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 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 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.

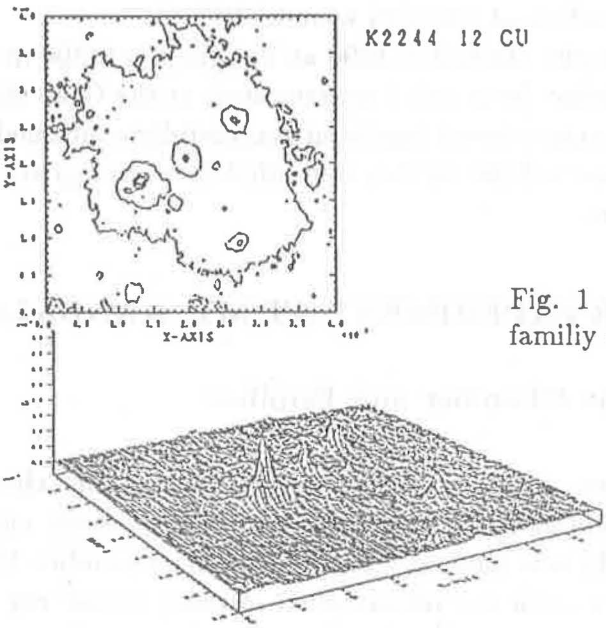

Fig. 1 Density map of showers in a familiy on the X-film.

As an example we show a density map of showers, at the depth of 12 cu in EC, in the family with ΣE = 2200 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.

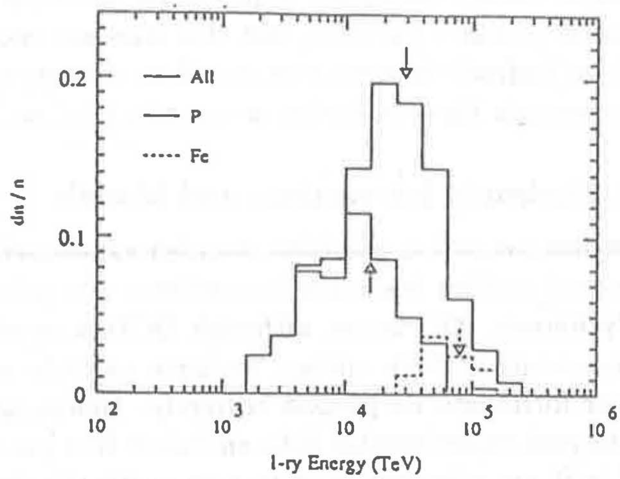

Fig. 2 Energy distribution of primaries responsible for generating families with $\sum E \geq 500$ TeV at Mt.Kanbala.

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 σ_{in}(p-air) = 290 $(E_0/1TeV)^{\delta}$ mb, where δ 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.

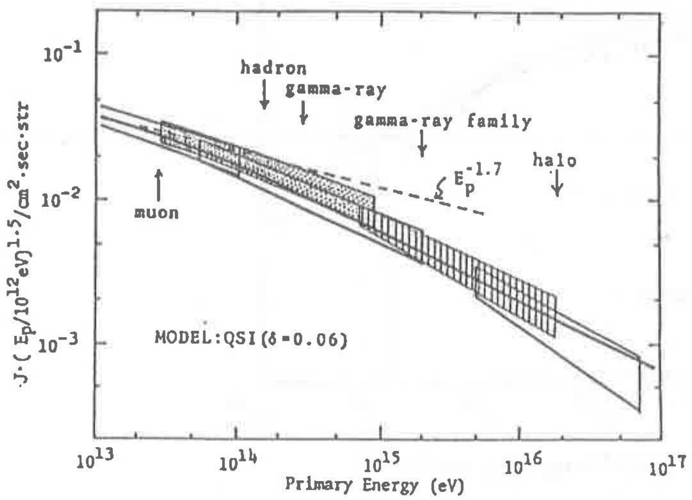

Fig. 3 Energy spectrum of protons estimated from the emulsion chamber experiments.

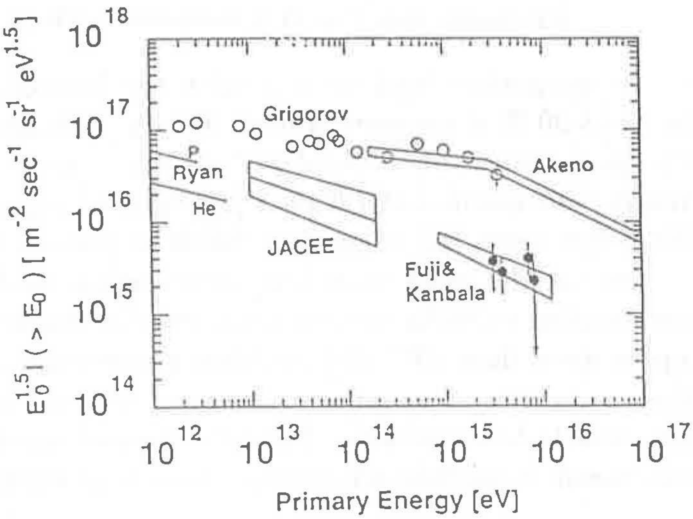

Fig. 4 Proton fluxes (closed circles) estimated from the Norikura experiment are compared with other experiments.

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 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].

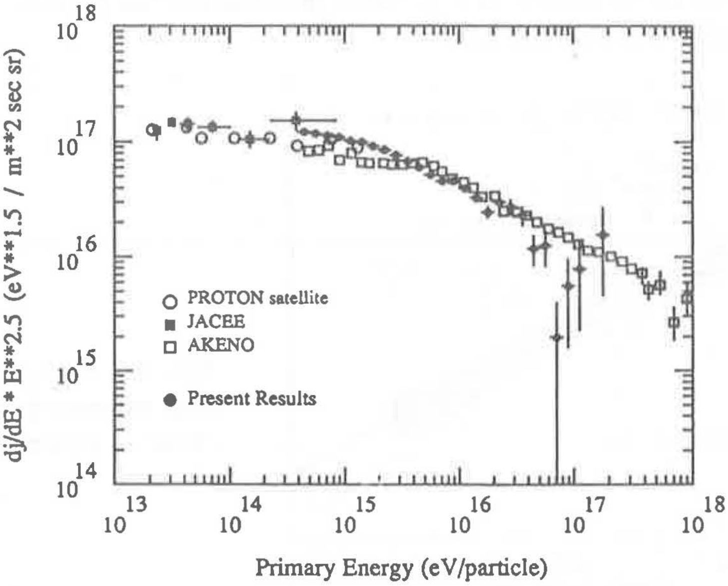

Fig. 5 Energy spectrum of total cosmic rays estimated from the Tibet air shower experiment is compared with other experiments.

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 constarint to particle acceleration models at UHE region.

B. AIR SHOWER EXPERIMENT AT YANGBAJING

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

After finishing the emulsion chamber experiment at Mt.Kanbala, we have started new collaboration experiment at Yangbajing in Tibet (The Tibet ASγ 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.

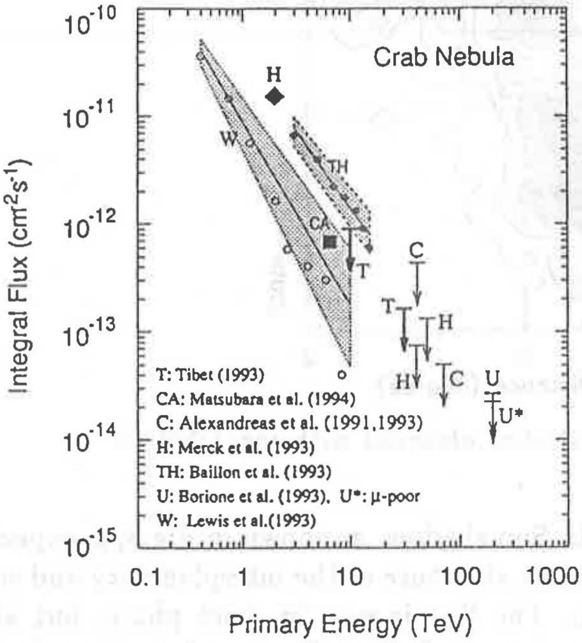

Fig. 6 Gamma-ray fluxes from the Crab Nebula.

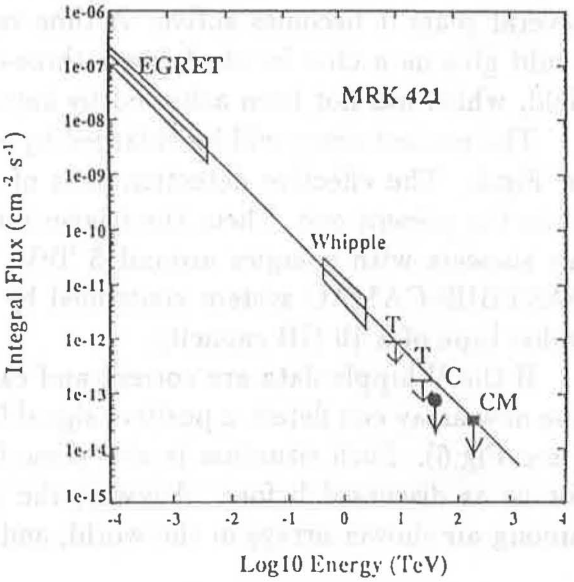

Fig. 7 Gamma-ray fluxes from Mrk 421. T : Tibet, C : CYGNUS , CM : CASA-MIA.

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 mesuements [21].

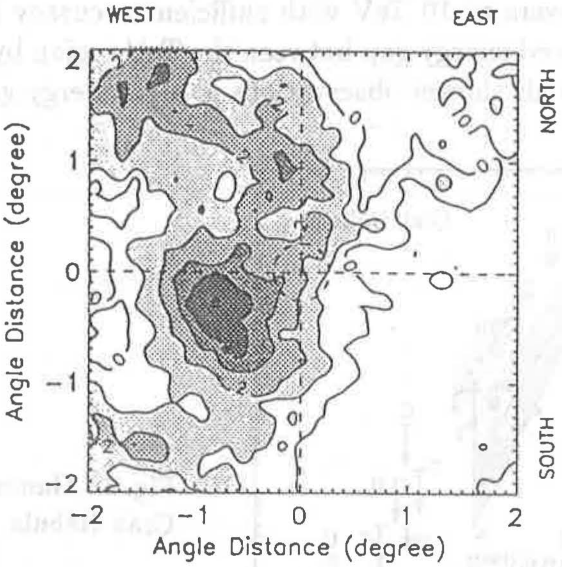

Fig. 8 Contour map of the Sun shadow observed with the Tibet air shower array.

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.

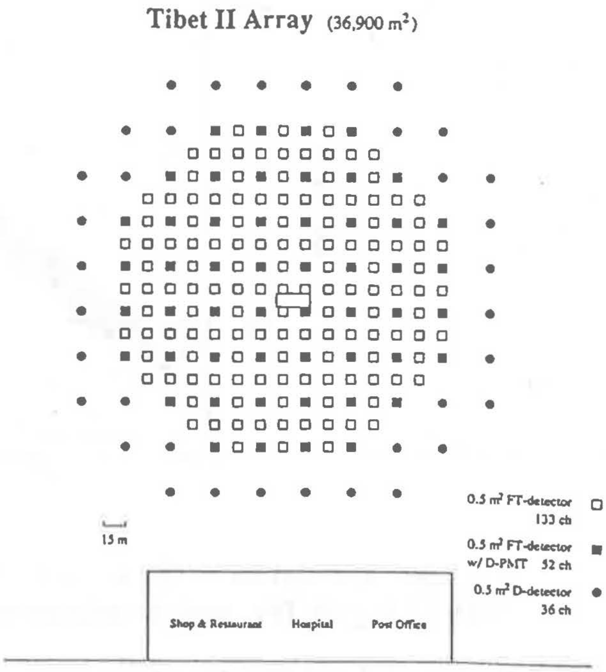

Fig. 9 Layout of the new Tibet array.

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.

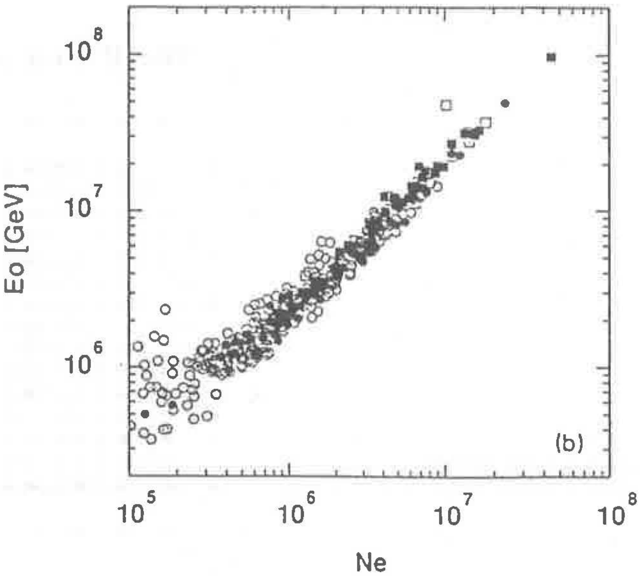

Fig. 10 Correlation of the air shower size Ne, accompanying a family with $\sum E \geq 30$ TeV, and the primary energy E_0 at Yangbajing altitude.

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.

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