimeter: resolution is taken as $\sigma/E = 0.5/\sqrt{E} + 0.02$.
- Jets: whole detector coverage in $\phi$ range of $[0,2\pi]$ and $\eta$ range of $|\eta| < 3$ is divided into 100 sub-range seperately giving total $10^4$ cells, i.e. the granularity is $\Delta\phi \times \Delta\eta = 0.062 \times 0.06$. Jets are reconstructed by somehow modified LUPCELL algorithm, using all the effective hit cells of energy deposit larger than 1.5 GeV, as well as taking the jet cone size to be $R \equiv \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.5$. The reconstructed jet's transverse momentum are required to be larger than 10GeV/c.
• The total missing transverse momentum of event $p_T^{\text{miss}}$ can be obtained either from all the reconstructed jets or effective cells.

• As for the pile-up effect study, switches in PYTHIA are turned on to take account of low $p_T$ + double and single diffractive processes of total 15 pile-up events, which corresponds to LHC luminosity $\mathcal{L} \sim 1.2 \cdot 10^{34} \text{cm}^{-2}\text{s}^{-1}$ of 15 ns inter-bunch spacing.

3 Events Identification

3.1 Network Structure and Training

A three layered NN, with 13 neurons in input layer, 15 in hidden layer and 3 in output layer, is designed for this purpose. The 3 output neurons correspond to 3 training M.C. data sets with target value 1 for signal and 0 for backgrounds from other two processes.

13 observable physical variables are selected as the input of this NN, which are:

1. $N_{\text{JET}}$, total number of jets.

2. $p_T$, transverse momentum of $e^-$ or $e^+$.

3. $p_{T,\text{iso}}$, transverse momentum of the jet, to which $e^-$ or $e^+$ belongs, substracts $p_T$.

4, 5. $p_T^{\mu}, p_{T,\text{iso}}^{\mu}$, same as above for $\mu$'s.

6. $|\phi_e - \phi_\mu|$, the $\phi$-angle difference of $e$ and $\mu$ track.

7. $|\eta_e - \eta_\mu|$, the rapidity difference of $e$ and $\mu$ track.

8. $N_{\text{HIT}}$, the number of effective cells with deposited energy more than 1.5 GeV in it.

9. $E_{\text{T}}^{\text{total}}$, total transverse momentum of the event.

10. $E_{\text{T}}^{\text{EM}}$, total transverse electromagnetic momentum of the event.

11, 12. $E_{x}^{\text{miss}}, E_{y}^{\text{miss}}$, the $x$ and $y$ components of missing transverse energy calculated from reconstructed jets of the event.

13. $E_{T,\text{max}}^{\text{jet}}$, the largest transverse energy of jet which contains no $e$ or $\mu$ track.
Each of the above observables, which more or less reflects the difference of separate process, is properly nomalazed to $[0,1]$. Considering that Drell-Yan and $H^0$ events are irreducible background to each other, and there are no any reasons to assume the $H^0$ mass value in intermediate energy range, 5000 Higgs events with mass equally distributed in the range $80 GeV < M_H < 130 GeV$ are produced as first training sample set for both Drell-Yan and $H^0$ processes, $t\bar{t}$ and $W^+W^-$ events of each 5000 as second and third set.

The back-propagation training algebra is almost the same as reference [4] but the temperature parameter $T$ in sigmoid activation function

$$f(x) = \frac{1}{1 + exp(-x/T)}$$

are set to be 0.4 in order to make it more behave threshold function to increase compressing ability. The training procedure uses typically 500 million loops. In each loop an event from each of the three training data sets are sequentially fed into the network, and each event in certain set is randomly chosen. The linking weights $W_{ij}$’s and threshold $\theta_j$’s are initialized randomly in $[-0.1,0.1]$. At the very beginning learning strength $\eta$ and “momentum” parameter $\alpha$ are taken to be 0.07 and 0.5. As the training goes $\eta$ is gradually reduced every 10000 loops according to

$$N_{k+1} = N_k \cdot 0.99$$

but not less than 0.0001. The weights and thresholds are adjusted for each loop and updated for every three loops.

If after first training run the result is not so optimal, the outputed weights and thresholds can be taken as initial values to restart next run with newly adjusted $\eta$ and $\alpha$ parameter, in this way the CPU time would be saved for next training procedure.

### 3.2 Test and Result

Once the network is successfully trained, all the weights and thresholds are fixed, it becomes a black “function box" which will give a certain answer for a given input. Independently produced Higgs M.C. data samples with $M_H = 100 GeV$, 110 GeV, 130 GeV respectively or Drell-Yan’s are taken as the first testing set, $t\bar{t}$ and $W^+W^-$ as the second and third ones, each of them consists of 5000 events, are used as inputs to test the NN performance. By setting a cut on each of the three output neuron seperately, the selection efficiency for the corresponding signal process and background rejection level from other two’s are obtained as showing in Fig. 1. It can be seen that Higgs with higher mass has lower selection efficiency and higher contamination to other two processes, and Higgs with lower mass has
higher selection efficiency and lower contamination. Table 1 gives a numerical result by setting 0.7 cut on each of the three outputs.

Table 1: Selection efficiency of different processes by setting 0.7 cut on the corresponding output neuron

<table>
<thead>
<tr>
<th>output neuron No.</th>
<th>Higgs 100 GeV</th>
<th>Higgs 110 GeV</th>
<th>Higgs 130 GeV</th>
<th>Drell-Yan</th>
<th>t#</th>
<th>W⁺W⁻</th>
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</thead>
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<tr>
<td>1</td>
<td>78.9%</td>
<td>74.3%</td>
<td>65.2%</td>
<td>80.7%</td>
<td>4.1%</td>
<td>6.8%</td>
</tr>
<tr>
<td>2</td>
<td>1.7%</td>
<td>2.3%</td>
<td>3.5%</td>
<td>1.9%</td>
<td>65.8%</td>
<td>3.9%</td>
</tr>
<tr>
<td>3</td>
<td>3.2%</td>
<td>3.5%</td>
<td>3.6%</td>
<td>2.6%</td>
<td>4.5%</td>
<td>70.4%</td>
</tr>
</tbody>
</table>

4 Mass Reconstruction

4.1 Network Structure and Training

With this purpose a three layered NN is designed with 12 input neurons, 14 hidden neurons and only one output neuron to give invariant mass information. 33000 $H^0 \rightarrow \tau^+\tau^-$ M.C. events with $M_H$ equally distributed in the range [50GeV,220GeV] are produced as the training set.

The 12 inputs are the same as above defined variables except last one. It could use the same 13's, but it was done this way at the time. All these inputs not only make NN learn enough mass information, but also be able to suppress background events contamination. The target value of output neuron is designed to be $(\log M_H - 3.91)/1.51$ corresponding to $M_H$ range to make it in [0,1].

Training method is almost the same as above, but choosing temperature parameter $T$ to be 1. During training the error change

$$
\sigma = \sqrt{< (M_H^{NN}/M_H^O)^2> - <(M_H^{NN}/M_H^O)>^2}
$$

is watched every 30000 loops, here $M_H^{NN}$ and $M_H^O$ are the $M_H$ NN output and target value respectively, to make sure it goes down all the way until reaching flat, otherwise to stop it, this is out of the consideration that in a limited number of loops $\sigma$ may fluctuate but should keep decreasing trend for every enough number of loops. The weights and thresholds are updated for every 10 loops. Also after first training run if the result is not so optimal, the outputed weights and thresholds are taken as initial values to restart next run with newly adjusted $\eta$ and $\alpha$ parameter for saving CPU time.
4.2 Test and Result

At the testing stage Higgs events of mass being 110GeV and 130GeV, are separately fed into the NN input to see how is its performance. Fig. 2 gives the result and comparison with conventional mass reconstruction method, in which (a,b) for $M_H=110\text{GeV}$, (c,d) 130GeV, (a,c) without $|\phi_c - \phi_\mu|$ cut, (b,d) with this cut. It can be seen that this NN correctly reconstructs the Higgs invariant mass peak position and better width. With $|\phi_c - \phi_\mu| < 0.8$ cut the NN result is consistent with that of conventional method except the later has a peak shift towards low mass end, which can be improved a bit by using the missing transverse energy calculated from all the hit cells as mentioned above.

Fig. 3 gives the result by using Drell-Yan, $t\bar{t}$ and $W^+W^-$ events as input. The $Z^0$ mass peak is well shown up, but no peak in $t\bar{t}$ and $W^+W^-$ mass spectrum, so it exhibits the background suppressing ability of this network.

4.3 Mass Reconstruction for Pile-up Events

As already mentioned that the crucial problem for $H^0 \rightarrow \tau^+\tau^-$ search at high luminosity comes from the impossibility of Higgs mass reconstruction by conventional method because of pile-up effect. Here NN method, in principle the same as before, is employed to see if it helps. Using a training sample of $M_H$ equally distributed in $[50\text{GeV},180\text{GeV}]$ with the above given pile-up parameter, test results for $M_H = 100\text{GeV}$ and 130GeV events are shown in Fig. 4, from which we can see the correct peak position.

5 Conclusion and Discussion

This work is a phenomenological study based on M.C. simulation, in real data analysis the consistency of data and Monte Carlo have to be checked carefully. From the deep study of detector responses better physical variables representing events properties can be chosen to improve the NN performance.

Drell-Yan process as a irreducible background to Higgs events is hard to separate, it can only be suppressed by invariant mass cut when $M_H$ is far away from $M_{Z^0}$.

At high luminosity run with existence of pile-up effect, NN method has particular importance, as higher event rate may make the Higgs search in intermediate mass range through $H^0 \rightarrow \tau^+\tau^- \rightarrow e\mu x$ become possible.
References


Figure Captions

Figure 1: Selection efficiency and background rejection level for different channel with output cut: (a) Higgs and Drell-Yan as signal for first output neuron, (b) $t\bar{t}$ as signal for second neuron, (c) $W^+W^-$ as signal for third neuron.

Figure 2: $M_H$ reconstructed by NN, dotted line are results by conventional method. (a) $M_H=110$GeV, no $|\cos(\phi_e - \phi_\mu)|$ cut; (b) $M_H=110$GeV, with $|\cos(\phi_e - \phi_\mu)| < 0.8$ cut; (c) $M_H=130$GeV, no $|\cos(\phi_e - \phi_\mu)|$ cut; (d) $M_H=130$GeV, with $|\cos(\phi_e - \phi_\mu)| < 0.8$ cut.

Figure 3: Invariant mass of (a) $t\bar{t}$, (b) $W^+W^-$ and (c) Drell-Yan reconstructed by NN.

Figure 4: Invariant mass of (a) $M_H=100$GeV, (b) $M_H=130$GeV reconstructed by NN for pile-up events.
Figure 1

(a) NNOUT1 CUT

(b) NNOUT2 CUT

(c) NNOUT3 CUT

- Drell-Yan
- Higgs
- ttbar
- w pair
Fig. 2
Fig. 3
Fig. 4
Are Quark Mass Differences Responsible for anti-Centauro Events?

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Abstract

High energy reactions may produce a state around the collision point that is best described by a classical pion field. In such configurations, and in the neglect of isospin breaking due to quark mass differences, all directions in isospin space are equally allowed leading to a sizable probability of events with, essentially, only charged particles (Centauros) or all neutral particles (anti-Centauros). (In more common statistical models of multiparticle production, the probability of such events is suppressed exponentially by the total multiplicity.) We find that the isospin violation due to the mass difference of the up and down quarks has a significant effect on these distributions and enhances the probability of all neutral events, without significantly changing the probability of events with only charged particles.

Several unusual high energy events, in which there is an enormous imbalance in the number of charged and neutral particles have been observed. These are the famous Centauro [1] events in which a large number of charged

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particles and no $\pi^0$'s have been observed; candidates for the opposite situation, namely regions of phase space with a large number of $\pi^0$'s and very few charged $\pi$'s, “anti-Centauros”, have also been reported [2]. In usual statistical models of pion production we expect the distribution in the number of neutrals to peak at 1/3, $(n_+ = n_- = n_0 = 1/3$ as $n \to \infty))$ and to decrease exponentially with $n$ as $f$ deviates from this value. A mechanism for producing such skewed distributions has been suggested by several authors [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. This mechanism involves the production of a classical pion field: an interesting example is the “disoriented chiral condensate” [8, 9]. In these situations a region of space around the production point will have the chiral field point along some Cartesian isospin direction. In the process of aligning itself with the normal vacuum this region will radiate mainly pions whose isospin aligns itself with that direction. In events where the isospin is oriented (almost) parallel to the 3-rd axis one would expect mainly neutral pions while in events where the isospin lies in the perpendicular plane predominantly charged pions would be produced. Let $(\pi_1, \pi_2, \pi_3)$ be the three Cartesian isotopic amplitudes of the classical pion field. As all the orientations are equivalent, the distribution in the amplitude $\pi_3$ is

$$dw \sim d\pi_3; \quad \pi^2 = \pi_1^2 + \pi_2^2 + \pi_3^2 = \text{const.} \tag{1}$$

The number of neutral pions, $n_0$, is proportional to $\pi_3^2$ while the total number of produced pions, $n = n_0 + n_+ + n_- \sim \pi^2$. With $f = n_0/n$, the fraction of neutral pions, one has from (1),

$$dw = \frac{df}{2\sqrt{f}}; \tag{2}$$

this distribution is normalized to unity.

The distribution (2) corresponds to the limit $n \to \infty$ and gives for the relative number of events with the fraction of neutrals less than $f$

$$P(f) = \int_0^f \frac{dw}{df} \, df' = \sqrt{f}. \tag{3}$$

For a typical Centauro event $f \sim 1/100$ and $P \sim 10\%$. This seems to be a reasonable number as the five “classic” Centauros represent about 1% of events with appropriate energies [1].
We shall be interested in the spectrum, near \( f = 1 \), the probability of an event having an anomalously large fraction of \( \pi^0 \)'s is

\[
1 - P(f) = 1 - \sqrt{f} \sim \frac{1}{2}(1 - f).
\]  \(\text{(4)}\)

We do not have the square root enhancement exhibited in (3) and instead we find a linear dependence at the end of the spectrum; however, there still is a finite probability of finding events with a large number of \( \pi^0 \)'s. We shall present a mechanism for enhancing the probability of such situations over that of (4).

The distribution (2) results from exact isospin symmetry. At the quark level this symmetry is rather strongly violated due to the up-down quark mass difference, \( m_u \neq m_d \). We shall demonstrate that this mass inequality can enhance the probability of anti-Centauros.

A class of solutions for the pion field whose dynamics are governed by a non-linear chiral Lagrangian was presented in Ref. [5]. The Lagrangian is

\[
\mathcal{L} = \frac{f_\pi^2}{2} \text{Tr} (\partial_\mu U \partial^\mu U^\dagger),
\]  \(\text{(5)}\)

where \( f_\pi = 93 \text{ MeV} \) and the unitary matrix \( U \) is connected to the pion fields by

\[
U = \exp \left( \frac{i \tau \cdot \pi}{f_\pi} \right).
\]  \(\text{(6)}\)

At large distances from the collision point we require the normal structure of the vacuum, i.e. \( U = 1 \). Solutions with these requirements reduce to

\[
U = \exp [i \tau \cdot n \theta(x)]
\]  \(\text{(7)}\)

for some direction \( n \) in isotopic spin space and with

\[
\partial^2 \theta = 0,
\]  \(\text{(8)}\)

and \( \theta(r, t) \rightarrow 0 \) as \( r \rightarrow \infty \). A possible scenario for the production of a classical pion field discussed in [8, 9] is that inside a certain volume around the collision point a state corresponding to a constant (in the volume) \( \theta \) is produced. This state is degenerate with the normal vacuum (in the limit \( m_\pi = 0 \)) but is rotated with respect to it in isotopic spin space. In [8, 9] this situation is referred to as "disoriented chiral condensate".
We now introduce interactions of pions with quarks; the pion field may be viewed as the chiral phase of the quark field [13, 14]. In the presence of a classical pion field the quark fields should be modified

\[ q_L(x) \rightarrow \exp\left(\frac{i}{2} \tau \cdot n \theta(x)\right)q_L \]

\[ q_R(x) \rightarrow \exp\left(-\frac{i}{2} \tau \cdot n \theta(x)\right)q_R. \]

The quark mass terms give rise to the quark-pion interaction Hamiltonian

\[ \mathcal{H} = m_u \bar{u}u + m_d \bar{d}d \rightarrow \bar{q}\exp\left(i \frac{\tau \cdot n \theta}{2}\right)(m_+ + m_- \tau_3)\exp\left(i \frac{\tau \cdot n \theta}{2}\right)q + \text{h. c.,} \]

where \( m_\pm = \frac{1}{2}(m_u \pm m_d) \). For the solution (7)

\[ \mathcal{H} = \bar{q}(m_+ + m_- \tau_3)q - (1 - \cos \theta)\bar{q}(m_+ + m_- \tau_3 \cdot n)q + \sin \theta \bar{q} i \gamma_5 (m_+ \tau \cdot n + m_- n_3)q. \]

Due to the quark masses the energy depends on \( \theta \) and the probability of creation of different \( \theta \)'s will be different. This however will not lead, by itself, to the deviation from the inverse square root law as the three dimensional isotopic space remains isotropic. Quark mass differences do lead to an anisotropic distribution; we would like to know, qualitatively, the form of this deviation. Eq. (11) leads to the chiral perturbation result, \( m_\pi^2 = -m_+(\bar{q}q)/f_\pi^2, \ \pi = f_\pi \theta \) [14]. In the presence of hadronic matter and at finite temperatures the changes in the condensate change the effective pion mass. We should also note that use of current quark masses in the above interactions does not imply that there are light quark excitations in the hadronic matter. The strength of their coupling to pions is, nevertheless, given by the current quark masses. The constituent quark mass, again, depends on the details of the chiral symmetry breaking [14]. Finite values of the other bilinear quark averages, besides providing us with an effective pion mass that depend on the surroundings, give the possibility that \( \theta \) is non-zero at the minimum of the potential.

We would like to know what the effect of this mass difference is on the distribution of the parameters \( \theta \) and \( n \). We assume that in the region of a very high energy collision a disoriented chiral vacuum, in contact with
thermalized quark matter [11], is produced. The temperature of the matter is larger than $T_c$, the temperature of chiral symmetry is restoration [8, 9]. The average of $\theta$ over the whole collision region will vanish; however smaller regions may have non-zero values for this average. As time progresses this region grows and the temperature decreases. In Refs. [8, 9] the system is assumed to stay in thermal equilibrium as it cools down through $T_c$ and to hadronize at some $T < T_c$. In Ref. [10] this transition is assumed to take the system out of equilibrium by quenching the high temperature configuration and then letting it evolve by equations of motion at fixed energy (microcanonical ensemble). For the present discussion it is not important to know whether the quark matter does or does not stay in equilibrium, as long as it is correlated over large regions; this assumption will be needed further on. The probability of finding a distribution of $\theta(x)$ will be assumed to be thermal and determined by the Hamiltonian of (11) and some temperature $T < T_c$.

$$dw \sim \int \prod_x d\theta(x) \exp \left( -\frac{1}{T} \int d^3x \mathcal{H} \right) d\eta \delta(n^2 - 1).$$

(12)

In the rest of the paper we shall take $T = T_c$ and note that this assumption under-estimates the size of the effects we are interested in. A crucial question, to which we have no answer, is what is the probability of forming such correlated regions; for a recent review see Ref. [11].

If the quark density in the collision is not too high $\langle \bar{q}q \rangle$ should be set equal to its usual vacuum value. Expanding around $\theta = 0$ (12) becomes

$$dw \sim \int \prod_x d\theta(x) \exp \left( -\frac{m_+ |\langle \bar{q}q \rangle|}{2T^2} \int d^3x \theta^2 \right) d\eta \delta(n^2 - 1).$$

(13)

For $T = T_c \sim 140$ MeV and a volume $V \sim 100$ fm$^3$ the above is $\exp[-4 < \theta^2 >]$; large values of $\theta$ will not be excited. However, after the functional $\theta$ integration the distribution in isospin directions remains uniform leading immediately to (2).

Our critical assumption is that in the high density medium created by such collisions the quark density and other bilinears in $q, \bar{q}$ acquire classical values that may be comparable to or larger than the vacuum chiral condensate $\langle \bar{q}q \rangle \simeq -(250$ MeV)$^3$. From the explicit dependence of (11) on $n_3$ we see that isospin rotation symmetry is broken. We consider the possibility that $P(x) = \langle \bar{q}i\gamma_5q \rangle \neq 0$, in addition to $S(x) = \langle \bar{q}q \rangle \neq 0$ and is sizable. $\langle \cdots \rangle$
denotes the averaging over quantum fluctuations and we allow for a smooth (on the microscopic scale) position dependence. The value of \( S(x) \) may differ significantly from the vacuum value of \( \langle \bar{q}q \rangle \). The distribution is given by

\[
dw \sim \int \prod_x d\theta(x) \exp \left\{ \frac{1}{T} \int d^3x \exp \left[ m_+ S(x) (1 - \cos \theta) - m_- n_3 P(x) \sin \theta \right] \right\} d\mathbf{n} \delta(n^2 - 1). \tag{14}
\]

The functional integral can be done and, aside from a prefactor, yields

\[
dw \sim \exp \frac{1}{T} \int d^3x \left[ +\sqrt{m_+^2 S^2(x) + m_-^2 P^2(x) n_3^2 + m_+ S(x)} \right] dn_3. \tag{15}
\]

Although we could analyze this result it is simpler to consider the situation where \( |m_-/m_+ S| < 1 \). Keeping only the first term in the expansion of the square root we obtain (ignoring, in the case \( S(x) \) is positive, terms not depending on \( n_3 \))

\[
dw \sim \exp \left[ \frac{1}{2T} \int d^3x \left. \frac{P^2(x)}{|S(x)|} \right| n_3 \right] dn_3. \tag{16}
\]

Remembering that \( f = n_3^2 \) we find

\[
dw = N(A) e^{Af} \frac{df}{2\sqrt{f}}, \tag{17}
\]

where

\[
A = \frac{1}{2T} \int d^3x \left. \left. \frac{P^2(x)}{|S(x)|} \right| \right. \tag{18}
\]

and the normalization factor

\[
N^{-1}(A) = \int_0^1 dx e^{Ax^2}. \tag{19}
\]

The change in the distribution from that of (2) is important only if \( A \) is large enough. However, as we shall see \( A \) is proportional to the collision volume and we will argue that it cannot be small. In this case the distribution (17) has a minimum at \( f = 1/2A \) and, contrary to the situation described by (2), grows as \( f \) approaches 1. For \( A \gg 1 \) an approximate evaluation of (19) yields

\[
dw \sim Ae^{-(1-f)A} \frac{df}{\sqrt{f}}. \tag{20}
\]
This distribution has a peak at $f = 1$ and is enhanced near that value by a factor $2A$ over that of (2) making anti-Centauros more probable.

We shall now try to estimate possible values for $A$. Note that (18) depends on the absolute value of $S(x)$ and on the square of $P(x)$; thus, all spatial regions will add to the value of $A$. In a region of significant nuclear density $S(x)$ will differ from its vacuum value and will be related to the sum of the quark and anti-quark densities. We would like to compare it to $\rho(x) = \langle \bar{q}q^0 \rangle$, which is the difference of quark and anti-quark densities. Although the collision region of interest will contain an equal number of quarks and anti-quarks, $\rho(x)$ may be either positive or negative and large over sizable regions (see discussion following (12)). For $|\rho(x)| \geq (250 \text{ MeV})^3$, $S(x)$ will coincide with $\rho(x)$ rather than with its vacuum value. $P(x)$ can be represented as

$$P(x) = \xi R \sigma(x) \cdot \nabla \rho(x).$$

(21)

Here $\sigma(x)$ is some spin density, $R$ is a characteristic linear size of the effective volume (or characteristic time before hadronization) and $\xi$ is a constant, probably smaller than one.

Integrating (18) we get

$$\int d^3x \frac{P^2(x)}{|S(x)|} = 4\pi R^2 r^2 \frac{\xi^2 \rho^2}{r^2} \frac{1}{\rho} = \frac{4}{3} \pi R^3 \frac{3R}{r} \frac{\xi^2}{r} \rho.$$

(22)

We use $r$ as a characteristic length for the gradient; this variation in density is likely to be confined to the surface of the quark matter produced in the collision. We assume that the volume over which $P(x)$ does not vanish is $4\pi R^2 r$. The spin densities are averaged approximately to unity. Thus for the parameter $A$ we have:

$$A = \xi^2 \frac{m^2}{2T} \frac{3R}{m_+} \frac{N}{r} \simeq \frac{1}{70} \frac{R}{r} \xi^2 N.$$

(23)

Here $N = 4\pi R^3 \rho/3$ is the number of quarks produced. We believe one could expect $N \geq 200$ in a sphere of $R \simeq 3 \text{ fm}$ (note that for the vacuum $\rho = <\bar{q}q> = 2 \text{ fm}^{-3}$, so that $N \approx 200$). For $R/r \simeq 5$ we find $A \sim 15 \xi^2$. Note that $\xi \leq 0.8$ is required for the approximation in going from (15) to (16); sizable values of $A$ are to be expected. We are well aware of the crudeness of these estimates and the purpose of this exercise was only to show that values of $A \geq 1$ are not excluded. As $A$ is proportional to the volume it is unlikely to be very small; we have presented almost a dimensional estimate.
References


Abstract

Expected atmospheric $\bar{\nu}_e$ fluxes will result in a significant number of resonantly produced, free electrons, low mass hadronic vector states, as the $\rho$, in large volume neutrino telescopes. The existence of sources of higher energy neutrinos will result in the production of higher mass states, as the $D_s^*$ and the $(\bar{t}b)_{J=1}$. The production rates of these states, independent of theoretical flux determinations, will be a tool for experimentally determining these fluxes. We present a calculation of the rates of production of several of these resonances.

Below $10^4$ GeV atmospheric neutrinos are a certain source of such high energy particles [1]. Interesting sources of neutrinos with energies higher than $10^4$ GeV have been postulated; Active Galactic Nuclei (AGN) [2] are the most promising source in that TeV gamma rays have been detected from Markarian

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†Supported by the Swedish Research Council and an EEC Science grant
and there is consensus that fluxes of all neutrino flavors of comparable intensity exist [4]; as a large number of AGNs is known to exist one can estimate the expected diffuse neutrino flux [5]. Unexpected sources might be early universe relic neutrinos [6]. $\nu_e$'s with such energies are kinematically capable of producing hadronic resonances when scattered off free electrons.

Large volume high energy neutrino telescope with potential effective areas of the order of $10^9$ cm$^2$ and volumes greater than $2 \times 10^{13}$ cm$^3$ [7, 8, 9] are being planned. In this note we point out a method of determining or setting bounds on $\bar{\nu}_e$ fluxes at various energies corresponding to the production of the standard vector quark-antiquark resonances, namely $\rho$, $D_s^*$ and possibly $(\bar{t}b)$; rates for the production of other states is significantly lower because of Cabibbo or helicity suppression. This complements the Glashow [10] mechanism for resonant $W^-$ production.

We study the resonance production of hadronic states: $\rho$'s, $D_s^*$'s with a mass of 2.1 GeV and of the $J = 1$ state of the $(\bar{t}b)$ system. For completeness we also present results for the helicity suppressed $\pi$ production and the Cabibbo suppressed $K^*$ production. For a vector meson $R$ the production cross section is

$$\sigma = \frac{12\pi \Gamma(R \rightarrow e\nu)\Gamma}{M_R^2 (E_{cm} - M_R)^2 + \Gamma^2 / 4}. \quad (1)$$

Integrating over a $\bar{\nu}_e$ flux, $\Phi(E)$, the production rate in a volume $V$ is

$$\text{Rate} = \frac{48\pi^3 \Gamma(R \rightarrow e\nu)\Phi \left( \frac{M_R^2}{2m_e} \right)}{M_R m_e} N_e V, \quad (2)$$

where $N_e$ is the electron density (in water $N_e = 3.4 \times 10^{23}$/cm$^3$). In the above we assume that the flux does not change rapidly over the width of the resonance. The flux, $\Phi(E)$ is averaged over azimuthal angles. Resonance production in $\bar{\nu}_e e^-$ scattering has been previously discussed by Mikaelian and Zheleznykh [12].

We need a theoretical model for the leptonic partial widths of these resonances. The partial width $\Gamma [(Q\bar{q})_{J=1} \rightarrow e\nu]$, for a vector resonance made out of $Q$ and $\bar{q}$ quarks, is obtained from the related electromagnetic widths of the $QQ$ system. For the latter we use the empirical relation [11]

$$\Gamma [(Q\bar{Q})_{J=1} \rightarrow e^- e^+] = 12e_Q^2 \text{keV}, \quad (3)$$
where $e_Q$ is the charge of the $Q$ quark. In terms of the nonrelativistic quark model this implies that the wave function at the origin is proportional to the reduced mass. Using these facts we find

$$\Gamma [(Q\bar{q})_{J=1} \rightarrow e\nu] = 192M_Q^2M_q^2 \left( \frac{G_F}{4\pi\alpha} \right)^2 \text{keV}. \quad (4)$$

For the $\rho$ meson conservation of isospin gives a firmer result, consistent with the one above,

$$\Gamma (\rho \rightarrow e\nu) = 12M_\rho^4 \left( \frac{G_F}{4\pi\alpha} \right)^2 \text{keV}. \quad (5)$$

Combining Eq. (2) and Eq. (4), we find for a volume of $2 \times 10^{13} \text{cm}^3$ (the smallest of the proposed neutrino telescope volumes)

$$\text{Rate} = 8 \times 10^{11} \frac{M_Q^2M_q^2}{M_R} \Phi \left( \frac{M_R^2}{2m_e} \right) /\text{year}, \quad (6)$$

where $\Phi$ is in units of $(\text{cm}^2 \text{ s sr GeV})^{-1}$ and all masses are in GeV. For the $\rho$ meson, the corresponding result is

$$\text{Rate} = 1.7 \times 10^{10} \Phi(580 \text{ GeV})/\text{year}. \quad (7)$$

The results, with calculated atmospheric neutrino fluxes (ATM) [1] and theoretically estimated active galactic neutrino fluxes (AGN) [5, 13] are given in Table 1. (For the calculations we use a $t$ quark mass of 175 GeV.) For production of the $\rho$ resonance we agree with Ref. [12]; results for other resonances differ as we used a different, and more conservative, model for $\Gamma [(Q\bar{q})_{J=1} \rightarrow e\nu]$.

**Table 1: Unsuppressed Vector Meson Production in $2 \times 10^{13} \text{cm}^3$.**

<table>
<thead>
<tr>
<th>State</th>
<th>Energy(GeV)</th>
<th>ATM Flux</th>
<th>AGN Flux</th>
<th>Events/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>$5.8 \times 10^2\times 10^{13}$</td>
<td>$6 \times 10^{-11}$</td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>$D^*_s$</td>
<td>$4.4 \times 10^3$</td>
<td>$10^{-13}$</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td>$(\bar{t}b)_{J=1}$</td>
<td>$3.2 \times 10^7$</td>
<td>$5 \times 10^{-21}$</td>
<td></td>
<td>$3.5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Table 2: Suppressed Meson Production in $2 \times 10^{13}$ cm$^3$.

<table>
<thead>
<tr>
<th>State</th>
<th>Energy (GeV)</th>
<th>ATM Flux</th>
<th>Events/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>19.4</td>
<td>$10^{-5}$</td>
<td>0.05</td>
</tr>
<tr>
<td>$K^*$</td>
<td>$7.8 \times 10^2$</td>
<td>$6 \times 10^{-11}$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

We also present, in Table 2, results for the production of two low mass states that are either helicity suppressed $\pi$ or Cabibbo suppressed $K^*$.

The atmospheric neutrino flux calculations [1] are conservative and we certainly expect that the neutrino telescopes will see several $\rho$ events per year. The $\nu_\mu$ fluxes are calculated to be an order magnitude larger. Should there be any significant neutrino mixing [14] enhancing the $\nu_e$ flux, the rates due to atmospheric neutrinos would go up significantly. As mentioned earlier the rates presented in this work are for the smallest volume telescope planned. Although the rate for production of $(t\bar{b})_{J=1}$ due to the calculated AGN neutrino flux is well below the feasibility of any telescope, there might be totally unexpected sources. The detection of hadronic resonances will provide an experimental determination or limit on $\bar{\nu}_e$ fluxes. We have presented rates for events totally contained in the neutrino telescope volume. These events will be characterized by having no visible particle entering the volume and 600 GeV or more of hadronic energy deposited locally in the detector in thin hadronic and/or electromagnetic shower of length 6 m to 10 m. [15].

References


Study on UHE $\gamma$ Point Source in Different Coordinate

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Abstract

The famous suspect gamma point source Hercules X-1 has been analysed in detail by using the data from June 1990 to January 1992 with the Tibet air-shower array. Based on the traditional method, the same data were studied in the horizontal coordinate. The results show that the significance in the horizontal coordinate is lower than that in the equatorial coordinate. The upper limit of Hercules X-1 was obtained in horizontal coordinate, the reason of adopting the horizontal coordinate is discussed and the fact that the analysis of background data is helpful for reporting the significance properly is pointed out.
1 Introduction

Study on UHE gamma point source has been become an important subject for last decade in the cosmic ray field. Obviously, the confirmation of the point sources would be helpful for solving a series of problems, such as cosmic ray origin, propagation and acceleration. But there are some difficulties in confirming the point source, the main problem is that the significance and upper limit estimations reported for a few of famous UHE suspected sources (Cygnus X-3, Crab Nebula, and Hercules X-1) are different because of different selecting standards adopted by different groups. For example, for the Cyg X-3, there have not been other reported since Kiel group reported the 4.4σ DC excess in 1983.

Hercules X-1 is a binary system, where the accompanied star is neutron star with 2.4 solar mass and 1.24s period, the binary orbital period and the modulaties in this system are 1.7day and 35days seperately. VHE γ-ray emission was first reported by the Durham group pulsed at the 1.24σ period.[1] UHE γ-ray emission pulsed at the 1.24σ period was first observed at the Fly’s Eye during 40 minutes in July 1983.[2] From then on, although many group indicated that the Her X-1 was a UHE gamma point source, the significances were less than 3σ. In this paper, the method of analysis the UHE gamma data in the horizontal coordinate will be reported.

2 Study on UHE γ point source of Her X-1

2.1 Data selecting

For studies on cosmic-ray sources we first made a database by imposing the following conditions on the recorded events. (1) Each of any four detectors should detect a signal more than 1.25 particles. (2) Among the four detectors which record the highest particle densities, two or more should be in the inner 5×5 detectors. (3) The mean lateral spread of showers <r> should be less than 25m, where <r> = Σr_iρ_i/Σρ_i and r_i is the distance of the i-th detector from the estimated core and it's particle density. Events satisfying these conditions are called "contained" events: about 25% of the total recorded events.[3] For getting the background, we exduced the data of days power-off, our judgement is that there are not power-off when the source around culmination in 2 hours, and the interval of two events must less than 10 minutes. Under above judgement, we get data of 384 days from 16th Jane 1990 to 14th January 1992. Using the data of 384 days, we study the steady emission and burst, and estimate the upper limit using all the data.

2.2 Traditional analysis method

According to the traditional analysis method, on-source events N_on and off-source events N_off in equatorial coordinate are recorded respectively. For the Her X-1 (α=254.5°, δ=35.2°), the on-source events are located in the 1° × 1° square field of the center of Her X-1, and the off-source events in 4 same fields of the center left and right. Comparing the N_on
with \( N_{\text{off}} \) each day, the significances can be estimated by using following expression:

\[
S = \sqrt{2N_{\text{on}} ln\left[\frac{(1 + \alpha)}{\alpha(N_{\text{on}}/(N_{\text{on}} + N_{\text{off}})) + N_{\text{off}} ln\left[\frac{(1 + \alpha)(N_{\text{off}}/(N_{\text{on}} + N_{\text{off}}))}{(1 + \alpha)(N_{\text{on}}/(N_{\text{on}} + N_{\text{off}}))}\right]}\right]}^{1/2}
\]

(1)

here, \( \alpha \) is the ratio of observation of on-source and off-source, \( \alpha = 1/4 \). The significances of 384 days is given in Fig(1a), it can be fit well by Gaussian distribution without \( 3\sigma \) excess. For the short burst of Her X-1, dividing every day into 50 bins, then the distribution of background with time is obtained by using data of 384 days. The time correction is considered as follows because the time which the source gets to the culmination each day is different: under the element day (48060 of Modified Julian Day), the variation of counts with the time is obtained, the time of source getting to the culmination after a year (365.25 days) is the same as last year, so the time difference of two days is \( 1/365.25 \) days. From the element day, the time of the data after that is \( T_n - 365.25 \). Excluding the background, we get the significance of on-source events of same time period each day.

### 2.3 The method in the horizontal coordinate

Considering the zenith angle effect and the angular resolutions of the array (about \( 1^\circ \)), there is insufficiency of selecting the background windows in the same right ascension belt and the square source field \( 1^\circ \times 1^\circ \) can't embody the angular resolution of the array. So we consider another method in the horizontal coordinate as below: At any time, using the right ascension and the declination of source and the time of the events (MJD), we can determine source coordinate \((\theta, \phi)\) in the horizontal coordinate. \( \theta \) is zenith and \( \phi \) is azimuth, then in the same \( \theta_0 \) belt, select the different cones as on-source window and off-source's. [5] Fig.2 shows how to select in the horizontal coordinate. Here, \( r_0, r_{01}, r_{02} \) is the arbitrarily vector of space, and

\[
r_0 = r_{01} = \cos \theta \tag{2}
\]

\( \theta \) is the angle between two vectors, assuming the directional cosine of \( r_0 \) and \( r_{01} \) is \( l_0, m_0, n_0, l, m, n \). We get

\[
l_0 = \sin \theta_0 \cos \phi_0 \tag{3}
\]

\[
m_0 = \sin \theta_0 \sin \phi_0 \tag{4}
\]

\[
n_0 = \cos \theta_0 \tag{5}
\]

\[
l = \sin \theta_0 \cos \phi_{01} \tag{6}
\]

\[
m = \sin \theta_0 \sin \phi_{01} \tag{7}
\]

\[
n = \cos \theta_{01} \tag{8}
\]

and then we prove

\[
r_0 r_{01} = l l_0 + m m_0 + n n_0 \tag{9}
\]

here we use \( \theta = 2^\circ \),

\[
\sin^2 \theta_0 \cos \phi_0 \cos \phi_{01} + \sin^2 \theta_0 \sin \phi_0 \sin \phi_{01} + \cos^2 \theta_0 = \cos 2^\circ \tag{10}
\]

Solving the equation (10), get two \( \phi_0 \), one is \( \phi_{01} \), another is \( \phi_{02} \). The center point of two cone right and left the source are \((\theta_0, \phi_{01}), (\theta_0, \phi_{02})\) respectively. Similarly, we can get many
cone in the same zenith belt around source, thus we have confirmed the windows of on-source and off-source. For the experiment data, using the method below, we can calculate the \((l,m,n)\) with the time and \((\theta,\phi)\) of every event, if

\[ r.r_0 = l\phi + m\phi + n_0 > \cos 1^\circ \]  

(11)

this event is on-source event, if

\[ r.r_{01} = l\phi + m\phi + n_{01} > \cos 1^\circ \]  

(12)

this event is in background 1, etc.

2.4 Upper limit estimation

Using the method of reference [4] to estimate the background of on-source observation, \(B = \alpha N_{\text{off}}, \alpha\) is time ratio of on-source observation to off-source's. Using the method of reference [6] to calculate the 95% confidence level \(S_{95}\), from the equation (13), the upper limit of steady emission of Her X-1 is:

\[ J(\geq E_{\text{min}}) = S_{95}/(T \times A \times \eta) \]  

(13)

here, \(T\) is the time of on-source observation, \(A\) is the effective area of array, \(\eta\) is the observation efficiency. Using the counts of \(N_{\text{on}}\) and \(N_{\text{off}}\) of horizontal coordinate, the upper limit of Her X-1 is,

\[ J(\geq 10 TeV) = 4.2 \times 10^{-13} \text{cm}^{-2}\text{s}^{-1} \]  

(14)

the upper limit of suspected explosion is: \(J(\geq 10 TeV) = 4.54 \times 10^{-10} \text{cm}^{-2}\text{s}^{-1}\), this is lower than the result of reference [3].

3 Discussion and Conclusions

The significance of on-source events every day for 384 day data were calculated in the horizontal and equatorial coordinates respectively. The distributions of significances in these coordinates are shown in Fig. (1a) and (1b), it can be seen there are not 3\(\sigma\) excess.

In the equatorial coordinate, the suspected of 30 minutes for Hercules X-1 was found in our calculations, in which, the significance is 4\(\sigma\) in the time interval 48513.72-48513.74, the distribution of on-source counts and background counts around 48513 are shown Fig (3a). The on-source and background counts are 25 and 11 respectively when Hercules X-1 pulsed. But in the horizontal coordinate, the significance is only 3\(\sigma\) in the same time interval, corresponding distribution is shown in Fig (3c).

For the source observation, the highest efficiency of observation is that when the source arrive at culmination. So we are interested in studying the data of culmination in two different coordinate respectively. It is noted that there exists 5\(\sigma\) in the background of equatorial coordinate, see in Fig (4). However in the horizontal coordinate there is not more than 4\(\sigma\) excess. But the counts in the background are also higher than the on-source counts. If the traditional method is reliable, and the 4\(\sigma\) excess of the counts is a possible short burst, what's the physics meaning of the 5\(\sigma\) excess in the background in equatorial coordinate. This is a question available to further study.
4 Acknowledgement

We are grateful to Professor L.K.Ding and Professor Q.Q.Zhu of IHEP, Academia Sinica, for their support and encouragement. We also wish to thank all the member of Tibet AS-γ collaboration.

5 References

Fig 1. The significance distribution of off-source counts of 384 days in different coordinate of Her X-1 source.

Fig 2. Selecting the windows in horizontal coordinate.
Fig 3. On-source counts and background distribution with the time of suspected pulse day (Modified Julian day) in different coordinate.

Fig 4. Significance distribution of two time bins' counts around the culmination of selective background (equatorial coordinate).
PLASMA WAKE-FIELD ACCELERATE COSMIC RAY PARTICLES

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Abstract

Analysing and comparing the corresponding data and physical conditions, find that it is possible that there is a new type cosmic ray particles acceleration mechanism: nonlinear plasma wake-field acceleration, which is advanced in the research of high energy accelerator, and explain the cosmic ray particles acceleration with it.

I. Introduction

Since Pisin Chen and J. M. Dawson et al[1] put forward the plasma wakefield accelerator (PWFA) firstly in 1985, it has been the subject of much theoretical investigation recently[2]. Under the assumptions necessary for linearization of the fluid equations, it is shown that it can generate strong acceleration field which is larger than 1 GeV/m, but the transformer ratio is less than or equal to two for symmetric longitudinal beam-current profile. Excitation of nonlinear plasma oscillations by an ultra-relativistic electron beam is considered by Jams Rosenxweig[3]. It is shown that under certain conditions on the relative densities of the electron beam and the plasma, extremely large longitudinal electric field can be generated in the wake of the beam, and the ratio of the maximum amplitude of the accelerating field behind the driving beam over the maximum amplitude of the decelerating field inside of the beam, can be made arbitrarily large, dependent only on the length of the driving beam.

In this paper we introduce the nonlinear plasma wakefield acceleration theory in Sec. II, and in Sec. III, we analyse and compare the corresponding data and physical condition of cosmic rays, and discuss the cosmic ray particles acceleration, Finally, we summarize the analysis in Sec. IV.

II. Nonlinear plasma wakefield acceleration theory

In relativistic case, large amplitude plasma oscillation frequency is smaller than the plasma frequency, this change can be attributed to two physical effects: the relativistic mass increase of the plasma electrons, which causes a downshift in the frequency, and the modulation of the plasma electron density
during the oscillation, which can both increase or decrease the local oscillation frequency. The nonlinearity of these oscillations can be useful attribute to create large amplitude electrostatic plasma waves in the wake of an intense electron beam.

Considering that the driving beam is ultrarelativistic, we introduce a change of dependent variable:

\[ \chi(\tau) = \left( \frac{1 - \beta}{1 + \beta} \right)^{1/2} \]

\[ \tau = \omega_p(t - z/V_{ph}) \]

where \( V_{ph} \) is the wave phase velocity, the direction of propagation is \( Z \) axis. Defining \( \alpha = n_b/n_e \), where \( n_b \) is the density of electron beam, and \( n_e \) is the density of plasma. The equation for nonlinear electron oscillations in a cold collisionless plasma with stationary ions is thus

\[ \chi''(\tau) = \frac{1}{2} \left( \frac{1}{\chi^2} - 1 + 2\alpha \right) \]

(1)

The first integral of equ. (1) is then

\[ (\chi'(\tau))^2 = 2(1 - \alpha) - \frac{1}{\chi} - (1 - 2\alpha)\chi \]

(2)

To take the most physically interesting and mathematically transparent case, set \( n_b = n_e/2 \), we get

\[ (\chi')^2 = 1 - \frac{1}{\chi} \]

(3)

Integrating 3, we have

\[ \tau = \chi^{1/2}(\chi - 1)^{1/2} + \ln[(\chi - 1)^{1/2} + \chi^{1/2}] \]

(4)

In the limit of large \( \chi \) (in a long bunch), \( \tau \) becomes approximately equal to \( \chi \).

With the continuity conditions on \( \chi \) and \( \chi' \), we can calculate the oscillation amplitude and electric field in the wake of the bunch. From equ. (2), we get

\[ \gamma_m = \gamma + \frac{1}{2}(\chi')^2 \]

\( \gamma \) is the Lorentz factor of the plasma electrons; \( \gamma_m \) is its maximum value. The electric field behind the beam is thus

\[ E = \pm \frac{m e \omega_p}{e} (2\gamma_m - (\chi + \frac{1}{\chi}))^{1/2} \]

(5)

Defining \( \tau_f = 2\pi n_b/\lambda_p, \lambda_p = 2\pi C/\omega_p \), and \( \chi_f = \chi(\tau_f) \), where \( \gamma_m = (\chi_f + 1)/2 \). The maximum accelerating field amplitude behind the bunch is given by
The maximum decelerating field inside the bunch is

\[ E_- = \frac{m c \omega_p}{e} \left( 1 - \frac{1}{\chi_f} \right)^{1/2} \]  

Thus the transformer ratio is

\[ R = \frac{E_+}{E_-} = \chi_f^{1/2} \]

### III. The plasma wake-field accelerate cosmic ray particles

The research of the acceleration mechanisms of high energy cosmic ray is an important subject. Here we discuss that the plasma wakefield accelerate the solar flare particles.

The solar flare is a process in solar corona in which huge energy is suddenly released, and the most violent active phenomenon. On the mechanisms of solar flare, scientists have put forward many kinds of models and hypotheses. The magnetic field line rebinding theory which is advanced by American astronomer Stalac recently is popular. In the theory, he thought that the flare energy comes from the magnetic field, as in Fig. a, there is not only block magnetic field, but also open magnetic field and neutral points as n. Near by the neutral points, the magnetic field is unstable, and it is possible that the magnetic field lines rebind and shape as Fig. b shown, and release huge energy in this process, and form upward and arc track downward particle beam. This theory has been confirmed by observation. All the particles in the beam formed in the solar flare are relativistic. The upward beam propagates through the solar corona. The corona is the region \( \geq 10^4 \text{km} \) above the photosphere joining on continuously to the interplanetary medium. At base of corona number density \( n_e = 10^9 \text{cm}^{-3} \). The corona is homogeneous on a large scale, with overdense regions called streamers, and under-dense regions called holes. Density up to ten times larger in streamers. Now we consider to inject a solar flare beam into the corona streamer. The wake-field formed can accelerate the late-coming flare particles. The wake-field can be given by nonlinear acceleration mechanisms. From equ. (6)

\[ E_+ \approx n_0^{1/2} \left( \chi_f - 1 \right)^{1/2} \]
For $l_b \gg \lambda_p$,

$$E_+ \approx n_0^{1/2}(2\pi l_b/\lambda_p)^{1/2} \quad (10)$$

We take $n_0 = 10^{10} \text{ cm}^{-3}$, the effective acceleration length $l_b = 1 \text{ km}$, and $\lambda_p = c/f_p = c/8.98 \times 10^3 n_e^{1/2}$, so $E_+ \approx 1.37 \times 10^9 \text{ V/m}$. The electrons entering this electric field can get energy higher than Tev.

IV. Summary

We think it is possible that nonlinear plasma wavefield accelerate the propagation solar flare particles to energy higher than Tev. Certainly there are many other problems to be discussed, for example, the probability of $n_b = n_o/2$ that nonlinear wakefield acceleration demand, and the efficiency of this acceleration mechanism in the astronomy.

Reference

Critical exponent $\beta$ and deconfinement
phase transition in SU(2) lattice gauge theory*

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Abstract

Based on the sixth order cumulant expansion calculation of the order parameter, Polyakov line $\langle L \rangle$, of the SU(2) lattice gauge theory at finite temperature ($N_c = 1$), the critical exponent $\beta$ is shown to be compatible with the universality conjecture. An extrapolating approach to determine the deconfinement phase transition point is discussed.

1. Introduction

The study of lattice gauge theories at finite temperature has attracted much attention in recent years. The formation of the quark-gluon plasma (QGP) in the relativistic heavy ion collisions or of the high energy cosmic ray interactions is linked with the deconfinement phase transition. Most of the information has came from Monte Carlo simulations (MC). However, in order to get a more insight into the physical essentials, the analytical study is necessary.

For a lack of an exact solution to the problem, a series of analytical approximate methods have been developed. Among them the variational cumulant expansion method (VCE) provides a systematic approximate analytical calculation scheme in lattice gauge theories in the whole range of coupling constant at zero temperature [1] and at finite temperature [2]. The deconfinement phase transition is happened in the intermediate coupling region, where the strong and weak coupling expansion methods fail to work, while the mean field theory (MF) is poor in precisely describing the critical phenomena. Therefore, as a step forward to the calculation of the realistic

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deconfinement phase transition in the lattice QCD, here we study the order parameter \( \langle L \rangle \) of the SU(2) lattice gauge Wilson model at finite temperature \( (N_t=1) \) by VCE to the sixth order expansion. In this way we can show the convergency of the VCE in the intermediate region and elaborate the method in determining the deconfinement phase transition point.

On the other hand, the universality idea, backed by renormalization group calculations, predicts that, if the transition is continuous, the critical behaviour of a \((d+1)\)-dimensional gauge theory and of a \(d\)-dimensional spin system with the same symmetry will be the same \([3,4]\). In particular, the critical exponent \( \beta \) of the \((3+1)\)-dimensional SU(2) gauge model will be the same as that of the 3-dimensional Ising model \( \beta = 1/3 \). The idea has been tested and confirmed by MC for the SU(2) lattice gauge model at \( N_t = 2 - 4 \) \([4,5]\). But as we know, the data of \( \langle L \rangle \) from MC are data from "computer experiments", thus the test from the analytical calculation would be desirable. Based on the calculated \( \langle L \rangle \) by CVE to the sixth order, we will show that the critical behaviour is compatible with the universality prediction in our case.

In turn, adopting the universality prediction, we propose an extrapolating procedure to improve the determination of the deconfinement phase transition point.

The paper is arranged as follows. In sect. 2 the calculational scheme of VCE is briefly described. In sect. 3 the determination of the variational parameter and the calculation of \( \langle L \rangle \) are presented. The emphasis is put on the intermediate coupling region. In sect. 4 the critical behaviour of \( \langle L \rangle \) is shown to be compatible with the universality conjecture. Finally in sect. 5 an extrapolating procedure is discussed.

2. Variational cumulant expansion (VCE)

We will consider a SU(2) lattice gauge model on \((3+1)\)-dimensional hypercubic lattice at finite temperature \( T = 1/(N_t a) (N_t = 1) \) with the Wilson action

\[
S = \bar{\beta} \sum_P \text{tr} U_P,
\]

where \( \bar{\beta} = 2/g^2 \), \( U_P \) is an ordered product of \( U \in SU(2) \) around the boundary of a plaquette, and the sum is over all the plaquettes. The partition function is

\[
Z = \int [dU] e^S, \quad (2)
\]
where \([dU]\) is an invariant Haar measure.

According to VCE [1], a trial action \(S_0\) is introduced

\[
S_0 = J \sum_i \text{tr} U_i,
\]

(3)

where sum is over all the links, and \(J\) is the variational parameter to be determined later. An auxiliary system with the action \(S_0\) has a calculable partition function

\[
Z_0 = \int [dU] e^{S_0} = \left[ \frac{I_i(2J)}{J} \right]^{N_i},
\]

(4)

where \(N_i\) is the total number of links and \(I_i(2J)\) is the modified Bessel function.

Then, the partition function \(Z\) can be expressed as

\[
Z = Z_0 \exp \left( \sum_{n=1}^{\infty} \frac{1}{n!} \langle (S - S_0)^n \rangle_c \right),
\]

(5)

where \(\langle \cdots \rangle_c\) is the cumulant average in the auxiliary system. Only the products of statistically correlated elements have nonzero cumulant averages.

The order parameter \(\langle L \rangle\) can be expressed as [2]

\[
\langle L \rangle = \langle L \rangle_0 + \sum_{n=1}^{\infty} \frac{1}{n!} \langle L(S - S_0)^n \rangle_c,
\]

(6)

with

\[
L = \frac{1}{2} \text{tr} U_r(x),
\]

(7)

In our case \(N_r = 1\), \(U_r(x)\) is the SU(2) element defined on the time-like link started from the site \(x\) and ended at the same site by the periodic condition. Now, \(\langle L \rangle\) can be calculated systematically order by order.

3. Determination of \(J\) and calculation of \(\langle L \rangle\)

The formula (6) is exact and \(\langle L \rangle\) is independent of the parameter \(J\). In practice one truncates the expansion to get the \(i\)-th order approximation

\[
\langle L \rangle \approx \langle L \rangle_i = \langle L \rangle_0 + \sum_{n=1}^{i} \frac{1}{n!} \langle L(S - S_0)^n \rangle_c,
\]

(8)

It is the function of \(\bar{\beta}\) and \(J\). By scanning \(J\) at fixed \(\bar{\beta}\), one chooses such values of \(J\) with which \(\langle L \rangle_i\) converges best. Similar to the U(1) case calculated to the higher order expansion [6], in the strong coupling region \(J = 0\) and \(\langle L \rangle = 0\), and in the intermediate and weak coupling regions in the \(i\)-th order approximation we choose \(J_i\).
as the solution of the equation
\[
\sum_{n=1}^{i} \frac{1}{n!} \langle L(S - S_0)^n \rangle_c = 0 \quad \text{for } \beta \text{ fixed}
\] (9)

Then
\[
\langle L \rangle_i = \langle L \rangle_0 \mid_{J=J_i} \quad \text{for } \beta \text{ fixed}
\] (10)

In fact, \( J_i \) correspond to the intersection points of the scanning curves \( \langle L \rangle_i \) with \( \langle L \rangle_0 \) at fixed \( \bar{\beta} \). A typical pattern of scanning curves is shown for \( \bar{\beta} = 0.84 \) in Fig. 1. It is seen that with increasing \( i \), \( J_i \) and the corresponding \( \langle L \rangle_i \) show a good convergent behaviour. Then, varying \( \bar{\beta} \) and using eq. (10), the \( \langle L \rangle_i \) versus \( \bar{\beta} \) are obtained and plotted in Fig. 2.

Since \( \langle L \rangle \) is related to the free energy of an isolated quark \( F_q \) and the vacuum energy \( F_0 \) via
\[
\langle L \rangle = e^{-\beta(F_q + F_0)},
\] (11)
the change of \( \langle L \rangle = 0 \) to \( \langle L \rangle \neq 0 \) at \( \bar{\beta}_c \) corresponds to the deconfinement phase transition from the confinement phase to the deconfined phase. In the \( i \)-th order approximation the change of \( \langle L \rangle_i = 0 \) to \( \langle L \rangle_i \neq 0 \) gives the approximate phase transi-
tion point $\bar{\beta}_c$, which are presented in table 1.

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
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<td>0.6667</td>
<td>0.7303</td>
<td>0.7557</td>
<td>0.7782</td>
<td>0.7901</td>
<td>0.7995</td>
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</table>

With increasing the order of expansion $\bar{\beta}_c$ form a convergent series. $\bar{\beta}_c$ is very close to the MC estimation $\bar{\beta}_c = 0.80$ [7].

4. Test of the universality conjecture

The universality conjecture has been tested for SU(2) Wilson model by MC[4, 5]. Suppose that the conjecture holds and the deconfinement phase transition in our case is continuous, the order parameter $\langle L \rangle$ in $3 + 1$ dimension will behaviour like

$$\langle L \rangle = A(\beta - \beta_c)^\theta, \quad \beta \to \beta_c^+, \quad (12)$$

with A-constant and $\beta = 1/3$, the same value for 3-dimensional Ising model. Since it is hard to determine $\beta_c$ precisely in MC, to avoid the difficulty, eq. (12) is converted
<L>^3 = C(\bar{\beta} - \bar{\beta}_c), \quad \bar{\beta} \rightarrow \bar{\beta}_c^+. \quad (13)\]

\langle L \rangle^3 from MC data versus \bar{\beta} are fitted by a straight line, thus the linearity of eq. (13) or the universality conjecture is confirmed [5]. The intercept of the straight line on \bar{\beta} axis determines the value of \bar{\beta}_c.

We follow the same procedure with the difference that our \langle L \rangle \approx \langle L \rangle_1 are calculated analytically. The \langle L \rangle^3 versus \bar{\beta} are plotted in Fig. 3. The linearity of \langle L \rangle^3 vs. \bar{\beta} are clearly seen in the interval \Delta \bar{\beta} = \bar{\beta} - \bar{\beta}_c \approx 0.16 except in the very vicinity of \bar{\beta}_c, where \langle L \rangle^3 are curvic due to the approximation. In fact, the cumulant expansion is an expansion according to the correlations [6], while the correlation length increases with \bar{\beta} \rightarrow \bar{\beta}_c. Thus in the very vicinity of \bar{\beta}_c the approximation even to the sixth order is not enough. The same feature is observed in the MC test, where the linearity of \langle L \rangle^3 vs. \bar{\beta} is confirmed in the interval \Delta \bar{\beta} \approx 0.20 except in the very vicinity of \bar{\beta}_c, where \langle L \rangle^3 is not well determined [5]. Therefore, our analytical calculation is on an equal footing with MC in confirming the universality conjecture in the case of \( N_r = 1 \).
5. The extrapolating procedure

Let us consider inversely, if the universality idea is adopted, the exact calculated \( \langle L \rangle^3 \) will be a straight line with the intercept \( \bar{\beta}_c \) as the phase transition point. From Fig. 3 we see that the linear parts of \( \langle L \rangle^3 \) converge and \( \langle L \rangle^3 \) almost coincides with \( \langle L \rangle^3 \) for \( 0.86 \leq \beta \leq 0.97 \). Thus, this part of \( \langle L \rangle^3 \) provides us a good approximation to a part of \( \langle L \rangle^3 \). Then extrapolating that linear part of \( \langle L \rangle^3 \) in Fig. 3 down to the \( \bar{\beta} \) axis by a dashed line, we obtain the approximated \( \langle L \rangle^3 \) in the vicinity of \( \bar{\beta}_c \) with the intercept \( \bar{\beta}_c^* = 0.8108 \). Consequently, \( \bar{\beta}_c^* \) may be served as a good approximation to the phase transition point \( \bar{\beta}_c \). In the table 2 the phase transition points from the sixth order approximation \( \bar{\beta}_c \), the extrapolated \( \bar{\beta}_c^* \), from the strong coupling expansion (SC), from the mean field theory (MF) and from the MC[7] are presented for comparison.

<table>
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<tr>
<th></th>
<th>( \bar{\beta}_c )</th>
<th>( \bar{\beta}_c^* )</th>
<th>MF</th>
<th>SC</th>
<th>MC</th>
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<td>0.7995</td>
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</table>

In conclusion, for SU(2) lattice gauge model at finite temperature \( N_s = 1 \) the calculation of \( \langle L \rangle \), by VCE to the sixth order shows a good convergency in the intermediate coupling region. The critical exponent \( \beta \) is compatible with the universality conjecture. Adopting the critical exponent \( \beta \) predicted by the universality idea, we propose on extrapolating procedure to determine the deconfinement phase transition point more precisely.

However, the test by the linearity of \( \langle L \rangle^{1/\beta} \) is not a proof, since this linearity is not very sensitive to the small change of \( \beta \). It is desirable to calculate \( \beta \) directly for different models to get a more convincible test of the universality conjecture.
References

QUARK DELOCALIZATION, COLOR SCREENING AND THE N-N SPIN-ORBIT INTERACTION

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Sichuan University, Chengdu, 610064

We have proposed a new model to deal with hadron interactions. The new ingredients of the model are:

1. Quark delocalization

   In the usual quark cluster model, two single quark orbits are assumed:

   \[ \psi_L(r) = \left( \frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b^2}(r-r_L)^2} \]  
   \[ \psi_R(r) = \left( \frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b^2}(r-r_R)^2} \]

   Here \( r_L \) and \( r_R \) are centers of the clusters and \( R = r_L - r_R \) is the separation of the centers of two clusters.

   The delocalized quark orbits are:

   \[ \chi_L(r) = r_1 \psi_L(r) + r_2 \psi_R(r) \]  
   \[ \chi_R(r) = r_1 \psi_L(r) + r_1 \psi_R(r) \]

   \( r_1 = \frac{1}{N}, r_2 = \frac{\varepsilon}{N}, N = (1 + 2\varepsilon (\psi_L/\psi_R) + \varepsilon^2)^{1/2} \)

   The delocalization parameter \( \varepsilon (R) \) is determined variationally for every \( R \) in adiabatic approximation.

2. Color screening

   If \( i, j \) occur in the same cluster orbit

   \[ V_{ii}^s = -\lambda_i \cdot \lambda_j \cdot r_{ij}^s \]

   If \( i, j \) occur in different cluster orbit

   \[ V_{ij}^s = -\lambda_i \cdot \lambda_j \operatorname{ar}_\varepsilon^{-m_i^2} \]

   The color screening parameter is the only free parameter in our model and fixed by data.

Note that there is no van der Waals force problem for this model because we have taken color screening into account.
Our model has been successfully applied to the N-N \((S,T,L=0,1,0;1,0,0;0,1,2)\) channels and Delta-Delta \((S,T,L=3,0,0)\) channel. The phase shifts are reproduced qualitatively. The quark delocalization and color screening actually do seem to give rise to an effect very similar to the nuclear intermediate range attraction. It seems that they may play an effective role similar to meson exchange. Our first paper published in Phys. Rev. Lett. 69 (1992)2901.

Since then what we have done are:

(1) To separate the center-of-mass wave function and to eliminate the CM motion effect due to the quark delocalization by introduction the projection operator:

\[
\frac{1}{\sqrt{V}} \int e^{-r^2} dt \xrightarrow{p=0} \frac{1}{\sqrt{V}} \int dt
\]

Our calculation states that the CM motion correction is not too large a effect. We can adjust the color screening parameter to refit the phase shifts.

(2) To study how sensitive of our model results to the variation of color screening. The lattice gauge calculation \cite{1} give an effective q-q confining potential of the form

\[
V^r(r) \sim \frac{a}{\mu} (1 - e^{-nr})
\]

which almost the same short range behavior as those of we used before but different for the long range part. We approximate it to be

\[
V^r_{ij} = -\lambda_i \cdot \lambda_j \frac{a}{\mu} (1 - e^{-n^2})
\]

and get similar fit. It tells us the long range behavior of the screening confining potential is not critical because the Gaussian decreasing of the exchange overlap dominates the long range behavior of N-N interaction.

(3) To study the effects of the single particle orbit choice. Several trial give the exactly same results if the orbit is flexible enough to allow the six quark system to develop its preferred distortion.

(4) To determine the delocalization after orbit angular momentum \(L\) projected as PHF replace HF. Then the delocalization parameters not only depend on \((S,T)\) but also on \((L, J)\).

(5) To begin the spin-orbit interaction study.

The new results are shown in Fig. 1-5. The experimental phase shifts are taken from Ref. \cite{2}. The dash lines are the results of usual quark cluster model with color screening.
The solid lines of our model. It is well known that the pure quark cluster with gluon exchange can only give rise to a N-N oepulsive core. The figures, however, show that quark delocalization and color screening working together can produce a rather good description of the N-N interaction; it has both the repulsive core and an intermediate range attractive, and without the van der Waals force problem.

This model seems to imitate meson exchange to some extent. But the relation between quark delocalization and meson exchange is not yet clear. A better basis in QCD is needed.

The spin-orbit interaction calculation is to investigate our model further. Only the symmetric spin-orbit q-q interaction of the Breit-Fermi interaction has been included. The calculated $^3P_0$ phase shifts are enhanced to be about half the experimental one which is not good as the result given in Ref. [3] (to be about three-quarters), where an effective meson exchange potential consists of the central and tensor parts is included. However the fact that part of the meson exchange effect has been simulated by quark delocalization and color screening has obtained further confirmation. And we hope that if the antisymmetric spin-orbit and tensor q-q interaction is included the larger part of the N-N spin-orbit interaction may be generated by our model.
The quark delocalization parameters $\sigma(R)$ are in Table 1-2. It shows that when nucleons separate infinitely the delocalization is small, which means the six quarks prefer to be in two individual nucleons. However, when the two nucleons are close together the delocalization is large, which means that at short distances the six quarks prefer to merge into a six-quark state instead of two nucleons. This is our main physical picture, even if there are some structures in some channels. It is an open question to be studied in the future.

Tab. 1 The quark delocalization parameters (1)

<table>
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Tab. 2 The quark delocalization parameters (2)

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The Dependence of Transverse Energy Rapidity Distribution on Nuclear Geometry in High Energy Hadron—nucleus Interactions

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Mei Dongming
(Department of Mathematics and Physics, Tibet university, Lhasa 850000, China)

Abstract: We assume that the produced particles decay isotropically with respect to the center of reacting mass system, and give the transverse energy rapidity distribution in hadron—nucleus interactions. The calculated result can well analyses the recent experiment results given by HELIOS Collaboration working at CERN/SPS.

I Interaction

The study of proton interactions in a nucleus has become of renewed interest owing to the intense experiment and theoretical activities related to the possibility of parton disconfinement and the formation of a quark—gluon plasma in nucleus—nucleus (A—A) interaction [1, 2]. Data on proton—nucleus (h—A) interactions at high energy are needed for a better understanding of the interaction processes and also provide information for the complex A—A interaction.

The transverse energy rapidity distribution of h—A interactions has been analysed by some paper[3], which realized the processes of h—A interactions are the superposition of many h—h interaction in the target. They assume, to a pair of h—h interaction, that the energy conservation and transverse momentum cutoff[3], which can analyse the early h—A interactions results given by HELIOS Collaboration at a narrow rapidity region (0. 6<η<2. 4)[4].
In this paper, firstly, we define a reacting mass system consisting of one incident proton and $v$ collided nucleons by incident proton in target, secondly, assume the produced particles decay isotropically with respect to the center of reacting mass system, and finally give the transverse energy rapidity distribution in a broad rapidity region ($-2 < \eta < 6$) through superposing various events of having different impact parameter $b$ and transverse energy ($E_T$).

II Model

1. The new experiment features

Recently, HELIOS Collaboration has given the transverse energy rapidity distribution for Proton-Uranium (Copper) interactions at $P_{\text{lab}} = 200\text{GeV}/\text{C}$ [1], which gives three striking features:

(i) The energy region of $h-A$ interaction has increased over 40GeV, which is double more than that of $h-h$ interactions at the same incident energy.

(ii) Comparing to the previous publication for $h-A$ interactions given by HELIOS Collaboration [4], The new data [1] Covers much broader rapidity region. The distribution curves of transverse energy rapidity are different with the alteration of transverse energy region. With the increasing of transverse energy ($E_T$), the maximum place of distribution curve moves to small rapidity regions.

(iii) The distribution curves, to proton interacting different target, are different. The heavier the target, the smaller rapidity region to which the maximum place of distribution curve moves.

In the following, We will study the upper experiment features with our reacting mass system model.

2. The center of reacting mass system

The nuclear geometry play an important role in high energy $h-A$ interaction. The transverse energy distribution of produced particles depends on how many nucleons the incident hadron meets and how it interacts with
the nucleons. At a certain impact parameter $b$, supposing that $v$ nucleons inside the target are collided by incident hadron, the number of participating nucleons in the interaction system is $v + 1$. With respect to laboratory coordinate system, the rapidity of center of reacting mass system is (derivation see Appendix)

$$\eta_{CRS} = \frac{1}{2} \ln \left(1 + 2P_{lab}/v \right),$$

(1)

here, $P_{lab}$ is the momentum of incident proton ($P_{lab} = 200\text{GeV}/C$). The relation between the rapidity of Center of reacting mass system ($\eta_{CRS}$) and the number of participating nucleons ($v$) is given by Table. I, We Can Conclude that the rapidity ($\eta_{CRS}$) decreases with the increasing of $v$.

<table>
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</tr>
</tbody>
</table>

3. The transverse energy rapidity distribution

At a certain $b$, We suppose that the produced particles decay isotropically with respect to the center of reacting mass system. The rapidity distribution is

$$\rho(\eta) = \frac{1}{2 \cosh^2(\eta - \eta_{CRS})}.$$  

(2)

The transverse energy rapidity distribution of particles whose energy covers $(E_A, E_B)$ is

$$\frac{dE_T}{d\eta} = \sum_{v=1}^{\nu_{max}} \sum_{\mu=1}^{\mu_{max}} \int_{E_A}^{E_B} \frac{E_T}{2 \cosh^2(\eta - \eta_{CRS})} W(\mu \mid v, p) F_A(v) P(E_T \mid 1 + \mu) dE_T,$$

(3)
here, $\sum_{\nu_1} \sum_{\mu=1}^{\nu_1} \frac{E_T}{2 \cosh^2(\eta - \eta_{cbs})} W(\mu | \nu, p) F_A(\nu) P(E_T | 1 + \mu)$ is the probability of observing final state particles whose energy is $E_T$, $W(\mu | \nu, p)$ is the probability of $\mu$ of the $\nu$ nucleons inside the target interacts with the incident proton nondiffractively, whose form is $W(\mu | \nu, p) = \binom{\nu}{\mu} p^\mu (1 - p)^{\nu - \mu}$, here $p = 0.75$.

At a certain $b$, to $\mu$ nondiffractive collision, the transverse energy distribution is [5]

$$P(E_T | 1 + \mu) = \frac{(1 + \mu)^{1+\mu}}{\mu!} \frac{1}{E_T} \left[ \frac{E_T}{(E_t)_{hh}} \right]^{\frac{\mu}{2}} \exp\left[\frac{E_T}{(E_t)_{hh}}(1 - (1 + \mu) \frac{E_T}{(E_t)_{hh}})\right],$$

(4)

Using $(E_t) = \frac{1 + \mu}{2} (E_{t, hh})$, we get finally

$$P(E_T | 1 + \mu) = \frac{1}{\mu!} \left( \frac{2}{(E_t)_{hh}} \right)^{1+\mu} E_T^\mu \exp\left(-2 \frac{E_T}{(E_t)_{hh}}\right),$$

(5)

here $(E_t)_{hh}$ is the average transverse energy for $h-h$ interaction in the same incident energy as $h-A$ interaction. $(E_t)_{hh}$ is the only adjustable parameter in the paper.

III The Results

In Figure 1 (a, b), we give the transverse energy rapidity distribution for $P-U$ (Cu) interaction at $P_{lab} = 200$GeV/c. The solid curves are the calculated results from Eq. 3, the parameter $(E_t)_{hh} = 1.3$. Our calculated results can well analyse the data given by HELIOS Collaboration [1].

We can analyse the three features given by reference [1] in terms of our model. The interactions for smaller impact parameter $b$ might provide large participating nucleon number ($\nu$) of reacting mass system. From Eq.
Figure 1 (a, b) The rapidity transverse energy distribution in high energy proton-U (Cu) interactions ($P_{lab} = 200\text{GeV/C}$). The solid lines are our calculated results. The data is taken from reference [1].
and Eq. 3, we can deduce that the maximum place of distribution curve might move to smaller rapidity region with the increasing $v$. At a fixed transverse energy, incident energy and impact parameter $b$, the maximum place of distribution curve also moves to smaller rapidity region. We can conclude that the transverse energy rapidity distribution depends on the nucleons number of reacting mass system. In $h-A$ interactions, the number of nondiffractive nucleons $1 + \mu_{\text{max}} > 2$, therefore, the energy limits of $h-A$ interaction will exceed that of $h-h$ interaction.

**Appendix**

In laboratory coordinates, the momentum of incident proton is $P_{\text{lab}} (= 200\text{GeV/C})$. Suppose the mass of incident proton and velocity are, respectively, $m$ and $\beta$, therefore,

$$P_{\text{lab}} = \frac{m\beta}{\sqrt{1 - \beta^2}}, \quad (A1)$$

the velocity of incident proton is

$$\beta = \frac{P_{\text{lab}}}{\sqrt{P_{\text{lab}}^2 + m^2}}, \quad (A2)$$

The Lorentz factor is

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} = \frac{\sqrt{P_{\text{lab}}^2 + m^2}}{m}, \quad (A3)$$

At a certain $b$, suppose $\nu$ nucleons will be collided by incident proton, therefore, the total nucleons number of reacting mass system is $1 + \nu$. With respect to Lab Coordinates, the velocity of center of reacting mass system is
\[
\beta_c = \frac{\gamma_p m \beta}{\gamma_p m + m v} = \frac{P_{\text{lab}}}{\sqrt{P_{\text{lab}}^2 + m^2 + m v}},
\]

(A4)

The rapidity of center is

\[
\eta_{\text{cRS}} = \frac{1}{2} \ln \frac{1 + \beta_c}{1 - \beta_c} = \frac{1}{2} \ln \frac{\sqrt{P_{\text{lab}}^2 + m^2 + m v + P_{\text{lab}}}}{\sqrt{P_{\text{lab}}^2 + m^2 + m v - P_{\text{lab}}}},
\]

(A5)

here \(P_{\text{lab}} = 200, \ m \approx 1, \ \sqrt{P_{\text{lab}}^2 + m^2} \approx P_{\text{lab}}, \) therefore

\[
\eta_{\text{cRS}} = \frac{1}{2} \ln (1 + 2P_{\text{lab}}/v),
\]

(A6)

which is the Eq. 1 in the paper.

References

IS IT DARK MATTER NECESSARY TO EXPLAIN

GALAXY ROTATION CURVES?

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The aim of this speech is to show that the well known luminosity-rotation velocity relation in the galaxies and other large astronomical systems perhaps does not need the presence of dark matter.

It is well known [1,2,3,4,5] that the observations of discrepancies between the luminosity and dynamical masses in large astronomical systems have two possible explanations: the Universe contains significant amount of dark matter which manifests itself on the scale of individual galaxies, or the usual law of gravity does not apply on these scales.

We know that the stars in most galaxies lie mainly in a thin disk and travel on nearly circular orbits around the galactic center. The circular speed at a given radius can be determined from the Doppler shift of spectral lines in either the integrated starlight or the interstellar gas that rotates with the stars. If one compares the observed centripetal acceleration with the calculated gravitational acceleration due to the luminous mass, one finds that there are significant discrepancies between observed and calculated curves. For instance if one compares the observed rotation curve in the disk galaxy NCG 3198 with the circular speed derived from the assumptions that the disk surface brightness is proportional to the surface density and that there is no dark matter, one obtains that the predicted speed is more than a factor 3 lower than the observed speed at the outermost measured point even with the assumption that the mass-to-light ratio of the disk is taken as large as possible [5]. The shapes of rotation curves suggest that the dark matter is distributed in extended halos that surround the visible stars.
The same problem arises when one analyses the velocity dispersion curves of clusters of galaxies. For instance the analysis of velocity dispersion curves in the Coma cluster shows that the mass contained within 1.3 Mpc of the center of the Coma cluster is about $8 \cdot 10^{14} M_\odot$ while the derived mass is 30 times far larger than that expected for a mixture of stars like that seen in the cluster galaxies. Thus stars account only a few percent of the mass in the Coma cluster. Also if one takes into account the presence of gas mass that arises from considerations of the presence of X-rays in Coma cluster due from thermal bremsstrahlung in gas at a temperature of $\sim 10^8 K$, this additional gas mass contributes not more than 20% of the total mass inside 1.3 Mpc.

This problems happens also at cosmological scale when one consider questions connected with the density parameter $\Omega$ which is $\Omega_0 \approx 0.1$ when calculated from mean density as derived from observed mean luminosity, while many cosmologists believe that $\Omega$ is about 1 in order to include the inflation hypothesis and to resolve many problems connected with standard Friedmann-Robertson-Wlaker cosmology. So it seems that the hypothesis of a presence of dark matter is neccessary in order to explain all these things.

On the other hand, as for instance Milgrom did [1], it is possible that the apparent evidence of dark matter arises from inadequacies in the conventional laws of gravity: in fact ther is little evidence that Newtonian gravity is accurate on scales much larger than 0.1pc, the size of the solar system comet cloud.

Some people for instance considers a modified gravitational acceleration adding to the Newtonian expression $GM/R^2$ a term $GM/R_0 R$ where $R_0$ is some new fundamental length. In that case, the circular speed around a mass $M$ at a distance $R >> R_0$ would be $(GM/R_0)^{1/2}$ consistent with the flat rotation curves of disk galaxies. However in this case the circular speed should scale as $L^{1/2}$ (where $L$ is the total luminosity of the galaxy) while the observation gives $L^{0.25}$, then this modification of dynamic law is not satisfactory.

Milgrom [1] gives a much interesting modification of the Newtonian dynamics (MOND): he introduces a new fundamental acceleration $a_0$ so that the acceleration from a point mass $M$ is
In this case the circular speed at large distances is $(GMa_0)^{1/4}$ consistent with observations that circular speed should scale as $L^{1/4}$. The interesting thing is that (see for instance [6,7,8,9,10]) discrepancies tend to appear at low accelerations, not at large distance, and this is the principal empirical motivation for MOND. Moreover the success of MOND in explaining flat rotation curves of galaxies without dark matter is not just that MOND implies flat rotation curves: it predicts the exact form of the rotation curve for a specific galaxy from the observed distribution of stars and gas more successfully than multi-parameter dark halo models [4]. The critical point that in general many peoples emphasize, is that MOND is ad hoc: the introduction of fundamental acceleration $a_0$, despite the phenomenological success, is ad hoc; but as noticed in [10] the equality of fundamental acceleration $a_0 \approx 10^{-8}$ with $cH_0$ points to a possibly profound connection with cosmology and renders the theory less ad hoc.

Now we have a theoretical basis for the existence of a fundamental acceleration $a_0 = cH_0$: in fact if we introduce torsion in the general relativity theory, we find some minimal and maximal quantities [11] and, among other things, also a minimal acceleration $a_{\text{min}} = cH_0$.

The starting point is a generalization of general relativity. From physical point of view I think that one must generalize Einstein theory in the sense that when we like to apply general relativity to the field of elementary particles, we must take account of the spin. In fact every particle has not only mass but also the spin. As the mass is connected with the curvature of space-time, spin is connected with another geometrical property of space-time that is called torsion. This concept of torsion was introduced by Cartan in 1922 and represents a very little modification od Einstein theory, simply to take the affine connection non symmetric. The theory is called Einstein-Cartan theory and despite the slight and more natural modification of Einstein theory, the consequences are enormous (by the way with the
Einstein-Cartan theory is possible also to arrive at a quantum theory of gravity).

Einstein-Cartan theory is invariant respect the Poincaré group, and we know that in the torsion picture gauge fields described by tetrads transform invariantly under SL(2,C) gauge group (under local Lorentz rotations of tetrad). In this sense Einstein-Cartan theory is formally more complete that Einstein theory not only in mathematical sense but also in physical sense because, as already said, the spin enter in the theory.

Here we will underline the fact that spin cannot be neglected and then we must correctly use Einstein-Cartan theory.

In order to arrive at a definition of a minimal acceleration that we will see to be given by $a_0 = cH_0$, we will pass, as short as possible, through some relations derived by the introduction of torsion that at first sight seems to be very far for this aim.

First of all we recall that the spin-torsion interaction energy between spin $S$ and torsion $Q$ has been shown to be [12]

$$E = - S \cdot Q$$

(2)

and the formal analogy of this expression with the interaction energy of a magnetic dipole $\bar{\mu}$ in constant magnetic field $\bar{H}$ i.e. $\bar{\mu} \cdot \bar{H}$, shows that spin in spaces with torsion behaves like a dipole in a magnetic field, i.e. will orient predominantly along the torsion direction. Then it is easy to show that we are led to a magnetic field

$$B = (8\pi/3c)(2\alpha G)^{1/2} \sigma$$

(3)

where $\alpha$ is the fine structure constant and $\sigma$ the spin density.

Subsequently flux conservation would have made the field behave as $Bt = BT^{-2} = \text{const.}$ with expansion time $t$ and temperature $T$. Such a magnetic field would have accelerated charged particles in the early universe. For a particle with charge $e$, the relativistic Larmor frequency is given by $\omega = (ecB/h)^{1/2}$ implying a magnetic energy $\hbar \omega = (ehcB)^{1/2}$. It is known that this would imply a critical magnetic field when $(ehcB)^{1/2}$ equals the rest mass energy $mc^2$ of the particles – i.e. when the gyroradius $r/G$ becomes smaller than the Compton length. Thus quantum considerations impose a critical magnetic field strength of $B_c = \ldots$
m^2c^3/\hbar \). At the Planck epoch when \( m = m_{Pl} = (\hbar c/G)^{1/2} \), this implies a \( B_{\text{max}} \) of \( c^4/eG \approx 10^{58} G \); now, as \( \omega_L = (ecB/\hbar)^{1/2} \) implies a circular (or helical) acceleration in the magnetic field of the charged particle with \( a = \omega_L^2 r_g \) we will have \( a = (ecB/\hbar)r_g \). If we substitute \( B_{\text{max}} = c^4/eG \) and the corresponding \( r_g = (hG/c^3)^{1/2} \) at the Planck epoch we have the expression for maximal acceleration as

\[
a_{\text{max}} = c^{7/2}/(\hbar G)^{1/2} = m_{Pl}c^3/\hbar = 5 \cdot 10^{53} \text{ cm s}^{-2}
\]  

(4)

So this expression for maximal acceleration is originated as a quantum effect due to torsion and one can also note that in this expression of maximal acceleration for a charged particle the electric charge is not involved: instead there is the Planck constant which is connected with spin.

We can also remember that we can arrive at minimal length by considering the non-closure property of a contour in the space-time with torsion, that is:

\[
1^\alpha = \int Q_{\mu\nu}^\alpha \, dA^{\mu\nu} = 0
\]  

(5)

(where \( dA^{\mu\nu} = dx^\mu \wedge dx^\nu \) is the area element enclosed by the loop) over a closed infinitesimal contour is different from zero; this non-closure property can be treated as defects in space-time in analogy to the geometrical description of dislocations (defects) in crystals, and this can constitute a way to go toward the quantization of gravity. In fact torsion is related to the intrinsic spin, and then if we connect torsion to the fundamental unit of intrinsic spin \( \hbar \), we find that the defect in space-time topology should occur in multiples of the Planck length, so that we can write \( \int Q \, dA = n(hG/c^3)^{1/2} \) and for the same reason considering the fourth component we have also an analogous situation as regards the time, namely \( t = (1/c)\int Q \, dA = n(hG/c^5)^{1/2} \) which gives a minimum unit of time \( \neq 0 \) (for \( n = 1 \)). So the minimal length and the minimal time are dictated by torsion.

We shall now indicate how \( a_{\text{min}} \) can be defined: we have the formula for the acceleration due to torsion in an exact solution of Einstein-Cartan theory as
This relation can be used to obtain both $a_{\text{max}}$ and $a_{\text{min}}$. For $a_{\text{max}}$ using $S \approx h$ and $R_{\text{min}} = (\hbar G/c^3)^{1/2}$ (as explained earlier), we get

$$R_{\text{max}} = a_{\text{max}} = G^2 h^2 / c^4 (\hbar G/c^3)^{5/2} = c^{7/2} / (\hbar G)^{1/2}$$  \hspace{1cm} (7)

which agrees with what was stated above!

For $a_{\text{min}}$ we have to invoke cosmological parameters in the above equation. For $S$ we take the total spin of universe which, as was shown earlier [13, 14], was given by a cosmological solution involving torsion as:

$$S_0 = 10^{120} h$$ \hspace{1cm} (8)

(by the way this is the same as found in Gödel universe and the implied rotation of the universe is between the limits imposed by isotropy of background radiation). For $R$, the maximal radius i.e. $R = R_H$, the Hubble radius, we have from (7)

$$R_{\text{min}} = a_{\text{min}} = G^2 S_0^2 / c^4 R_H^5 = \left[ c^{7/2} / (\hbar G)^{1/2} \right] \left[ S_0 / h \right]^2 \left[ L_{\text{Pl}} / R_H \right]^5$$

$$= a_{\text{max}} \left( S_0 / h \right)^2 \left[ L_{\text{Pl}} / R_H \right]^5 \approx 10^{-8} \text{cm sec}^{-2}$$ \hspace{1cm} (9)

which agrees with what is assumed in MOND.

So we see that both $a_{\text{max}}$ and $a_{\text{min}}$ follow as consequence of an exact solution of Einstein-Cartan theory based on torsion.

In order to see that (9) is identical to $a_{\text{min}} = c H_0$, we will now proceed to estimate the maximal and minimal temperature associated with $a_{\text{max}}$ and $a_{\text{min}}$. First of all we notice that the minimal operationally definable temperature is

$$T_{\text{min}} = \hbar c / k_B R_H$$ \hspace{1cm} (10)

where $R_H$, the maximal background scale, is the Hubble radius.

Now we will show that this minimal temperature is connected with the minimal acceleration $a_{\text{min}}$ as given above by the effect of
torsion. In fact another familiar result that an observer in a state of uniform acceleration, $a$, finds himself in a thermal bath of temperature

$$T = \frac{ha}{k_B}c$$  \hspace{1cm} (11)

Thus if we put $a_{\text{min}}$ in (11), we will have a minimal temperature of

$$T_{\text{min}} = \frac{ha_{\text{min}}}{k_B}c$$  \hspace{1cm} (12)

Substituting for $a_{\text{min}}$ eq.(8), as found above through torsion, we find finally (after substituting also for $S_u$ etc.)

$$T_{\text{min}} = \frac{hc}{k_B}R_H$$  \hspace{1cm} (13)

which is the same as equation (10). Now from eq.(11) we can express $a_{\text{min}}$ as

$$a_{\text{min}} = k_B T_{\text{min}} c/h$$  \hspace{1cm} (14)

so that substituting equation (13) for $T_{\text{min}}$ and using $R_H = c/H_0$ then gives

$$a_{\text{min}} = c H_0$$  \hspace{1cm} (15)

This is just the formula required by MOND.

References

Multiquark Clusters In Three Body Systems

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Abstract

We study multiquark cluster effect in three body systems by use of electromagnetic processes in this paper. We propose a Hybrid Quark Hadron (HQH) model to describe nuclear structure. The model solves many long-standing puzzles in three-body systems. Our principal finding is that multiquark cluster effect plays an important role in understanding of some peculiar experimental phenomena of three-body systems at higher momentum transfers.

1 Introduction

The traditional picture of the nucleus in low energy nuclear physics is that of an interacting many-body system of structureless, point-like protons and neutrons. By the low energy nuclear physics we understand the region of excitation energies $\delta E$ smaller
than the Fermi energy ($\varepsilon_F \approx 30 - 40 \, \text{MeV}$) and momentum transfer $\delta q \leq 1/R$, where $R$ is the nuclear radius.

The situation changes as $\delta E$ and $|\delta q|$ increases by several hundreds of MeV up to a few GeV, the domain of intermediate energies physics. At this point, explicit mesonic degrees of freedom become directly visible. The pion, in particular, is of fundamental importance. With its small mass of $m_\pi = 140 \, \text{MeV}$, it is by far the lightest of all mesons. As mesons become important, nucleons begin to reveal their intrinsic structure. Inseparably connected with pionic degrees of freedom is the role of the $\Delta(1232)$, the spin 3/2 - isospin 3/2 isobar reached from the nucleon by a strong spin - isospin transition at an excitation energy of $\delta E = M_\Delta - M_N = 300 \, \text{MeV}$, the $\Delta$ - nucleon mass difference.

At the same time as these developments proceeded, Our colleagues of high energy physics provided strong evidence for the quark structure of hadron. In particular, since the discover of the $J/\psi$ particle we have become thoroughly convinced of the quark structure of hadron. As a consequence, there is an obvious necessity to investigate nuclear phenomena from a more fundamental point of view. In particular, study of short distance phenomenology of nuclear wave function where the quark cores of nucleons overlap become very interesting. Altogether, this is a challenging program, and there is little doubt that activities in this direction will represent a substantial branch of intermediate energy physics research in coming years.

In this paper, we study possible existence of quark degrees of freedom in nuclear phenomena. In sect. 2, we present some strong experimental signals for the presence of multiquark clusters in nuclei. In order to describe quark effect in nuclei we propose a hybrid quark hadron model in sect. 3. In sect. 4, we study the electromagnetic form factors of three - body systems in the HQH model. Finally, we reserve our concluding remarks stemmed from the present research for sect. 5.
2 Possible existence of multiquark clusters in nuclei

Since the discovery of $J/\psi$ particle, we have become thoroughly convinced of the quark structure of hadron. A nucleon consists of three valence quarks carrying about 36% of its momentum, a sea of virtual quark-antiquark pairs carrying 10% of its momentum, and gluons carrying 54% of its momentum. With these new developments, we may conclude that a nucleus can be thought of as being a system of quark clusters.

On the other hand, since the internucleon separation in nuclear matter is of the order of the diameter of a nucleon, a sizable fraction of nuclear matter consists of overlapping nucleons. In quark models which fit the baryon spectrum this leads to a large probability for a nucleon to be part of a six-quark cluster. Therefore, six-quark clusters, and even clusters with larger numbers of valence quarks may be an important part of nuclear matter. In fact, theoretical evaluations\(^{(1)}\) show that the probabilities of multiquark clusters in nuclei are very large, for example,

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>$P_{3q}$</th>
<th>$P_{6q}$</th>
<th>$P_{9q}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>0.96</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>$^3H_e$</td>
<td>0.84</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>$^4H_e$</td>
<td>0.76</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>$^9B_e$</td>
<td>0.87</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>$^{27}Al$</td>
<td>0.78</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>$^{10}C_a$</td>
<td>0.79</td>
<td>0.17</td>
<td>0.04</td>
</tr>
<tr>
<td>$^{56}Fe$</td>
<td>0.77</td>
<td>0.18</td>
<td>0.05</td>
</tr>
<tr>
<td>$^{88}Sr$</td>
<td>0.76</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>$^{208}Pb$</td>
<td>0.74</td>
<td>0.20</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Now the question coming immediately into our mind is that: Do we have some experimental evidences for the existence of multiquark clusters in nuclei? The answer is that
although there are no explicit evidences so far, we do have some strong signals for the presence of multiquark clusters in nuclei. For example,

1). The experimental charge form factors of \( ^3H \) vs. \( ^3H_e \) are in strong conflict with traditional hadronic theory with meson currents, and are thought of as being an explicit signal for six-quark clusters in nuclei at 15 \% level \(^2\).

2). The experimental distribution of the \( ^3H_e \) charge density has a central "hole" which cannot be understood by any traditional theoretical model of the \( ^3H_e \) charge density. As we see later, this is suggestive of multiquark clusters in the \( ^3H_e \)\(^3\).

3). The pion-nucleus double charge exchange reaction at 164 MeV provides another signal for the existence of multiquark clusters in nuclei. The first experimental minimum position of DCX angular distribution cannot be explained by any conventional theory with meson exchange currents but a new six-quark cluster mechanism\(^4\).

In one word, theoretical analysis and data from different experiments support the idea of the formation of multiquark clusters in nuclei. We may claim that modern nuclear physics should be hybrid: both hadronic and quark degrees of freedom must be included, with care not to double count.

3 Hybrid Quark Hadron Nuclear Structure

To describe quark cluster nuclear structure, we propose a hybrid quark hadron (HQH) model\(^5\). In the HQH model the configuration space is divided into two distinct regions:

i). An interior quark region where nucleon bags overlap and six- and /or nine- quark clusters are formed. All quarks interact with full color freedom, exchanging gluons. One no longer has nucleons, one applies the quark dynamics to describe this interior system.
ii). An exterior hadronic region where the quarks are confined within baryons. We have a traditional system of nucleons. As usual, we use the traditional hadronic dynamics to describe this exterior system.

The boundary separating these two distinct regions is described by a simple phenomenological parameter, \( r_0 \), in terms of which projection operators can be defined. The value of \( r_0 \) is determined by fitting to various existing experimental data and by satisfying QCD analysis. The best value of \( r_0 \) is about 1.0 fm.

To offer a better understanding of the HQH model, we consider a two-body bound system in a channel \( \alpha \). The wave functions for this system in the model can be written as

\[
\psi_{313_212_1}(r_{B_1}, r_{B_2}) = \begin{cases} 
\psi_{B_1}(3q) \psi_{B_2}(3q) \Phi_{B_1 B_2}(r) & r > r_0 \\
\psi_{6q}(r_1, ..., r_6) = \sum_t C_t^\alpha \psi_t^\alpha(6q) & r \leq r_0
\end{cases}
\]

where \( C_t^\alpha \) are amplitudes of the six-quark configurations \( \psi_t^\alpha(6q) \) with \( \sum_t |C_t^\alpha|^2 = 1 \).

The probability of six-quark cluster in this two-body bound system is determined by probability conservation law and is given in the following equation

\[
P_{6q} = \int d^3r \theta(r_0 - r) | \Phi_{B_1B_2}(r) |^2
\]

where the \( \Phi_{B_1B_2}(r) \) is traditional nuclear wave function of the system in the exterior hadronic region. Therefore, the probability for a nucleon to be part of a six-quark cluster is determined by traditional nuclear wave function in the exterior region, which is best known part of nuclear physics. The probabilities are not free parameters but determined by nuclear wave function and \( r_0 \) from conservation law. In comparison with quark cluster model which has as its starting point assumed quark-quark interaction, the HQH model has the following advantages

i). The model is based on the successful hadronic models of N-N forces for \( r \geq 1.0 \text{ fm} \) which is best known part of nuclear physics.
ii). In applications to electromagnetic and weak interactions no quark-quark interaction is explicitly introduced at all, and for strong interaction processes only transition matrix elements are calculated in the quark sector of the model.

In one word, the model avoids the detailed quark Hamiltonian by use of the general features of the hybrid representation of nuclear wave function and of experimental data to complete the model.

4 Electromagnetic properties of $^3\text{He}$ and $^3\text{H}$ in the HQH Model

The processes contributed dominantly to electromagnetic form factors of three-body systems are shown in Figs. 1 and 2. Calculations for electromagnetic form factors and charge density of $^3\text{He}$ and $^3\text{H}$ have been performed in the HQH model. Here, we briefly present our results

(1) The charge form factors of $^3\text{He}$ and $^3\text{H}$ in the HQH model

The charge form factor is the matrix element in the nuclear state of the time-like component of the electromagnetic current $j_0(q)$

$$F_{ch}(q^2) = \langle \psi | j_0(q) | \psi \rangle. \quad (3)$$

where $j_0(q) = j_0^{\text{I.A.}}(q) + j_0^{\text{pair}}(q) + j_0^{\text{6g}}(q) + j_0^{\text{9g}}(q)$ if one considers the processes of Figs. 1 and 2. The resulting theoretical expression of the charge form factors for $^3\text{He}$ and $^3\text{H}$ is

$$F_{ch}(q^2) = F_{ch}^{\text{I.A.}}(q^2) + F_{ch}^{\text{pair}}(q^2) + F_{ch}^{\text{6g}}(q^2) + F_{ch}^{\text{9g}}(q^2). \quad (4)$$
The totally antisymmetric wave functions of this three-body systems can be obtained in the usual way

$$\Psi(1, 2, 3) = (1 + P_{123} + P_{132}) \Psi_1(1, 23)$$

where $\Psi_1(1, 23)$ is the solution to one of the three coupling equations and is also antisymmetric in particles (2,3) only.

The calculations of $F_{L_{123}}^{6q}(q^2)$ and $F_{L_{123}}^{9q}(q^2)$ have been carried out in coordinate space by use of the solutions to five channel Faddeev equations of Los Alamos for several two-body potentials\(^6\).

Channels presented in the present calculations of electromagnetic form factors

<table>
<thead>
<tr>
<th>Channel</th>
<th>$l_{a}L_{a}$</th>
<th>$S_{a}$</th>
<th>$L$</th>
<th>states</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00</td>
<td>0</td>
<td>0</td>
<td>$S$</td>
</tr>
<tr>
<td>2</td>
<td>00</td>
<td>1</td>
<td>0</td>
<td>$S'$</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>1</td>
<td>2</td>
<td>$D_1$</td>
</tr>
<tr>
<td>4</td>
<td>02</td>
<td>1</td>
<td>2</td>
<td>$D_2$</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>1</td>
<td>2</td>
<td>$D_3$</td>
</tr>
</tbody>
</table>

Six- and nine-quark probabilities in $^3He$ for different NN potentials and $r_0 = 1.0fm$.

<table>
<thead>
<tr>
<th>NN Potential</th>
<th>$P_{6q}(%)$</th>
<th>$P_{5q}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raid soft core</td>
<td>13.396</td>
<td>0.427</td>
</tr>
<tr>
<td>Supersoft core</td>
<td>14.129</td>
<td>0.500</td>
</tr>
<tr>
<td>Argonne $V_{14}$</td>
<td>14.230</td>
<td>0.498</td>
</tr>
</tbody>
</table>

As we have seen from the table, the probabilities of multiquark clusters are not very sensitive to the choice of nuclear potentials.

For quark part of the calculations, $F_{ch}^{6q}(q^2)$ and $F_{ch}^{9q}(q^2)$, we use shell model wave
functions for quark states,

$$\psi_i(6q) = c_1 |(1s_{1/2})^6 > + c_2 |(1p_{3/2})^2(1s_{1/2})^4 > + c_3 |(1p_{1/2})^2(1s_{1/2})^4 > + \ldots.$$  

The single quark wave functions are taken as those obtained in MIT quark bag model. The $c_1 = 0.71$, $c_2 = 0.50$ and $c_3 = 0.50$ are used. Note that the intrinsic form factor depends upon the unknown distribution of quark configurations in principle, but that there is very little dependence on the occupation probabilities of the individual orbits. For instance, if one takes the bound-state six-quark cluster configuration to be $|(1s_{1/2})^6>$ or if one introduces a configuration $|(1p)^2(1s_{1/2})^4>$ with an amplitude of 0.5, then the changes in the final results are not noticeable. The main parameter in the problem is $\mu_0$, which controls the multiquark cluster probability.

Our results and comparisons with existing data are shown in Figs. 3, 4 and 5.

(2). Magnetic form factors of $^3He$ and $^3H$ in the HQH model

The measurement of magnetic form factors of three-body systems now extends up to $q^2 = 32 fm^{-2}$, well beyond the region of the first diffraction minimum, probing distance smaller than 1.0 fm, where new degrees of freedom are expected to shown up. In this subsection we calculate the magnetic form factors of $^3He$ and $^3H$ in the HQH model. Since all parameters have been determined by fitting the $^3He$ charge form factor, the present calculations should be an excellent test of hybrid quark hadron structure of three body systems.

The magnetic form factors $F_M(q^2)$ of a nucleus for M1 electron scattering on the nucleus is defined by

$$<\psi_{JM}^{JM} | \hat{T}_{1,0}^M(q) | \psi_{JM}^{JM}> = \frac{iq}{\sqrt{6\pi}} \frac{e}{2M} \mu_N F_M(q^2)$$

where $\mu_N$ is the nuclear magnetic moment in nuclear magneton. The dipole magnetic operator $\hat{T}_{1,0}^M(q)$ has the form of
\[ F_{1,0}^{M}(q^2) = \int d^3 \vec{r} \: j_{1,0}(q \vec{r}) \tilde{V}_{11}^{M}(\Omega, \vec{r}) \]  

with

\[ \vec{j} = \vec{j}_{1,0} + \vec{j}_{\text{pair}} + \vec{j}_{e_f} + \vec{j}_{g_q}. \]

being space - like component of nuclear electromagnetic current in the HQH model. The resulting theoretical magnetic form factors of three-body systems also consist of four terms

\[ F_{M}(q^2) = F_{M}^{L,A}(q^2) + F_{M}^{\text{pair}}(q^2) + F_{M}^{e_f}(q^2) + F_{M}^{g_q}(q^2) \]

Our HQH model predictions and comparison with data are shown in Figs. 6 and 7. The HQH model in its present form produces a satisfactory fit to both the charge and magnetic form factors of three-body systems. Using parameters \( r_0 = 1.0 \text{ fm} \) and \( R_6 = 1.2 \text{ fm} \) determined from \(^3\text{He}\) charge form factor, the \(^3\text{H}\) charge form factor and the magnetic form factors of \(^3\text{He}\) and \(^3\text{H}\) can be accurately reproduced without any adjustment of the parameters.

(3). The Central "hole" of \(^3\text{He}\) charge density in the HQH model

The long-standing puzzle for the \(^3\text{He}\) charge density is the central " hole" of the experimental charge density as shown in Fig.8. According to our best knowledge, the observed " hole" has not been, so far, reproduced by any traditional three-body wave function. We believe this may also be suggestive of the existence of multiquark clusters in \(^3\text{He}\). The reason is quite simple. The density of the \(^3\text{He}\) can be written as

\[ \rho_{r_0}(\vec{r}) = \langle \psi^{(3\text{He})} | \sum_{i} \epsilon_i \delta^3(\vec{r} - \vec{r}_i) | \psi^{(3\text{He})} \rangle. \]

which depends on \( r_0 \). In order to see the responsibility of multiquark clusters for the central " hole", we calculate the ratio of the central density \( \rho_{r_0=0}(r = 0) \) in our hybrid
quark hadron model, and \( \rho_{r=0}(r = 0) \) in traditional hadronic model. The resulting ratio is:

\[
\rho_{r=0}(r = 0) = \frac{1}{1 - F_{\rho} - F_{\rho_{q}} \rho_{r=0}(r = 0)}. \tag{12}
\]

where \( P_{\rho_{q}} \) and \( P_{\rho_{q}} \) are the probabilities of six- and nine- quark clusters in \( ^3He \). Evidently, due to the formation of multiquark clusters in \( ^3He \), the charge density at the center is greatly reduced. Therefore, the problem of the observed "hole" is then naturally resolved.

In fact, we have carried out the Fourier transformation of the \( ^3He \) charge form factor, \( F_{\rho q}(q^2) \), and obtained the charge density as shown in Fig. 8 by solid curve, where the dashed curve is the prediction of traditional hadronic theory with meson exchange current. The HQH model reproduces the "hole" in a successful way. That is, Quark cluster effect seems to be responsible for the observable.

5 Concluding remarks

Based on quark structure of hadron, we claim that the multiquark clusters may present in nuclei. We study the multiquark clusters by use of electromagnetic processes in three body systems. Our principal findings this paper are as follows:

1) Many experimental observables are in strong conflict with the expectation given by traditional nuclear theories with meson exchange currents, and support the theoretical idea of the formation of multiquark clusters in nuclei.

2) Although our HQH model is still in its infancy, it gives a good description of many long-standing puzzles in nuclear physics. The model reproduces the data for \( ^3He \) quite well. With no adjustment of parameters, the data of \( ^3H \) is fit very well, testing the isospin nature of the long range impulse and pion pair processes. These successes would be thought of as being strong signals for multiquark clusters in nuclei.
However, it is difficult to say that our new finding in this paper is a great evidence of quark degrees of freedom in nuclei. Looking for quark degrees of freedom in nuclei is like looking for Mafia in Sicily. Everyone knows they are there but it is very hard to get evidences. In order to obtain unique explicit evidences, a great deal of work is in abundant demand. In Particular, we must study nuclear phenomena at higher momentum transfer where the quark degrees of freedom are expected to show up.

References


Figure Captions

Fig.1. Impulse approximation (a) and pair current (b) contributions to electromagnetic form factors of the $^3He$ and $^3H$ in the exterior hadronic region of the HQH model.

Fig.2. Six-quark cluster (a) and nine-quark cluster (b) contributions to electromagnetic form factors of the $^3He$ and $^3H$ in the interior quark region of the HQH model.
Fig. 3. Contributions from individual terms in the HQH model to the charge form factor of the $^3$He.

Fig. 4. The charge form factors of the $^3$He in the HQH model and comparison with experimental data. The dashed curve is impulse approximation and the dot-dashed curve is the contribution of S-wave component of nuclear wave function. The solid curve stands for the HQH model prediction.

Fig. 5. The HQH model prediction of the $^3$H charge form factor. The parameters are the same as those in Fig. 4 for $^3$He charge form factor.

Fig. 6. The HQH model prediction of the $^3$He magnetic form factor. The parameters are determined by fitting the $^3$He charge form factor.

Fig. 7. The theoretical magnetic form factor of the $^3$H in the HQH model and comparison with recent experimental data.

Fig. 8. Charge density of the $^3$He. The dashed curve is the result of the traditional nuclear wave function$^{(3)}$, and the solid curve stands for the HQH model prediction using the supersoft core wave function and $r_0 = 1.0\,fm$. The experimental data comes from ref. (6).
Charge Form Factor of $^{3}\text{He}$

$F_{ch}(q^2)$

$q^2$ (fm$^{-2}$)

Fig. 3
Fig. 4.
Charge Form Factor of $^3\text{H}$

$F_{ch}(q^2)$

$q^2$ (fm$^{-2}$)

Fig. 5
\[ F_m(q^2) \]

Super-soft-core wave function

--- 1.A.

HQH Model

Fig. 6
$3_H$

Super-soft-core wave function

HQH Model

Fig. 7
Fig. 8

\( \rho(r) \)

\[^3\text{He} \text{ charge density}\]

\( r (\text{fm}) \)
A cosmic ray observation station of Yan Nan in China observed a possible steady charged particle with heavy mass \(m: 10\sim 40\ \text{Gev}; \ \tau: 0.5\times 10^{-8}\ \text{s.}\) in 1972. For more than 20 years, it has been very difficult to explain the observation in existing theories. Recently, Professor He ZuoXiu and several other particle physicists come up with a new explanation of "Yun Nan Particle" based upon smallest supersymmetry standard model (MSSM). Their computation shows, the case could be the following interaction:

\[ P + \tilde{x}^0 \rightarrow P + \tilde{x}^+ + \pi + \text{anything} \]

\(\tilde{x}^0\) and \(x^+\) are supersymmetry particles whose spin is of \(1/2\) unit in MSSM. \(x^0\) is the lightest steady supersymmetry electroneutrality particle predicted by the new theory to be existing in large quantity in the universe. It is also presumed to be colourneutrality particle and and has an extraweak interaction with matter. If this presumption is true, it can help us to solve the paradox that the aritical mass of the universe predicted by cosmic extraiexpanding theorem is 10 times larger than that actually observed. That implies the existence of dark matter unobserved which accounts for 90% of the total mass of the universe. \(\tilde{x}^0\) particle, which is extremely hard to probe, perhaps in one of the forms in which the dark matter exists in the universe. In this way, "a bridge between particle physics and cosmic physics can be found, and that means there is a harmony between universe the largest and particles the smallest."

MSSM theory also presume, the coupling-constant of the three kind of interaction (strong, weak, electromagnetic et al.) reach at one point when
energy is $10^{16}$ Gev; proton had a half life of more than $10^{34}$ years; a new \( \sin^2 \theta_w \) value. These new presumption coordinate much better with experimental value than previous theories.

However, we cannot be sure that we have found the \( \bar{x}^0 \) particle only by case such as “Yun Nan particle”. From above introductions, we can see that reobserving of “Yun Nan particle” has a more and more important significance. For the time being, all existing and under-construction high energy particle accelerator and collider can only produce particles with less than $10^{14}$ energy, much less than superhigh energy particles in cosmic ray whose energy could reach $10^{20}$ ev. But it is likely that only particles in superhigh energy cosmic ray can have some effect on \( \bar{x}^0 \). So we should restart the work of probing \( \bar{x}^0 (\bar{x}+) \) in cosmic ray. There are two ways of reprobing “Yun Nan particle”:

1. Analyse undisposed date of background cosmic particle traces of these years using BES which is a spare part of BEPC, and calculate mass and life of particles by improved software package of distant-line analysis.

2. Construct a spectrum meter whose characteristics extra fine than one’s on Luosi mountain to make the discovery of \( \bar{x}^0 (\bar{x}+) \) particle more possible and to improve trace of particle.

If no result is got by new efforts, we can only get a density Limit of \( \bar{x}^0 \) in the univers. And the density would certainly be very small. Failure of our new efforts could result in a substantial modification or breakthrough of existing theories, just like the “ether” probing in old days by Michelson interferometer. In this point of view, reinvestigation into \( \bar{x}^0 (\bar{x}+) \) particle is also an important experiment worth doing.

If our new efforts break “unseen quarks” and “missing symmetries” are called by professor Li Zenduo to be “two puzzlz” in 1990s. Other people also think “Yun Nan particle” is a free quark. It is likely that Violent Collision by superhigh energy particle in cosmic rays can break the “closed” and produce free quark.
“Yun Nan particle” is by all means an important work worth doing.

Some reference materials of my article are provided by Mr. Zhu Qing Qi of Institute of High Energy Physics Academia Sinica. Here I’d like to express my gratitude to him.
VARlATIONAL FINITE ELEMENT METHOD FOR THE DESIGN
OF 2-D CONTRACTION SECTIONS OF LOW-SPEED WIND TUNNELS

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Shanghai Institute of Applied Mathematics and Mechanics

ABSTRACT: In this paper, a numerical method for the design of 2-D contraction sections of low speed wind tunnels is presented by using the variational finite element method with variable domain. Two numerical examples for plane flow and axially symmetrical flow with unknown wall geometries (but with prescribed velocity or pressure distributions) are given, which show a good convergence to the geometries required for the desired velocity or pressure distributions. It is concluded that the method in this paper is a reliable and valuable design method for engineering application.

I. INTRODUCTION

The ideal contraction section of subsonic wind tunnel is designed to accelerate the gas flow steadily from the stable section to the testing section. Theories and experiments show that low turbulence flow can be obtained with a contraction section of high ratio of construction, but it is not economic in that a rather long section is needed to keep the transition of boundary layer from happening. Sometimes, inverse pressure gradient near the wall constructed too rapidly will cause flow separation. To date, contraction sections are often manufactured according to the recommended curves resulted from experiments or the widely used Witzinsky formula. However, computational design methods are necessary when some special wind tunnels are needed in experiments. In this paper, a variational FEM of design is introduced with numerical examples.

II. BASIC EQUATIONS, BOUNDARY CONDITIONS AND THE VARIATIONAL PRINCIPLE

The nondimensional equations governing the 2-D homentropic and homenthalpic flow are:

\[
\frac{2}{\lambda}r^2(\rho^2r \lambda_r) + \frac{2}{\lambda^2}(\rho^2r \lambda_x) = 0 \quad (1)
\]

\[
\frac{\lambda r}{\lambda x} - \frac{\partial \lambda x}{\partial r} = 0 \quad (2)
\]

\[
\frac{\rho}{\rho} + \frac{k-1}{k+1} \lambda^2 = 0 \quad (3)
\]

\[
P = \rho^k \quad (4)
\]
where $\epsilon = 0, 1$ represents respectively that the flow is of plane or axial

From Eq. (1), a stream function can be defined as:

\[ \frac{\partial \psi}{\partial r} = r^\epsilon \rho \lambda_x, \quad \frac{\partial \psi}{\partial \lambda} = -r^\epsilon \rho \lambda_r \]

(1)

\[ \rho = \left[ 1 - \frac{\lambda_r}{\lambda + 1} \lambda_x \right]^{1/\epsilon} \]

(3)

The boundary conditions (BC.) are as following (Fig. 1): on $C_1$ (inlet boundary):

\[ \psi = \psi_{pr} = \frac{1}{r^{\epsilon+1}} \frac{r^{\epsilon+1}}{\lambda_x} \]

(5)

on $C_2$ (outlet boundary):

\[ \lambda_\lambda = 0 \]

(6)

on $C_3$, which is the boundary with unknown geometry but the velocity or pressure distributions are given, the BCs. on it are as following:

\[ \lambda = \lambda_{pr} \quad (p = p_{pr}) \]

(7)

\[ \psi = \psi_{pr} \]

(8)

on $C_4$, it can be considered both as a axis of symmetric flow or a tunnel wall, the BCs. in the two cases are same:

\[ \psi = 0 \]

(9)

The solution of the aforementioned flow problem makes the function $J(\psi, S)$ stationary, $\delta J = 0$ under constrains Eqs. (1) and (3), where $\psi$ and $S$ should be varied independently.

\[ J(\psi, S) = \int_A \rho (1 + \lambda_x^2) r^\epsilon \lambda_x \lambda_r - \int_{C_3} \frac{\lambda_x}{\lambda + 1} \lambda_x \lambda_r \]

(10)

where the superscript 'o' represents 'unpermitted variation', namely, the parameter with it keeps unchanged in variation process.

Prove: The variation of $J(\psi, S)$ can be deduced according to the following formulas of functional variation with variable domain:

\[ J(\psi, S) = \int_A F(\psi, \psi_x, \psi_y) dx \]

\[ \delta J(\psi, S) = \int_A (dF \psi_x - v \cdot \delta \vec{G}) \psi dx + \int_{C_4} \left[ \delta \lambda_x \psi_x + (\lambda_x - \lambda_x) \psi dy \right] ds \]

(11)

where $\vec{G} = \frac{dF}{d\psi_x} \psi_x + \frac{dF}{d\psi_y} \psi_y$

The variation of Eq. (10) is:

\[ \delta J(\psi, S) = \frac{2\lambda_r}{\lambda + 1} \int_A (\frac{\partial \psi}{\partial \lambda_x} - \frac{\partial \psi}{\partial \lambda}) \delta \lambda + \int_{C_4} \left[ \lambda_x \delta \psi + (p - p_{pr}) r^\epsilon \delta S_n \right] ds \]

(12)

\frac{\delta J}{\delta S} = 0 \quad the \ following \ set \ of \ stationary \ conditions \ for \ J(\psi, S) \ are \ obtained

Euler's Eq. Eq. (2)

Natural BCs. Eqs. (6) and (7).

while the Eqs. (5), (8) and (9) are imposed respectively on boundaries $C_1$, $C_3$ and $C_4$ as essential BCs.

To this end, it is proved that the variational principle above can provide the entitle solution of the flow considered.
III. FINITE ELEMENT METHOD WITH VARIABLE DOMAIN

A self-adapting finite element with moving nodes is employed to determine the unknown boundary \( C_3 \) \([2,3]\). Let \( \Psi(\psi_1, \psi_2, ..., \psi_n) \) and \( \hat{R}(r_1, r_2, ..., r_n) \) be the vectors of stream function at the notes in flow field and \( r \)-coordinates at the notes on \( C_3 \) respectively. After being discretized with a 9-note isoparameter element, the original variation problem of \( J(\Psi, C) \) is equivalent to the extremum problem of \( J_F(\Psi, \hat{R}) \). The first variation of \( J_F \) can be expressed as:

\[
\delta J_F(\Psi, \hat{R}) = \frac{\partial J_F}{\partial \Psi} \delta \Psi + \frac{\partial J_F}{\partial \hat{R}} \delta \hat{R}
\]

(13)

because \( \hat{R} \) and \( \Psi \) are all free, from \( J = 0 \), we get:

\[
\frac{\partial J_F}{\partial \Psi} = 0
\]

(14)

and

\[
\frac{\partial J_F}{\partial \hat{R}} = 0
\]

(15)

From Eq.(14) we obtain the following matrix form of the global FE Eqs.:

\[
[M(\hat{\rho}, \hat{R})] \cdot \hat{\Psi} = \hat{f}
\]

(16)

where

\[
\hat{\rho} = \hat{h}(\Psi, \hat{R})
\]

(17)

Similarly Eq.(15) yields the nonlinear Eqs.:

\[
\hat{h}(\Psi, \hat{R}) = 0
\]

(18)

which, to solve the equation efficiently, is replaced by the following unsteady problem\([4]\):

\[
\partial \hat{R} / \partial t + B \cdot \partial J_F / \partial \hat{R} = 0
\]

(19)

till the asymptotic solution at \( t=\) is sought. Discretized in time, Eq. (19) becomes:

\[
\hat{R}^{n+1} = \hat{R}^n - \Delta t \cdot B \cdot (\partial J_F / \partial \hat{R})^n = \hat{R}^n - \Delta t \cdot \hat{R}^n = -B \cdot \hat{R}^n (\Psi^n, \hat{R}^n)
\]

(20)

where \( B \) is chosen to accelerate iteration convergence.

The nonlinear Eqs.(16),(17) and (20) are solved by iterations alternately between them until convergence is reached.

IV. RESULTS AND DISCUSSIONS

The design method and the computational code are assessed by the numerical examples given. In order to decrease the risk of searching a nonexistent solution, we started the inverse problem from existing contraction wall (in Witzinsky curve), the corresponding velocity or pressure distribution obtained from the direct code are imposed as required distribution. The accuracy of the method is guaranteed by the results in Fig.2, which shows a tiny difference between the calculated geometry and the known one after a good agreement between the calculated and the prescribed velocity distribution.

The second example concerns the design of a contraction section of a wind tunnel with stright walls. The velocity distributions are given in the form \( \lambda_{pe} = \alpha t (bx+c)+d \), in which the coefficients \( a-d \) are determined by the geometries and the flow conditions on both the inlet and outlet boundaries. The final geometry of the wall is shown in Fig.3b, the velocity distributions calculated in direct code are in good agreement with the prescribed ones in Fig.3a.

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V. CONCLUSIONS

Taking the advantage of variational method with variable domain, a FE code for the design of contraction sections of wind tunnels is developed in this paper. This design code can also be used as an analysis code. Numerical examples of the design for contraction sections have been performed successfully with required precision. This method, proved to be reliable, can be extended to other engineering applications as well as the design of wind tunnel.

REFERENCES

THE APPLICATION OF MINI-PRESSURE SENSOR
IN HIGH MEAN PRESSURE CONDITION

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ABSTRACT:

An experimental set-up of heat-pump type thermoacoustic engine which is measured by the personal computer is designed and built to testify the thermoacoustic energy conversion effect. The suitable material and manufacturing technology for the engine are also studied here. All this is helpful for designing and building a practical equipment. Because the coefficient of performance of the system is determined by the transient characteristics, so it is important to find and use a kind of mini-pressure sensor which was usually applied in low mean pressure condition. It is the first time that we apply the mini-pressure sensor into the measurement of dynamic pressure under the high mean pressure condition and get the transient characteristics of the dynamic pressure and temperature on the experimental system as well.

The energy conversion effect of the thermoacoustic fluid has been testified in the experiments by means of these sensors. Changing the operating parameters, the level of the effect can be raiseded. By using a frequency spectral analysis software program, we can also get the transient time domain signals as well as the frequency spectrum characteristics of the pressure and the temperature.
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