Strange Quark Matter and the Astrophysical Nature of Anomalous Effects in 1–100 PeV Cosmic Rays

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The composition of cosmic rays is of decisive importance for the determination of reasons for change in the slope of the spectra of extensive air showers (knee) at energies of 1–100 PeV. The characteristics of the extensive air showers, where the highest energy secondary hadrons are concentrated, have been analyzed. Some anomalous effects such as an increase in the absorption length of hadron showers, scaling violation in the spectra of secondary hadrons, an excess of muons in extensive air showers with gamma-ray families, the appearance of the halos, and the alignment of energy centers along a straight line are observed in X-ray emulsion chambers in the knee region. At the same energies equivalent to 1–100 PeV in the laboratory system, LHC and RHIC data demonstrate a scaling behavior of the hadron spectrum, which means that new nuclear processes are absent. These data imply that anomalies observed in cosmic rays are due to astrophysical reasons, i.e., changes in the composition of cosmic rays. The analysis of the data on the EAS cores suggests that the knee in their spectrum is formed by a nonnuclear component of cosmic rays, possibly consisting of particles of strange quark matter.

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1. INTRODUCTION

The spectrum of cosmic rays (CRs) above 0.1 PeV is reconstructed from data on extensive air showers (EASs). The spectrum of EASs has a bend at \( E_0 = 3 \) PeV [1], which is called the knee. One of the most important aims of astrophysics for more than half a century is to determine reasons for the knee. The data on EAS cores collected in this time make it possible to formulate a new model of formation of the knee.

Cosmic rays consist mainly of five groups of nuclei: protons, He, CNO, Si, and Fe produced in supernovae [2]. Nuclei are accelerated by shock waves [3] to the maximum energies determined by magnetic rigidity \( R_{\text{max}} \approx E_0/Z \); where \( E_0 \) and \( Z \) are the energy and charge number of the nucleus, respectively.

According to this scheme, there are two variants of the knee: (i) \( R_{\text{max}} \approx 0.1 \) PV; this knee at 3 PeV is formed by iron-group nuclei with the maximum charge number \( Z \); and (ii) \( R_{\text{max}} \approx 3 \) PV; the knee in this case is formed by the proton component of cosmic rays. The calculations in [4, 5] show that both variants can be theoretically justified by selecting the model parameters.

Another scheme of the knee is associated with an anomalously large contribution from a single nearby source [6–8]. A model demonstrates that the single source located at certain distances in the Galaxy can emit radiation comparable in intensity with the total spectrum of CRs and, moreover, it can naturally be responsible for the observed sharp bend in the spectrum of CRs at 3 PeV [6].

There are numerous models of the composition of CRs in the knee region; most of them assume the acceleration of CRs at \( R_{\text{max}} \approx 3 \) PV [9]. The main reason for this assumption is the necessity to match the spectra of galactic and extragalactic CRs at an energy of \( 10^{18}–10^{19} \) eV. The spectrum of galactic CRs at \( R_{\text{max}} \approx 0.1 \) PV ends at an energy of \( 3 \times 10^{15} \) eV, and no model can explain in this case the existence of CRs with energies up to \( 10^{18}–10^{19} \) eV, at which the characteristics of EASs change significantly [10, 11].

In this work, we review the results of studies of EAS cores. According to these data, the model with a magnetic rigidity of \( R_{\text{max}} \approx 0.1 \) PV can also be consistent with the spectrum of the extragalactic component.

According to results from the LHCf and RHICf experiments [12–16], scaling is observed at energies equivalent to 1–100 PeV in the laboratory reference frame; i.e., the characteristics of the nuclear interaction do not qualitatively change in the knee region.

Two regions in EASs are particularly sensitive to the primary composition of CRs. These are the elec-
tromagnetic periphery at a radius of hundreds of meters, which will be referred to below as the proper EAS, and a small region near the axis of the EAS, which contains the highest energy hadrons of the shower constituting the EAS core.

Methods for detecting the electromagnetic and nuclear components of EASs are substantially different. The most complex instruments are used to detect EAS cores. These are either ionization calorimeters or X-ray emulsion chambers. An X-ray emulsion chamber is the most informative detector of EAS cores. A high spatial resolution (~100 μm) allows the measurement of energies of gamma-ray photons above several TeV from the $\pi^0 \rightarrow 2\gamma$ decay.

The entire instrument should combine a detector of cores and an EAS array because only this combination makes it possible to obtain information on the energy of primary CRs.

Instruments for studying EAS cores surpass EAS arrays in informativity, but are behind them in statistics of events. For this reason, their area of applicability is limited to energies of $10^{15}$–$10^{18}$ eV, i.e., the knee region of the spectrum of EASs.

Since the gamma-ray photon detection threshold in an X-ray emulsion chamber is high, events initiated by primary protons are mainly selected. This significantly simplifies the determination of the spectrum of protons and the magnetic rigidity of the knee $R_{\text{max}}$.

2. EXPERIMENTAL RESULTS OF THE STUDY OF EAS CORES

2.1. Aerostatic JACEE Experiment

Figure 1 shows the spectra of nuclei obtained in the aerostatic JACEE experiment with an emulsion chamber. It is seen that the spectrum of protons has a kink at an energy of $E_{\text{max}} \approx 0.1$ PeV [17]. The kink in the spectrum of nuclei is observed at a magnetic rigidity of $R \approx 0.1$ PV. According to these data, the kink in the spectrum of all particles should be due to iron-group nuclei; consequently, a new component of CRs should appear at energies above 3 PeV.

2.2. ASγ Experiment

The JACEE result is confirmed by measurement at a mountain level. The proton spectrum at energies above 100 TeV was obtained in the hybrid ASγ experiment in Tibet (at a height of 4300 m above sea level, 606 g/cm²) [18–20]. In this experiment, the region of EAS cores was studied with a burst detector and an 80-m² X-ray emulsion chamber united with an EAS array. The observed spectrum can be approximated by power laws with the exponents $\kappa_{\gamma} = -2.74 \pm 0.01$. The spectrum obtained is shown in Fig. 2 in comparison with the spectrum of protons obtained in the experiment KASCADE-Grande (Karlsruhe) from the data on the electromagnetic component of EASs at sea level. The KASCADE-Grande data are also given in two variants within the models QGSJET and SIBYLL. The data in the latter variant are in agreement with Tibet data, but the model QGSJET implies the kink of the proton spectrum near an energy of 3 PeV.

The ASγ data shown in Fig. 3 confirm that the composition of CRs becomes heavier. The fraction of nuclei heavier than helium in primary CRs around the knee region increases with the primary energy. The authors of the ASγ experiment believe that this means that the knee in the spectrum of all particles is due to nuclei heavier than helium.

Figure 3 also presents data of the KASCADE-Grande experiment. Being processed within the SIBYLL model, they are in agreement with ASγ data. When the QGSJET model is used, the fraction of the heavy component also increases, but this fraction is smaller by one-third. It also follows from Figs. 2 and 3 that ASγ data are much less model dependent.

As in the JACEE data, the kink of the spectrum of protons occurs at a magnetic rigidity of $R_{\text{max}} \approx 0.1$ PV.

2.3. EAS Experiment

The first evidence of the penetrating component of CRs was obtained in the calorimeter experiment in Tien Shan [21]. It was found that the absorption cas-
cascade length in a lead calorimeter at a hadron energy of \( \sim 100 \) TeV increases from 800 to 1100 g/cm².

2.4. PAMIR Experiment

This effect was confirmed in works by the PAMIR Collaboration with a thick lead X-ray emulsion chamber [22, 23]. The reduction of hadron absorption with an increase in the absorption length from \((200 \pm 5)\) to \((340 \pm 80)\) g/cm² was observed at a depth of more than 50 cm in lead.

2.5. HADRON Experiment

In the hybrid experiment HADRON (Tien Shan mountain cosmic ray station, 3330 m above sea level), families of gamma rays in the X-ray emulsion chamber were united with EASs, which made it possible to determine the total number of electrons in EASs \( N_e \) (the primary energy \( E_0 \)) for each family and the energy spectra of gamma rays in the Feynman variables \( E_\gamma/E_0 \) for various \( N_e \) ranges [24, 25].

Figure 4 shows the dependence of the slope of the spectrum of gamma rays on \( N_e \). The horizontal gray band corresponds to scaling in spectra. A change in the slope of experimental spectra means violation of scaling. According to the \( \chi^2 \) criterion, the probability of random violation of scaling is no more than \( P = 10^{-8} \) [25].

Violation of scaling coincides with the kink in the spectrum of EASs at \( \log N_e = 6.1 \). This coincidence is hardly random and the kink in the spectrum of EASs should be attributed to violation of scaling corresponding to a change in the composition of CRs. A decrease in the slope of spectra indicates an increase in the energy of hadrons or the appearance of the penetrating component of CRs.

Another feature is a local character of violation of scaling. The number of events in spectra decreases with increasing energy; hence, more accurate results for the maximum energy of scaling violation can be

![Fig. 2. Spectrum of primary protons obtained in the AS\( \gamma \) experiment compared to data of other experiments [18]: (1) PROTON satellite, (2) Tibet-III, (3) AKENO, (4) QGSJET + HD, (5) QGSJET + PD, (6) SIBYLL + HD, (7) SIBYLL + PD, (8) Tibet-B.D.(QGSJET + HD), (9) Tibet-B.D.(QGSJET + PD), (10) KASCADE(QGSJET), (11) KASCADE(SIBYLL), (12) JACEE, and (13) RUNJOB.](image)

![Fig. 3. Fraction of nuclei heavier than He in the mass composition of primary cosmic rays obtained within the QGSJET and SIBYLL nuclear interaction models. The AS\( \gamma \) data are given in comparison with the KASCADE-Grande data [18]: (1) QGSJET + HD, (2) QGSJET + PD, (3) SIBYLL + HD, (4) SIBYLL + PD, (5) KASCADE(QGSJET), and (6) KASCADE(SIBYLL).](image)

![Fig. 4. Slope of the spectrum of gamma rays detected in X-ray emulsion chambers versus the total number of electrons in EASs \( N_e \)[25].](image)
obtained from the dependence of the total energy of families $\Sigma E_\gamma$ on $N_e$ shown in Fig. 5. According to this dependence, the maximum energy of scaling violation corresponds to $N_e = 10^7$ or to the energy $E_0 = 20$ PeV, where $\Sigma E_\gamma$ decreases from 100 to 50 TeV.

Figure 5 shows the approximation of experimental data within various models proposed by Japanese researchers. Model A is based on accelerator data and has two variants for light and heavy compositions of CRs. Model B involves an exotic variant of the presence of Centauro events in CRs [27]. It is important that models A and B used in [26] differ by almost an order of magnitude in the energy transfer to gamma rays, and no model reproduces the experimental data in the entire energy range.

Muon data help to reveal the nature of the penetrating component. Figure 6 shows the dependence of the average number of muons $\langle N_\mu \rangle$ on $N_e$ for all EASs (circles) and EASs with gamma–hadron families (triangles) [28]. The dashed line qualitatively indicates the expected number of muons in EASs with gamma–hadron families for the standard nuclear model.

According to nuclear model concepts, most of the EASs with gamma–hadron families detected in the X-ray emulsion chamber are initiated by protons; consequently, the expected number of muons in these events should be a factor of 1.5 smaller than the average number for all EASs [29]. The simultaneous increase in the energy of hadrons in EASs and in the number of muons in the same events is inconsistent with a nuclear model of the cascade. Taking into account accelerator data, these two effects can be explained neither by an anomalous character of the interaction nor by a change in the composition within the nuclear model of CRs.

The revealed contradiction is general. The selection of EASs with gamma-ray families is based on the selection of fluctuations in the development of nuclear cascades, when a relatively small fraction of the primary energy is scattered in the atmosphere and, in particular, is transferred to muons. At the same time, an increase in the number of muons indicates increasing dissipation of the energy. Therefore, it remains to assume a nonnuclear nature of the new component in Fig. 1.

Events detected in the X-ray emulsion chamber (gamma–hadron families) correspond to EAS cores. So-called superfamilies with energies $\Sigma E_\gamma \geq 300–500$ TeV constitute a specific class in these events. Two striking effects were observed in these events: the formation of a continuous darkening spot (the halo) and azimuthal symmetry breaking caused by the alignment of energy centers of a family along a straight line.

2.6. Halo

Figure 7 exemplifies a gamma–ray family with the halo (PAMIR experiment, Fianit halo) [30]. The area of the halo can vary from tens of square millimeters to square centimeters. The halo in Fig. 7 has an area of $S = 10.17$ cm$^2$. The total energy of gamma rays is
ΣE_γ = 20 PeV and the primary energy is estimated at 4 × 10^{17} eV.

A series of calculations and experiments show that the formation of the halo is due to electromagnetic processes initiated by high-energy gamma rays with a significant contribution from subthreshold photons.

The authors of [31] (Chacaltaya and the Pamir Collaboration) emphasize that a change in the nuclear interactions in EASs is necessary to explain the observed characteristics of superfamilies with the halo because these gamma-ray families exhibit clusters of electromagnetic origin with low transverse momenta (P_t ~ 10 MeV) and an anomalously high penetrating ability. The development of clusters in lead of the X-ray emulsion chamber leads to the formation of the continuous the halo with the penetrating ability of hadrons. Since clusters include hadrons with electromagnetic transverse momenta, the authors of [31] conclude that new processes in the fragmentation region should be taken into account.

The dependence of the spectrum of families with the halo on the primary energy was obtained in the HADRON experiment. Figure 8 shows the dependence of the number of events with the halo on logN_e. Most of the events with the halo are concentrated in the knee region. The event distribution has a maximum in the region of violation of scaling at N_e ≈ 4 × 10^6 (E_0 ~ 10 PeV). This point can be treated as the energy threshold for the halo formation. The result is in agreement with the initial energy of the halo formation estimated in [32]. The maximum of events with the halo detected in the HADRON experiment is marked by the star in Fig. 4. According to this figure, events with the halo correspond to the hardest gamma rays. Their energy and multiplicity are about a factor of 4 higher than the respective average values in this N_e range.

2.7. Alignment of Energy Centers

Figure 9 exemplifies the alignment of energy centers in gamma-ray families. The alignment of energy centers along a straight line violates isotropy, which is one of the main geometrical properties of the nuclear interactions.

The alignment of energy centers is enhanced with increasing total energy of families ΣE, and is observed approximately in half of the superfamilies; i.e., it is a general characteristic of the interaction inconsistent with a random sample of events. It is impossible to explain alignment by trivial processes.

It was shown in [32] that the threshold of alignment appearance, as well as the halo, corresponds to an energy of about 10 PeV, i.e., in the knee region.

2.8. Centauros

Another anomalous effect was observed by the Japanese–Brazilian Collaboration on Chacaltaya Mountain (5200 m above sea level) in the X-ray emulsion chamber consisting of two chambers separated by an air gap of 158 cm. Events called Centauros consisted only of charged hadrons, whereas gamma rays were almost absent [27].

In particular, 49 hadrons and only one gamma-ray photon were observed in the CENTAURO-I event. In this case, according to estimates of the detection effi-

Fig. 7. (a) Halo obtained in the PAMIR (Fianit) experiment with X-ray emulsion chambers. (b) Densitogram of the Fianit halo [30].

Fig. 8. Distribution of gamma-ray families with the halo versus logN_e.

Fig. 9. Examples of aligned energy centers in gamma-ray families.
ciency, 22 hadrons should pass through the X-ray emulsion chamber without interaction.

According to the JACEE and ASγ experiments [17–20], the magnetic cutoff rigidity of nuclear spectra of CRs is \( R_{\text{max}} \simeq 0.1 \) PV. Therefore, the galactic nuclear component should end at energies of \(~3\) PeV.

Scaling violation observed at energies above 3 PeV indicates the appearance of the penetrating component of CRs. The knee should be due to either to light nuclei (protons) accelerated by a more efficient mechanism than acceleration on shock waves or to the different-nature component of CRs. The proton variant is excluded because ASγ data indicate that the composition of CRs becomes heavier in the knee region presented in Fig. 3.

Furthermore, the energy of hadrons generating gamma-ray families in the knee region increases [24, 25] and the number of muons increases simultaneously [28]. Taking into account accelerator data [12–16], the observed effects cannot be explained by a change in the nuclear interactions. Muon data also contradict the increase in the fraction of light nuclei (protons) because the number of muons should decrease in this case. The explanation of the simultaneous increase in the energy of hadrons and the number of muons should be sought beyond the nuclear composition and should involve a nonnuclear component of CRs.

The possibility of involving nonnuclear particles is limited by a necessary condition of their stability (quasi-stability) because CRs include only particles that can cover cosmic distances from stars and reach the Earth.

It seems that these can be only particles of hypothetical strange quark matter [33, 34]. This variant is based on the discovery of the quark structure of matter [35, 36] and on some theoretical works, e.g., [34], where it was shown that particles of strange quark matter at large baryon numbers \( A = 10^{3}−10^{7} \) become stable and charged; just these particles are called strangelets.

The region of existence of strangelets is limited. Their charge is due to the difference in the densities of the \( u, d, \) and \( s \) quarks at baryon numbers \( A = 10^{3}−10^{8} \), which arises because the masses of the \( u, d, \) and \( s \) quarks are significantly different. At a larger number of quarks in a strangelet (larger \( A \)), the densities of different quarks become equal and particles of strange quark matter become neutral. The baryon number of neutral particles can increase to a star value \( A = 10^{32} \). Such a hadron is a strange quark star.

The intense formation of strange quark stars could have occurred at the phase transition of the quark–gluon plasma to hadrons in the early Universe, which resulted in the separation of matter into the nuclear and quark components, finally ending with the formation of nuclear and quark stars [34]. The properties of such astronomical objects are drastically different because processes of synthesis of heavy nuclei occur in nuclear stars, whereas the evolution of quark stars is simpler; emitting they are cooled from a temperature of 170 MeV possibly to a temperature of cosmic microwave background. In this case, being in thermal equilibrium with cosmic microwave background, quark stars can make a contribution to dark matter [34, 37]. However, the problem of the rate of cooling and evaporation of strange quark stars is still unsolved.

In addition to the variant with the early Universe, the modern formation of strange quark stars is possible. In supernovae, the compression of a neutron star can continue and result in a quark star because its density and stability exceed the respective characteristics of nuclear matter (see review [38]).

If a phase transition from a neutron star to a quark star occurs in nature, strangelets, as well as nuclei, can be formed in supernovae. However, if quark stars from the early Universe exist, they can be injected to the surrounding space at the coalescence of double star systems, which involves at least one quark star. The presence of strangelets in CRs also follows from Cen-tauro events [27]. Being interpreted within the nuclear cascade model, the fundamental property of isotopic invariance is violated in these events. To explain this violation, Bjorken and McLerran [33] assumed that CRs include particles of strange quark matter. In this case, their decay should generate jets consisting of hyperons rather than of pions, which explains Cen-tauro events.

Taking into account the Coulomb barrier, neutral particles, primarily, \( \pi^{0}, K^{0}, \rho^{0}, \) neutrinos, and gamma rays, have an advantage. The inelasticity coefficient in this case is small, about \( K_{\text{in}} \simeq 0.001 \), and the interaction cross section is large \( \sigma_{\text{geo}} \sim A^{2/3} \), and the geometric cross section \( \sigma_{\text{geo}} \sim 10^{-3} \) b for \( A = 10^{3}−10^{7} \) [24]. The corresponding interaction length in air is \( \lambda_{\text{int}} \approx (A_{\text{air}} m_{p})/\sigma_{\text{geo}} = 10−0.01 \) g/cm².

At the stability boundary, strangelets consisting of \( u, d, \) and \( s \) quarks have a charge number of about \( Z = 30 \), and their maximum charge number can be \( Z \simeq 1000 \) at a large baryon number of \( A \simeq 10^{7} \). At baryon numbers larger than \( A = 10^{7}−10^{8} \), the densities of the \( u, d, \) and \( s \) quarks become equal, the electric charge of such hadrons vanishes, and their acceleration on shock waves ceases. As a result, the mass and charge numbers of strangelets are \( A = 10^{3}−10^{8} \) and \( Z = 30−1000 \), respectively.

3. ANOMALIES IN COSMIC RAYS

Calculations of the interaction between strangelets within QCD are absent because they are complicated. However, taking into account the presented characteristics of strangelets, we can try to qualitatively reproduce anomalies observed in CRs.
3.1. Acceleration of Cosmic Rays

An important advantage of strange quark matter models is that the shock wave mechanism of acceleration is the same for nuclei and strangelets because strangelets are quasi-nuclei. Since the electric charge number of strangelets can reach \( Z = 1000 \), the maximum energy of CRs at the magnetic rigidity of the kink in individual spectra \( R = 0.1 \) PV reaches \( E_0 = 10^{17} \text{ eV} \). The interaction length of a strangelet in the atmosphere is \( \lambda_{\text{int}} \approx 0.01 \text{ g/cm}^2 \); i.e., the strangelet undergoes about \( 10^5 \) interaction events in a nuclear interaction length of about \( 100 \text{ g/cm}^2 \). Even at the minimum inelasticity coefficient \( K_{\text{in}} \approx 0.001 \) and including absorption, one can expect that the number of electrons in this case is no less than the number of nuclei \( N_{e^S} \geq N_{e^{\text{nuc}}} \).

An increase in the slope of the spectrum of CRs (knee) is due to a much heavier mass of quasi-nuclei.

3.2. Spectrum of Cosmic Rays

According to estimates by Bjorken and McLerran [33], an EAS produced by strangelets is similar in characteristics to a nuclear EAS for the CNO group. Since the cross section for the interaction of strangelets increases strongly with the baryon number \( A \) (\( \sigma \approx 100 \text{ b} \)), one can expect that, having a maximum energy of 100 PeV, they can initiate EASs with the number of electrons \( N_e \approx 10^9 \), which ensures matching between the spectra of galactic and extragalactic CRs.

The absence of strangelets at energies below 3 PeV can be explained by the contribution of a single nearby source [6–8], e.g., a strange quark star [34], to the spectrum of CRs above the knee region.

3.3. Scaling Violation

Scaling violation in the range of \( N_e = 10^6–10^7 \) is quite naturally explained by the possible decay of strangelets at the edge of stability caused by the interaction with air. The local character of this region can be attributed to an increase in the binding energy of strangelets with increasing baryon number and to the appearance of stability with respect to the interaction for \( A = 10^8–10^9 \).

3.4. Muon Excess

The anomalous excess of muons is due to numerous interaction events of strangelets in the atmosphere. At a relatively low detection threshold of muons (5 GeV), the number of muons increases during the passage of a strangelet through the atmosphere and can finally exceed the average number of muons in nuclear EASs. The maximum number of muons is expected in EASs with gamma-ray families, where the strangelet decays into hundreds of hyperons.

3.5. Halo

Halo has an electromagnetic origin but has a high (hadron) penetrating ability. In the presence of a Coulomb barrier for the strangelet, it should most efficiently generate \( \pi^0 \) mesons and directly gamma rays, which have zero charge and zero mass. The production of high-energy gamma rays from the decay of \( \pi^0 \) and the intense direct generation of low-energy (sub-threshold) gamma rays are responsible for the halo. The penetrating ability of the halo is determined by the penetrating ability of the strangelet itself.

3.6. Alignment

Alignment can be explained, e.g., within the droplet model. The strangelet at large baryon numbers can decay into two stable (quasistable) strangelets rather than decaying completely as in the region of scaling violation. The decay of the strangelet should be accompanied by the formation of an intense jet consisting of hundreds of quark–quark strings between its parts. The rupture of such strings should result in the production of quark–antiquark pairs and the formation of mesons along a string.

3.7. Centauros

Centauro events are due to the decay of strangelets into hyperons, which explains the absence of \( \pi^0 \) mesons.

The current status of the explanation of the knee is as follows. Two models were proposed. The first model is based on the data on the electromagnetic component of EASs and implies that nuclei are accelerated to energies determined by the magnetic rigidity \( R \approx 3 \) PV. The second model is based on the data on EAS cores and implies that the kink in nuclear spectra occurs at a magnetic rigidity of \( R \approx 0.1 \) PV, whereas the knee up to the extragalactic component of CRs is formed by strangelets (particles of strange quark matter). We refer to these models as the EAS and CORE models, respectively. Both models have problems.

The main problem of the EAS models is a strong dependence of the result on the interaction model. The authors of [18] showed that the results of processing of the KASCADE-Grande data within the QGSJET and SIBYLL interaction models can differ by several times (Fig. 2).

The CORE model hardly involves the interaction of strangelets with air and, thereby, provides qualitative results. At the same time, this can be considered as an advantage. Empirical conclusions underlying the CORE model are independent of model representations or slightly depend on them.
4. EXPERIMENTAL EVIDENCE OF THE NONNUCLEAR COMPONENT OF COSMIC RAYS

The final choice between the models should be determined by experiment. Below, we present two experimental results that can confirm the presence of a nonnuclear component of CRs.

4.1. Muon Data

Some experiments demonstrate an excess of muons (muon puzzle) [39, 40]. The analysis of muon data with the parameter

\[ z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_p - \ln\langle N_\mu \rangle_p} \]  

(1)

showed that events with \( z > 1 \) are observed at energies above \( 10^{17} \text{ eV} \); i.e., CRs can include primary particles heavier than iron.

4.2. Delayed Showers

The so-called delayed showers with fronts spaced by hundreds of nanoseconds have been observed for about 70 years in some experiments beginning with [41]. These experiments were reviewed in [42]. In particular, this effect at sea level was studied at the facility of the Skobeltsyn Institute of Nuclear Physics, Moscow State University [43–45].

Although this brief review is focused on the detection of EAS cores, the existence of delayed showers is a striking effect that cannot be attributed to the development of an ordinary nuclear cascade. Previous attempts to explain this effect by the production of heavy hadrons in the atmosphere failed because particles heavier than TeV are necessary to explain the observed delays in the arrival of the front of EASs. The cross section for the production of such particles in the atmosphere is too small. Moreover, such processes contradict theoretical conclusions of QCD on the nuclear interaction and acceleration data. At the same time, the hypothesis of strange quark matter implies the presence of superheavy hadrons in primary CRs. The effect of delayed EASs is studied in detail at the Tien Shan mountain cosmic ray station.

The delayed fronts of EASs were first detected by V.I. Yakovlev et al. in the VEGA experiment at the Tien Shan High-Altitude Science Station, Lebedev Physical Institute, Russian Academy of Sciences [46]. These works were then continued at the Horizon-T array deployed at the Tien Shan High-Altitude Science Station, Lebedev Physical Institute, Russian Academy of Sciences [47–49]. Not only delayed fronts were detected in these works, but also important information was obtained on extraordinary properties of such showers. Pulse durations and particle densities in showers recorded by individual detectors appeared much smaller than those predicted by nuclear cascade models. The analysis of those data showed that EASs at energies above \( 10^{16} \text{ eV} \), i.e., in the knee region, consist of separate mini-showers between which delays can sometimes reach about microsecond. Studies in this field continue, but it is already clear that the existence of several delayed fronts in EASs cannot be explained by nuclear showers.

To summarize, experimental studies of EAS cores, muons in EASs, and spatiotemporal characteristics of EASs indicate the presence of nonnuclear particles in primary CRs.

5. CONCLUSIONS AND DISCUSSION

—A model of the composition of cosmic rays that is based on experimental data and is consistent with the magnetic rigidity \( R_{\max} = 0.1 \text{ PV} \) has been proposed.

—Within this model, cosmic rays until integration with the extragalactic component consist of nuclei and quasi-nuclei (strangelets).

—Nuclei and strangelets are accelerated by shock waves through a common mechanism.

—It is not excluded that the extragalactic component can also include strangelets [50].

The corresponding galactic spectrum of cosmic rays is presented in Fig. 10. The extragalactic component of cosmic rays is indicated by inclined shading.

Are strangelets exotic? The answer is no rather than yes because the Standard Model allows their existence. Single events that can be interpreted as strangelets were observed in cosmic rays in some experiments [51–53]. To finally solve the problem of existence of

![Fig. 10. Spectrum of galactic cosmic rays consisting of nuclei and quasi-nuclei (strangelets) according to the strange quark matter model. In Fig. 1 [17], a new component is replaced by strangelets.](image-url)
strange quark matter in nature, it is necessary to launch large-aperture telescopes into open space.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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