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Studies of Anomalous Phenomena in the Development of Electron-Nuclear Cascades in the EAS Cores Registered by a Modernized Complex Installation at Mountain Altitudes

Rauf Mukhamedshin ¹, Turlan Sadykov ², Abay Serikkanov ², Alia Argynova ^{2,*}, Bakhtiar Iskakov ^{2,3}, Korlan Argynova ^{2,4}, Hanshain Mahmet ², Olga Novolodskaya ², Tynyk Idrissova ², Valery Zhukov ^{2,5}, Vyacheslav Piskal ^{2,5} and Zhakypbek Sadykov ^{2,6}

¹ Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia

² Institute of Physics and Technology, Satbayev University, Almaty 050032, Kazakhstan

³ Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan

⁴ ITMO University, St. Petersburg 197101, Russia

⁵ Tien-Shan High-Mountain Scientific Station of the Lebedev Physical Institute of the Russian Academy of Sciences in the Republic of Kazakhstan, Almaty 050020, Kazakhstan

⁶ National University of Science and Technology "MISIS", Moscow 119071, Russia

* Correspondence: aarginova7@gmail.com

Abstract: Phenomena have been observed in mountain high-energy cosmic-ray experiments, namely, a delayed absorption of high-energy cascades initiated by cosmic-ray hadrons in a lead absorber at $E_0 \gtrsim 10^{14}$ eV (so-called long-flying component), a coplanarity of most energetic particles in the central region of γ -ray–hadron superfamilies, and the so-called Tien Shan effect in EAS cores at $E_0 \gtrsim 10^{16}$ eV ($\sqrt{s} > 5$ TeV). These effects are not described by theoretical models. The coplanarity is explained by the process of coplanar generation of most energetic secondary particles in interactions of superhigh-energy hadrons with the nuclei of air atoms. The other two phenomena are possibly explained with a high cross section for fragmentation-region charmed-hadron generation. To investigate these phenomena, a cosmic-ray detector array, including a very thick ionization calorimeter, is being upgraded to study EAS cores.

Keywords: cosmic rays; ionization-neutron calorimeter; scintillation detector; ionization chambers; hadron cascade; extensive air shower (EAS)



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1. Introduction

Although experiments with cosmic rays simultaneously make use of several models of interactions of high-energy hadrons with the nuclei of air atoms and the subsequent development in the atmosphere of so-called extensive air showers (EAS) (nuclear-electromagnetic cascades, initiated by protons and the nuclei of primary cosmic radiation (PCR) of ultrahigh energies), none of them can accurately reproduce the entire set of experimentally observed EAS characteristics.

In addition, some results accumulated in high-mountain and balloon X-ray emulsion chambers (XRECs) have not yet been explained. A decrease in the absorption rate of high-energy ($\sim n \cdot 10$ TeV) hadronic cascades in the lead absorber of the so-called Big Ionization Calorimeter (BIC) [1–5] with an area of 36 m² was first discovered about fifty years ago at the Tien Shan High-mountain Scientific Station (3340 m a.s.l.) in experiments with EAS. The BIC contained a lead absorber with a thickness of 850 g/cm², which corresponds approximately to five mean free paths for proton interaction in lead (see Figure 1, [6]). Due to the large BIC's thickness, this unique experiment made it possible to study the hadronic component of EAS in detail and showed that the absorption length $L(E_h)$ of the hadron component and the corresponding ionization in the BIC absorber in EAS cores intensifies

with the increase in hadron energy E_h in the calorimeter. Figure 1 (Figure 2, [6]) shows experimental data (crossed circles).

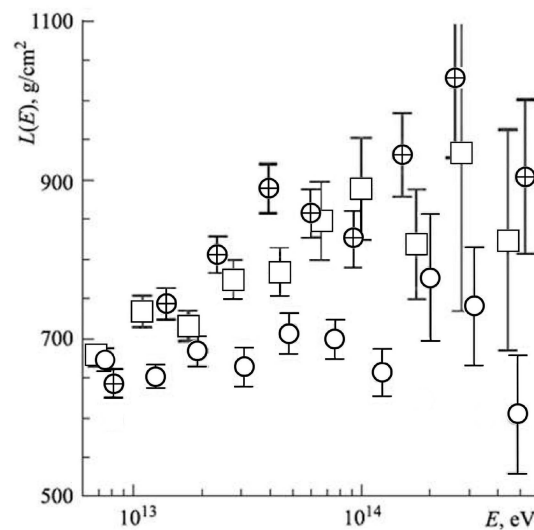


Figure 1. Attenuation length $L(E_h)$ of hadronic component in EAS cores observed with ionization calorimeter: crossed circles show the experimental data; Monte Carlo simulation results are shown with empty circles ($\sigma_{h \rightarrow c} \approx 0$) and empty squares ($\sigma_{h \rightarrow c} \approx 0.3 \cdot \sigma_{h-nucleus}$).

In order to explain the effect, a hypothesis on the existence of a so-called long-flying component was proposed. Later, after the discovery of charmed particles, it was shown that the above-described effect can be explained by assuming that the cross section for the production of charmed particles by hadrons reaches $\sim 30\%$ of the inelastic proton-nucleus cross section. Figure 1 (Figure 2, [6]) also shows Monte Carlo simulation results [7] obtained using two versions of the charm production cross section, namely, $\sigma_{h \rightarrow c} = 0$ (empty circles) and $\sigma_{h \rightarrow c} \approx 0.3 \cdot \sigma_{h-nucleus}$ (empty squares). At the same time, charmed particles could carry away a significant fraction of the energy of interacting hadrons (see the simulation results shown in Figure 1).

In high-mountain (4300 m above sea level) experiments with XRECs carried out by the *Pamir* Collaboration [8], an unusual deceleration in the absorption of hadrons with energies $E_h \gtrsim 10$ TeV was found at great depths in homogeneous lead XRECs 110 cm thick [9] (see Figure 3, [6]). In the XREC's upper part ($t < 78$ radiation lengths, *r.l.*), the distribution of hadron-initiated cascade origin depths obeys the standard exponential law with index $\lambda_{absq}^{(1)} = 212 \pm 19 \text{ g/cm}^2$. However, Figure 2 (Figure 4, [6]) shows that, at more significant XREC depths ($t > 78$ *r.l.*), the interaction-depth distribution changes, and the index increases to $\lambda_{abs}^{(2)} = 310 \pm 36 \text{ g/cm}^2$.

Both phenomena were explained as a consequence of the high values of the cross section for the production of leading charmed hadrons at energies $E_{Lab} \sim 50$ TeV in the Lab system. In order to explain the experimental data, both for overly intense ionization in the deep hadron calorimeter and for the overly flat distribution of hadron interaction depths in the deep XREC, it was necessary to assume that the cross section for the production of charmed particles in the fragmentation region of hadron interactions ($x_{Lab} \gtrsim 0.01$) rapidly increases with energy up to $\sigma_{cc}^{(NN)} \approx 2 - 4 \text{ mb}$ at $E_{Lab} \gtrsim 20$ TeV [6,7,9,10]. During the above-mentioned experiments, the values of charm-generation cross sections measured on accelerators were equal to a few tens of microbarns. Therefore, the results obtained in cosmic rays showed that the cross section of charm generation should increase rapidly with increasing energy. This strongly contradicted the theoretical concepts of the time.

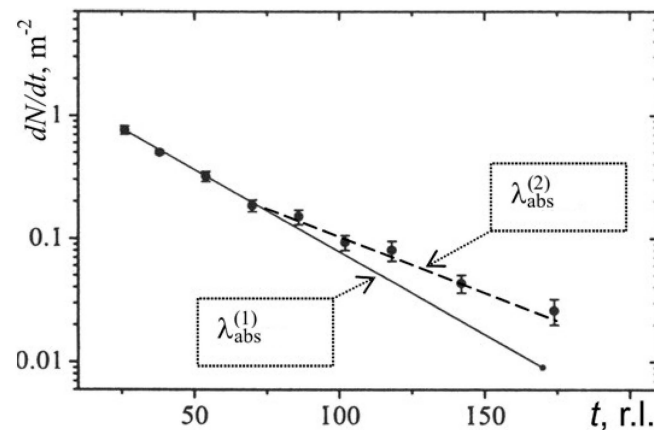


Figure 2. Distribution of hadron-initiated cascade origin points in deep uniform lead XREC 110-cm thick obtained by the *Pamir* experiment. $E_h \geq 6.3$ TeV.

An ionization calorimeter with a thickness in the order of six (or more) mean free paths for the interaction of hadrons can help to study these very interesting effects. In high-mountain experiments with XRECs, carried out by the *Pamir* Collaboration, a significant azimuthal effect was discovered, which is expressed in the form of a tendency for the coplanar arrival of the high-energy particles or narrow electromagnetic subcascades in the central regions of γ -ray-hadron families, i.e. groups of energetic ($E_h \gtrsim 10$ TeV) hadrons, γ -rays, electrons, and positrons near the axes of relatively “young” EASs. The word “young” means that the maximum of the cascade development of these showers has not yet been reached by the time of its registration at the observational level, and the number of most energetic particles (MEP) in these showers is higher than the mean number. These so-called γ -ray superfamilies with measured energies $\sum E_\gamma \gtrsim 500$ TeV are mainly initiated by the lightest particles of the primary cosmic radiation (PCR), namely by protons and helium nuclei with energies $E_0 \gtrsim 10^{16}$ eV ($\sqrt{s} \gtrsim 5$ TeV).

The high-mountain XREC experimental data [11–16] were first accumulated by the *Pamir* Collaboration on γ -ray superfamilies with measured energies $\sum E_\gamma \gtrsim 700$ TeV [11–13,15,16] and by the Mt. Canbala Collaboration $\sum E_\gamma \gtrsim 500$ TeV [14].

The overall picture is complemented by two superfamilies with ultrahigh energies, $\sum E_\gamma \gtrsim 1$ PeV detected using the emulsion technique at very high altitudes in the stratosphere on board a balloon (the *Strana* [17–19]) and a jet aircraft “Concorde” (JF2af2 [20,21]). Both superfamilies have a very high coplanarity of the most energetic particles. As established, the characteristics of showers observed in the stratosphere are much more sensitive to the parameters of the first interactions of PCR particles in the atmosphere (due to the much thinner atmospheric layer above the detectors exposed at these altitudes). The characteristics of showers studied at mountain level or, even more so, at the sea level are heavily polluted by secondary interactions of shower hadrons.

It should be noted that some deviations of experimental azimuthal effects from those in simulated events were observed in γ -ray families with lower measured energies $\sum E_\gamma \gtrsim 100$ TeV [22–24].

It is very interesting that the alignment effect discovered earlier in cosmic ray experiments with the X-ray emulsion technique has been studied on the basis of data obtained on the Big Ionization Calorimeter [2–5] at the Tian Shan combined cosmic-ray installation.

If there is some process in the hadron-nucleus interactions, this leads to the alignment of secondary particles. If so, this effect can also be detected using other detectors that do not have such a high lateral resolution as X-ray emulsions. Other things being equal, in this case it will be required that the interaction occurs at a greater distance from the detector, or that (at the same distance) the energy of the particles under consideration is correspondingly lower. For many years, the BIC with an area of 36 m² has been operating at the Tien Shan high-mountain station of the Lebedev Physical Institute for many years

as part of a complex installation for the study of EAS. During operation, a significant data bank with information on the electron-photon, hadron, and muon components of detected showers has been accumulated, which makes it possible, in contrast to XREC, to estimate the primary energy and other lateral-energy characteristics of each EAS. The EAS core mainly consists of a stream of hadrons generated in a series of successive interactions of a primary particle in the atmosphere. Secondary particles, if their energy is high enough, in turn also generate particles of next generations and their own “subcores”, from which the EAS core is formed. Hadrons in subcores are concentrated around the trajectory of the particle that generated them in a rather narrow cone.

If one considers the hadron structure of the EAS core in the target plane at the observation level, then at a high lateral resolution this will be a hadron flux of mainly not very high energies, which will not exceed the detection threshold of the XREC. As the resolution deteriorates, it becomes impossible to single out individual hadrons, but it is possible to single out individual subcores (jets) that often overlap with each other and belong to hadrons of earlier generations and higher energies.

The larger structures are considered, the higher energies and earlier generations of particles can be revealed if it is possible to register the integral energy fluxes within such jets and if the installation area is sufficient for this. In principle, the EAS core, without taking into account its structure, carries information about the primary particle. It should also be taken into account that, when passing through the atmosphere, all subcores irreversibly lose energy, mainly for the generation of electron-photon and muon components. The BIC registered the total energy released in its absorber by EAS core hadrons, regardless of the energies of individual hadrons. The summation was carried out within each registration channel (ionization chamber) with dimensions of 0.25 m^2 . With a channel width of 25 cm, the lateral resolution of the BIC for hadronic cascades is 50–75 cm, which does not allow one to separate individual hadrons, but does not interfere with the study of the large-scale structure of the EAS core.

Events with an energy of the primary particle $E_0 > 100 \text{ TeV}$ and an energy release in the calorimeter $E_c > 10 \text{ TeV}$ were selected for analysis. This guaranteed, with a high probability, that the EAS core would hit the calorimeter. The BIC had 19 rows of ionization chambers, interlayered with lead with a total thickness of about five mean free paths for nuclear interaction, and the carbon target of one more mean free path thick was located above it. The axes of the chambers in neighboring rows are directed perpendicular to each other, so the three-dimensional picture of the location of the jets in the calorimeter is represented as two projections on its side faces.

It was shown in that, as the depth increases, the substructures of the EAS core become more pronounced in the calorimeter. Namely, the jets become narrower, their number decreases, and the most energetic jets reach great depths. Therefore, when selecting jets, only the ionization registered under the absorber layer with a total thickness of at least five nuclear ranges was considered.

Preliminary results have indicated the presence of the effect in large-scale hadronic structures in the cores of high-energy extensive air showers at the level of six standard deviations above the background [25]. The share of such events grows with increasing energy and the amounts average approximately 25% in the energy range of 0.1–10 PeV. Thus, the new ionization calorimeter considered below, which is thicker than the BIC, will make it possible to study the above problem in more detail.

It is very difficult to explain, by cascade fluctuations, the entire set of experimental results related to the coplanarity of hadron generation, since the corresponding probability is very low ($\lesssim 10^{-10}$) [26–28]. On the whole, it can be concluded [29] that this phenomenon is associated with MEPs generated at the early stage of EAS development, that this process is not reproduced by simulations within the framework of QCD- and QGS-based models applied in the physics of high-energy cosmic rays, and that the cross section for the coplanar generation of MEPs is relatively large.

Although coplanarity was originally associated with relatively large transverse momenta in the coplanar plane, the evaluation of transverse momenta in coplanar events has not actually been carried out.

Theoretical ideas relate the coplanar particle generation with; the angular momentum of a quark-gluon string rotated by interacting hadrons [30], the semihard double inelastic diffraction and some QGS tension inside a diffraction cluster between a semihardly scattered quark and spectator quarks of an interacting hadron [31], leading systems with very high spin [32,33], QCD jet generation [34], and a temporary transition of three-dimensional space into a two-dimensional one [35–37].

The first four hypotheses [30–33] include large transverse momenta as an almost indispensable element that determines a coplanar plane. In this case, transverse momenta directed perpendicular to this plane still have standard values of traditional hadronic interaction models. Besides, the fourth hypothesis [34] cannot really explain the relatively large cross section for the generation of MEPs. The hypothesis [35–37] suggests a decrease in the dimension of space from three to two dimensions at sufficiently high energies. In this case, the transverse momenta are localized in a plane without significant changes in their mean values.

The lateral scale of coplanar events observed in the XREC, which are characterized by a very high lateral resolution (~ 100 microns), is very small, mainly about 1 cm or less, which corresponds to the selection of events produced by interactions of hadrons with the nuclei of air atoms at altitudes of 1–2 km above the detector. The ionization calorimeter at an altitude of the Tien Shan station has a much coarser lateral resolution of the order of the width of the ionization chambers used by the calorimeter. Therefore, the effects corresponding to the phenomenon of coplanar generation of particles and detected by ionization calorimeters should have a much wider lateral distribution (on the order of several meters). This will lead to the selection of events created by hadron-nucleus interactions at much higher altitudes above the calorimeter, namely, at altitudes to the order of tens of kilometers.

All the above-considered experimental results (the delayed absorption of ionization in the thick hadron calorimeter, the flattening of the depth distribution of hadron interaction in a thick homogeneous XREC, and the coplanarity of the most energetic EAS subcores) are observed in the EAS central cores. They are associated with the most energetic secondary hadrons generated with relatively high values of Feynman variable, $x_F \gtrsim 0.01$ – 0.05 , in the very-forward region of secondary-hadron generation. These experimental data show that we do not yet understand all the features of hadronic interactions. Unfortunately, these phenomena cannot currently be studied in experiments at the Large Hadron Collider (LHC) due to the specific design of the collider and the detectors of the ALICE, ATLAS, CMS, LHCb Collaborations, which allows one to study only particles in a relatively narrow kinematic region. In terms of particle rapidity y , most of the results accumulated in these experiments have been obtained in the region $|y| \lesssim 4$, i.e. for particles with relatively low energies $E < 10$ GeV ($x_F \lesssim 0.005$). In order to explore very-forward kinematic regions in collider experiments, new large detectors are required, located far (~ 100 m) from the point of collision of beam particles.

As a result, the generation of the forward-kinematic region hadrons at superhigh energies can only be studied in experiments using cosmic rays. However, this requires a large amount of Monte Carlo simulations. In order to implement the project discussed below, calculations of the development of extensive air showers containing a huge number of hadrons, electrons, positrons, γ -rays and muons, as well as the calculation of the observed EAS characteristics, have been started using the standard CORSIKA modeling software package, which is widely used in the international practice for experiments with cosmic particles at different levels of observation. While using the CORSIKA package, it is possible to choose from several models concerning the interaction of hadrons with oxygen and nitrogen nuclei in the atmosphere. At the first stage of our calculations, we used the QGSJet II-04 model based on the ideologies of quark-gluon strings (QGS) and quantum chromo-

dynamics (QCD), which describe the generation of hard hadron jets with large transverse momenta. QGSJet II-04 is one of the most popular models in international EAS experiments. The development of showers from the atmospheric boundary to the level of the location of the Tien Shan High-mountain Scientific Station (3340 m a.s.l.) initiated by various nuclei (from protons to iron nuclei) with energies of 1, 10, 30, 100 PeV (1 PeV = 10^{15} eV) was simulated. The lateral and energy characteristics of hadrons, electrons, and muons have been obtained at various threshold values of E_{thr} .

The preliminary results are not unexpected and can be formulated as follows:

1. Electrons are the most intense EAS component at the considered energies at distances of less than 1 km from the axis.
2. The PDF of hadrons, electrons, and muons strongly depends on their energies. The higher the energy of the particles, the narrower their PDF becomes.
3. The intensity of hadrons in EASs initiated by protons near the shower axis is approximately one order of magnitude higher than the corresponding intensity in iron-initiated EASs at $E_0 = 1$ PeV, but the difference rapidly decreases with increasing E_0 .
4. Similar behavior is shown by muons.
5. Differences in the behavior of correlations between the average hadron energy and the distance to the axis in vertical EASs initiated by primary protons and iron nuclei are not very significant.

2. «Hadron-M» Complex Installation

For decades, the Institute of Physics and Technology has been conducting research in the field of cosmic ray physics using experimental data from ionization calorimeters. The initial studies started with the “Hadron-9” [38–40] calorimeter with an area of 9 m²; after modernization, this installation changed its structure and area size. The next calorimeters were “Hadron-44” [41,42] with an area of 44 m², and “Hadron-55” [43–45] with an area of 55 m². All installations have been located at an altitude of 3340 m above sea level.

The upgrade of the ionization-neutron calorimeter “Hadron-55” expanded the area of research by increasing the thickness of the absorber of the installation. The thickness of the calorimeter includes two new rows of ionization chambers with iron absorbers. Two shower systems were added, the first one above the calorimeter and the second peripheral shower system around the calorimeter, in order to increase the statistics of the studied particles of cosmic radiation. The calorimeter and internal shower system are located in the laboratory building with an area of 324 m². An external shower system is installed outside the building along concentric circles with radii of 25, 40 and 100 m, 4 SDs for each circle. The main difference of this calorimeter from the previous similar installations is the added number of neutron counters for registering neutron fluxes resulting from the development of extensive air showers.

In connection with the reconstruction, a new name was assigned—“Hadron-M complex installation”, which included an ionization-neutron calorimeter with an area of 55 m² and an absorber thickness of 1244 g/cm² (out of eight rows of ionization chambers), one row of neutron detectors and two shower systems of scintillation detectors. The effective area of the “Hadron-M” complex installation was about 30,000 m² [46].

Figure 3 shows the layout of the external storm water system of the “Hadron-M” complex installation.

The snapshot shows three-color marks (red, yellow, green) indicating the location of the SDs around the calorimeter (rectangular depression). Each label has numbers that show the distance from the center and the number of a detector (for example, 40_1 means 40 m from the calorimeter and 1 is the number of the SDs).

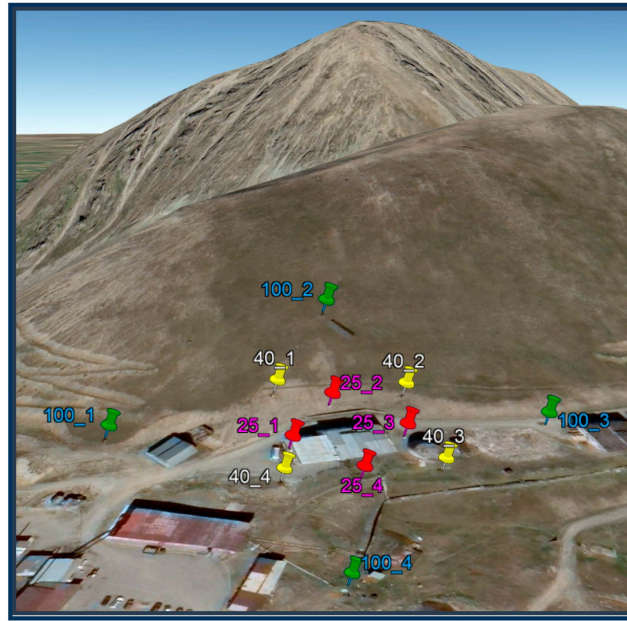


Figure 3. A snapshot of the location of the external storm system of the complex installation “Hadron-M”.

2.1. Ionization-Neutron Calorimeter

Currently, an improved series of a new computerized detector of hadron interactions of cosmic rays, the ionization-neutron calorimeter, has been put into operation. The calorimeter is designed to detect the most energetic hadrons and gamma rays in EAS systems. Studies and analysis of the data of each individual interaction recorded by the calorimeter detector system make it possible to obtain the primary energy of cosmic radiation particles, as well as the angular, spatial and depth distributions of secondary particles that characterize the main parameters of the shower. The new structure of the installation will make it possible to study the most central part of the forward kinematic cone of extensive cosmic ray air showers [46].

The ionization-neutron calorimeter includes an internal shower system of 30 SDs detectors and 1200 ionization chambers, which make up eight rows located in mutually perpendicular directions and one row of neutron counters. Taking into account the area of the calorimeter and the adjacent infrastructure (30,000 m²), which would increase significantly in the future, we can expect that the number of interactions with energies above $\sim 10^{15}$ eV would be more than 50,000 events per year. The peculiarity of the calorimeter is that it represents a set of various detectors, allowing for the more detailed study of the characteristics of interactions of particles of cosmic radiation, accurate calculation of the measurement of EAS arrival angles, and the development of the EAS core along the depth of the calorimeter.

Figure 4 demonstrates a diagram of a two-level ionization-neutron calorimeter: the upper level is a gamma block, the lower level is a hadron block.

The first two rows of the gamma block contain 238 ionization chambers, of which 100 chambers are in the first row and 138 chambers are in the second. Each row is separated by lead absorbers with a total thickness of 26.5 cm or 310 g/cm² (see Figure 4).

Figure 5 shows a snapshot of the gamma block, above which the internal shower system of SDs detectors is located. The shower system contains 30 detectors at a distance of approximately 1.0 m from each other with an occupied area of 320 m², nine of which are located in the gamma block.

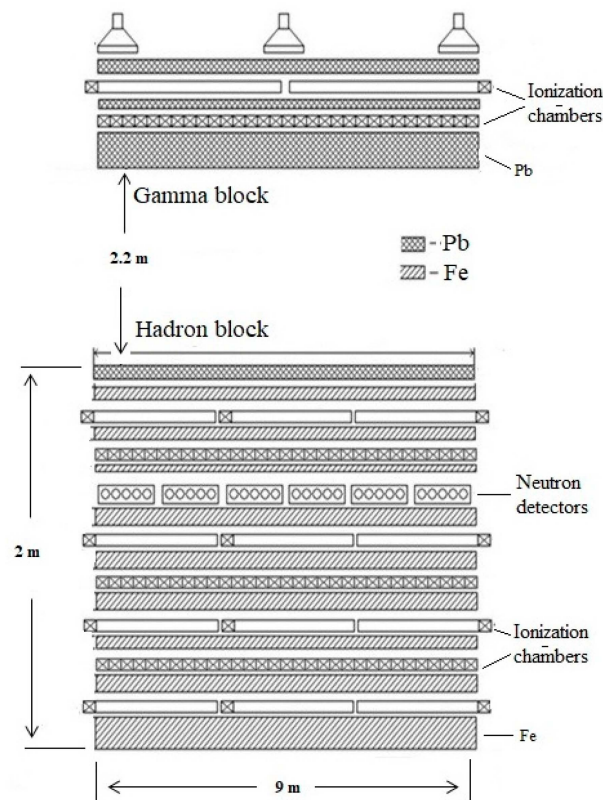


Figure 4. Scheme of the ionization-neutron calorimeter.

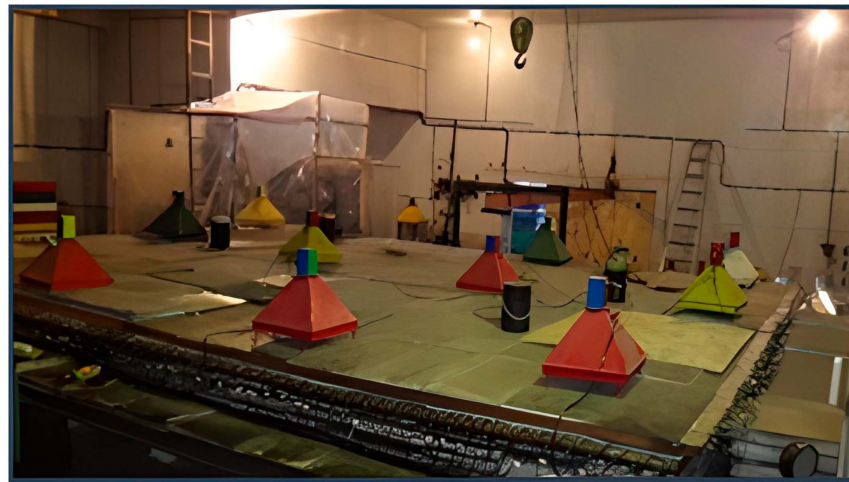


Figure 5. Gamma block with internal shower system of the SDs detectors of the ionization-neutron calorimeter.

The hadron block of the calorimeter contains 870 ionization chambers, which are placed in six rows. One row, which is located after the first pair of ionization chambers, contains neutron and Geiger counters. This row records and detects neutrons to obtain information about the properties of nuclear interaction at high energies, in particular, to detect neutron fluxes resulting from the development of EAS. Each row is separated by an iron or lead absorber (see Figure 6).

All rows of ionization chambers (from rows 1 to 8) are mutually perpendicular. The width of the ionization chambers is 11 cm. A pair of mutually perpendicular rows form the observation level (more precisely, they give the X, Y coordinates of the passage of particles). This makes it possible to define the coordinates of space tracks with accuracy up to the

width of the chamber. As a result, the calorimeter has 4 levels of observation: (1 + 2 row) are at the - 1st level; (3 + 4 row) are at the 2nd level; (5 + 6 row) are at the 3rd level; (7 + 8 row) are at the 4th level (see Figure 4).



Figure 6. Hadron block of the ionization-neutron calorimeter.

2.2. Registration and Analysis of “Hadron-M” Experimental Data

The database of the “Hadron-M” complex installation is available at www.tien-shan.org (accessed on 15 December 2022), which can be accessed via the local network by remote client programs with specific requests for data processing [46,47].

The experimental data bank of the “Hadron-M” complex installation has a two-level structure. The initial bank Bank-0 contains physical and test events of operational control of the installation. The test event recording mode is designed to analyze the operation of individual channels of the recording system. The secondary bank Bank-1 contains events recorded in the physical mode Bank-0, taking into account the calibration characteristics for each individual channel.

Currently, the “Hadron-M” complex installation is conducting and planning the below studies:

- a study of anomalous absorption of hadrons along the depth of the operating installation [48–50];
- a study of correlations between the primary energy E_0 (determining EAS parameters from the energies of hadrons, neutrons, and electron-photon components) [29,51,52];
- a search for exotic particles and events (such as strangelets and Centauro events, characterized by an anomalous ratio of charged and neutral hadrons) [53–57].

As a result of many years of research at the present stage of science development, the general form of the energy spectrum of galactic cosmic rays has become known, the magnitude of which is of at least the 10th order. Throughout this range, the spectrum has a universal power-law form, and its exponent γ changes sharply at several characteristic points. The origin of these features in the primary spectrum of cosmic rays remains unclear to date, even though more than half a century has passed since the discovery of the most famous of them, namely, a sharp break in the value of the exponent of the power spectrum at $E_0 \sim 3 \cdot 10^{15}$ eV [58]. In some articles, this break is associated with the contribution of the so-called strangelets (particles of strange matter) [54–56].

A more thorough study of the processes in the narrow front cone of EAS is one of the most important problems in the physics of cosmic rays. Earlier studies of EAS cores at the Tien Shan and Pamir-Chacaltaya [11] stations showed new results [59]. In the context of the problem, we should note two phenomena. First is the phenomenon of the coplanar emission

of particles observed as events with the geometric alignment of most energetic subscores in the EAS's central core [9–11]. Besides, events with an anomalous ratio of charged and neutral components have been observed, namely, the so-called “Centauro” events. To search for and study possible events of the “Centauro” type, the CMS-CASTOR detector (Centauro And Strange Object Research) very-forward calorimeter experiment [60,61] was designed and implemented as part of the CMS experiment at the LHC.

At present, the very-forward physics is being studied at the LHC by the LHCf (Large Hadron Collider forward) experiment [62]. LHCf is made up of two detectors which sit along the LHC beamline, at 140 metres either side of the ATLAS collision point. The location allows the observation of particles at nearly zero degrees to the proton beam direction ($8.81 < \eta < 9.22$ and $\eta > 10.76$). Each of the two detectors weighs only 40 kg and measures 30 cm long by 80 cm high and 10 cm wide. They can only detect neutral particles (neutrons, γ -rays etc.). Unfortunately, the dimensions of these detectors are too small to study correlations of most energetic particles.

One can formally say that the forward physics kinematic region is also studied by the FASER experiment [63]. However, FASER is searching for new light, long-lived and mostly weak-interacting particles that are produced at or close to the ATLAS interaction point, move along the beam collision axis line of sight, and then decay within the volume of FASER into visible decay products. Thus, the goals of the FASER experiment are not focused on the study of most energetic hadrons, which is what is considered in this paper. A certain contribution to these studies could be made by the “Hadron-M” installation, which is aimed at studying the EAS central core [64].

Research carried out at the “Hadron-M” installation is aimed at studying the most energetic particles to solve the fundamental problems of cosmic ray physics related to the nature and propagation of primary cosmic rays from their sources to the Earth. Considering that the “Hadron-M” installation has no analog in the world, it can qualitatively show new results in the problem of identifying the “true” properties penetrating the cosmic ray components due to the complex and diverse structure of the installed detectors and the depth of the ionization calorimeter.

One of the tasks being solved at the “Hadron-M” installation relates to a study from the field of gamma-ray astronomy to calculate the trajectory from the observed EAS characteristics to the primary energy [48].

The gamma radiation detection method is based on the fact that the gamma block absorbs the electron-photon component (EPC) of cosmic rays, and the hadronic component, due to the small thickness of the gamma block, passes without interactions through the gamma block. Further interactions and generation of particles develop in the hadron block.

Taking into account that the “Hadron-M” installation is located on uneven mountainous terrain, the new calculations in the standard method were introduced to find the coordinates of primary particles. To determine the coordinates of the primary particle, the installation data on the thickness of the atmosphere passed by the shower were used, such as: the zenith angle of arrival of the shower θ , the azimuth angle φ of the shower, the total number of particles in the shower N_e at the observation level and their lateral distribution. The number of detectors available on the installation allows for the reduction of errors when finding angles. Knowledge of θ , φ , EAS arrival time (UTC), and the geographical co-ordinates of the installation allows one to unambiguously determine the point of the celestial sphere from which the primary particle came.

One of the topical tasks solved at the “Hadron-M” installation is the study of the interactions of hadrons with the nuclei of air atoms and the identification of their properties during the generation of secondary particles in the energy range $E > 10^{15}$ eV.

To study the composition of primary cosmic radiation and the passage of EAS, as well as to confirm previously obtained results, it is necessary to collect statistical material, conduct and play several different cascades from hadrons and muons, taking into account the structure of the calorimeter and the method of registration of the “Hadron-M” installation; calculate the composition and spectra of hadrons and muons in the EAS core at

the height of the Tien Shan high mountain station for different energies and charges of primary nuclei using various models, including the CORSIKA package; and carry out a comparative analysis with the experimental data of the “Hadron-M” installation.

3. Conclusions

The new data obtained on the nature of the absorption of the hadronic component will provide an opportunity to obtain an answer to explain the anomalous absorption of cascades in EAS cores and, to some extent, establish the nature of the penetrating component of cosmic radiation.

The study of the penetrating component and coplanarity of EAS subcores is of fundamental importance, since it provides information both on the very-forward physics of strong interactions and on the PCR composition. Confirmation of the phenomenon of strong coplanarity of EAS subcores may indicate both insufficient understanding of the hadron-generation mechanisms in the forward cone [65] and problems in understanding of the cosmological characteristics of the dimension of our space [35–37].

Results of the Tien Shan high-mountain experiments to study EAS characteristics may indicate the appearance of an additional PCR component and support the hypothesis of the presence of particles of strange quark matter in the PCR [54,55] at energies above 10^{16} eV. Confirmation of this hypothesis may become an important discovery both in the field of astrophysics and in elementary particle physics, since the presence of such particles is impossible without the existence of stars consisting of stable strange quark matter with a lifetime exceeding the lifetime of the Universe [54].

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