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Method for Measuring the PCR Proton Spectrum in the Energy Range of $> 10^{16}$ eV

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Abstract—Criteria for selecting proton events among the total sequence of events from primary nuclei of cosmic rays with zenith angles $\theta < 20°$ are analyzed in the energy region of $E_0 \approx 10^{16}$ eV. These criteria are concretized for the case of the SPHERE-2 experiment geometry. The QGSJET-I and QGSJET-II model calculations show that the criteria based on the shape of the transverse distribution of Cherenkov light allow detection of more than 10% of proton events and rejection of 99% nuclear events.

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Introduction. Measurement of chemical composition of primary cosmic rays (PCR) and energy spectra of individual primary nuclei or groups of nuclei is one of the main problems of cosmic ray physics. Its solution is important to develop realistic models of PCR generation, acceleration, and propagation. Of particular interest from the viewpoint of model selection is the determination of the PCR composition at energies of $10^{15} - 10^{16}$ eV in the so-called "knee" region [1] where the spectral index of all particles increases by $\sim$0.4 with energy and where, according to conventional models of CR acceleration, the nuclear composition should be heavier, which has not yet been experimentally confirmed.

The data on CR composition in this energy region are contradictory. For example, according to the data of the KASKADE facility at the energy of 10^{16} eV = 10 PeV, the proton spectrum intensity is approximately ten times lower than that of helium nuclei, as well as the nuclei of carbon and iron groups [2]. The average mass number of PCR calculated by these data increases with energy immediately after the "knee" (3–4 PeV).

At the same time, another conclusion is made in the "Tunka" experiment: the average PCR mass number decreases in the energy range of 1–8 PeV; above 8 PeV, it sharply increases with energy [3]. In the next study of the same team [4] the results are the same at energies > 10 PeV; at lower energies, the average mass composition is almost unchanged.

The method used in [3, 4] is based on the correlation of the Cherenkov light (CL) pulse halfwidth at a long distance from the shower axis with the shower maximum position. It is well known that the CL transverse distribution function (TDF) is also sensitive to the primary nucleus mass. However, CL detectors of ground-based installations collect light from only a small fraction of the shower area; therefore, detailed reconstruction of the CL TDF is complicated. In the SPHERE-2 experiment, it is intended to use the shape of CL TDF to determine the PCR composition, since detectors of this installation can survey about half the shower area. The operating principle of this telescope is based on the idea to measure CL produced by extended atmospheric showers (EAS) and reflected from the snow surface [7]. The optical scheme of the SPHERE-2 installation represents a Schmidt camera with a mirror 1.5 m in diameter and a mosaic of 109 photomultipliers in the mirror focal surface. Thus, this system allows measurements of the quantity proportional to the total CL amount within the field of view of each detector of the mosaic.

In this paper, the criteria allowing separation of a certain known proton fraction from the total number of PCR nuclei are studied using the Monte Carlo method. The Lake Baikal level ($H_0 = 455$ m above sea level) and the detector spatial resolution $\delta r = 80$ m corresponding to the SPHERE-2 installation position at a height of 1 km over the snow surface of Lake Baikal are considered. In this case, the diameter of the telescope field of view is ≈1 km, the diameter of the photomultiplier field of view is ≈50 m, and the distance between photomultiplier fields of view is ≈85 m.

1. Simulation. Using the CORSIKA 6.50 code [8], the QGSJET-I/GHEISHA [9, 10] and QGSJET-II/GHEISHA nuclear interaction models (for brevity, hereafter QGSJET-I and QGSJET-II), a bank of model EAS events was obtained by complete statistical simulation.

The simulation yielded three-dimensional histograms of the density of the number of Cherenkov photons, consisting of 480 x 480 spatial bins 2.5 x 2.5 m^2 in size each. In each spatial bin, photons are distributed over 100 time intervals according to the time delay measured from the instant of the shower axis arrival at the reflection level. The time cell width is 5 ns. The last 101st cell is the integral one, i.e., contains all Cherenkov photons with delays longer than 500 ns. Thus, the data on the spatiotemporal distribution of EAS light from primary nuclei with different types, energies, and arrival directions, required for SPHERE-2 data processing are collected during simulation. The distribution of shower arrival directions is isotropic.

A part of the set of artificial events, i.e., events from protons and helium nuclei with an energy of 10 PeV and zenith angles $\theta < 20°$, was used to construct the criterion for separating proton events, based on the data on the time-integrated transverse distribution $\rho(\vec{r})$ of Cherenkov light of showers. The distributions shown below were plotted using the following event sample: 134 proton- and helium-induced showers calculated by the QGSJET-I model and 165 proton events and 152 helium-induced showers calculated by QGSJET-II, a total of 585 showers. Showers close to vertical yield almost azimuthally symmetric images ($\rho(\vec{r}) \approx \rho(r)$, where r is the distance from the shower axis), which can be analyzed by comparing the light amount in rings of different radii and widths around the symmetry center (shower axis).

2. Criteria for separating proton showers. To describe the CL TDF, we introduce the parameter η which has a physical meaning of the CL TDF slope equal to the ratio of the numbers of Cherenkov photons in two rings,

$$\eta(r_1, r_2, r_3, r_4) = \frac{\int_{r_1}^{r_2} 2\pi r \cdot \rho(r) dr}{\int_{r_3}^{r_4} 2\pi r \cdot \rho(r) dr},$$

$$r_4 \geq r_3 + \delta r, \quad r_3 \geq r_2, \quad r_2 \geq r_1 + \delta r.$$

The rings are characterized by four parameters: (r_1, r_2) are the inner and outer radii of the smaller ring, respectively; (r_3, r_4) are the inner and outer radii of the larger ring. The quantity δr is the characteristic spatial resolution of the installation.

The probability density of the random variable η for protons decreases at high η more slowly than in the case of helium nuclei. This fact allows separation of a certain proton fraction. The latter appears quite definite at a fixed criterion, and the criterion boundary not too strongly depends on the nucleus–nucleus interaction model.

The value of η_c is selected for protons so that all artificial helium-induced events would correspond to $\eta < \eta_c$. Then the criterion $\eta > \eta_c$ in the energy region of ≈10 PeV will separate proton events with helium nuclei component $\sim 1/N_{He}$ or 0.75% and 0.66% for the cases of QGSJET-I and QGSJET-II models, respectively.

For statistics of inclined showers ($20° < \theta < 60°$), selection criteria should be different, since the CL TDF azimuthal symmetry condition is violated in the case. In this paper, we restrict the analysis to events with zenith angles $\theta < 20°$.

3. 3. Results. In [11], the parameter $\eta_0 \equiv \eta$ (0, 130, 250, 350 m) was used to study the separability of showers from primary protons, nitrogen and iron nuclei. It was shown that this parameter depends weakly on energy near the "knee". In this study, we constructed a set of criteria η by varying the parameters (r_1, r_2, r_3, r_4) in the range from 0 to 600 m with the step $\Delta r_i = 10$ m ($i = 1 - 4$) in each parameter, studied the applicability of the quantity η_0 to the problem of separation of primary protons and helium nuclei, analyzed the set of criteria and choice of the optimum one.

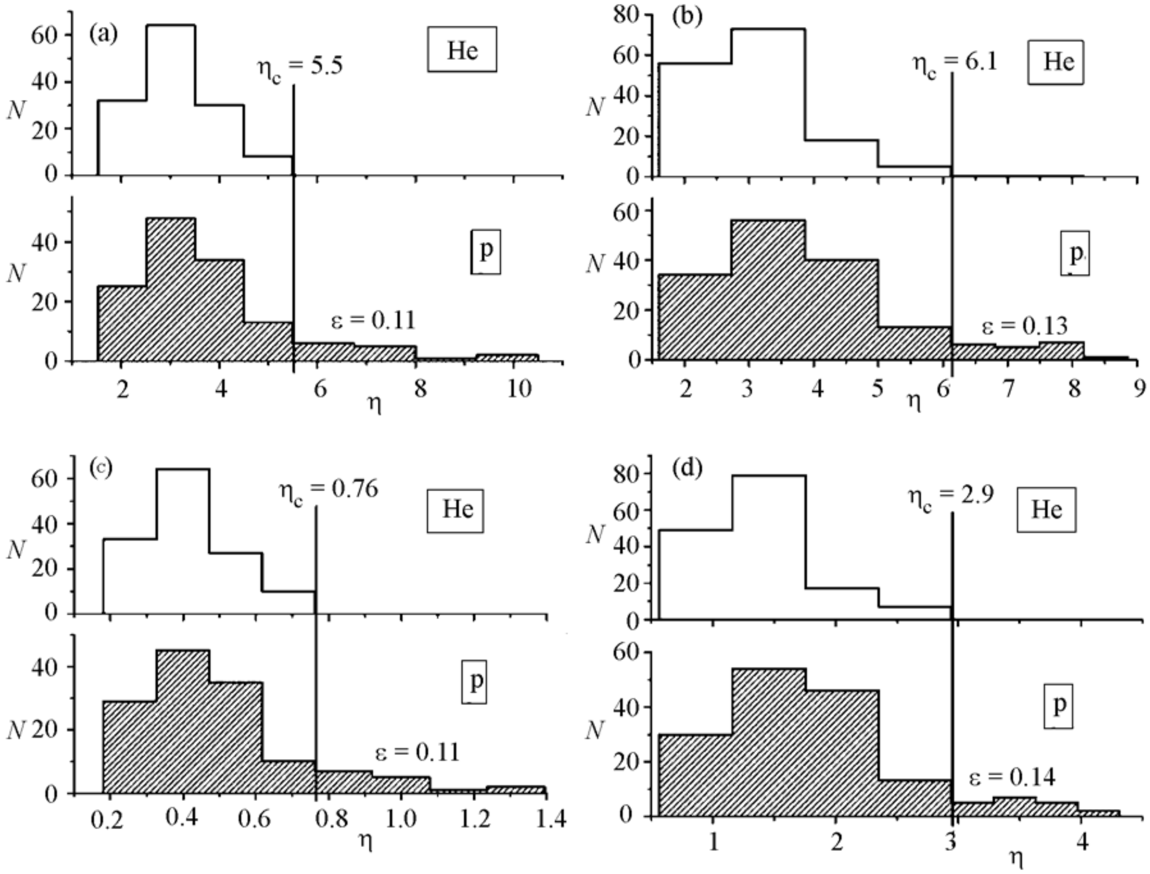

Fig. 1. Histograms of the distribution of η for the case of primary protons (shaded) and helium nuclei (unshaded) for ((a), (c)) QGSJET-I and ((b), (d)) QGSJET-II models. The upper ((a), (b)) and lower ((c), (d)) parts of figure were plotted for the criterion η_0 (0, 130, 250, 350 m) and the criteria optimized by the number of separated proton events, respectively. The bottom left and right panels correspond to η_1 (0, 80, 80, 320 m) and η_2 (80, 160, 160, 240 m). The proton separation threshold is indicated by a vertical line with a numerical value. In all cases, the fraction ϵ of separated proton events is indicated.

Indeed, a small number of used parameters makes it possible to optimize the criterion using direct enumeration within the set. The use of the procedure constructed in such a way allows us to determine the global maximum of a fraction of separated protons, both the unconditional one and with imposed additional conditions.

The figure compares the ((a), (b)) criterion η_0 and ((c), (d)) optimized criteria. Histograms of the distributions of η are shown; the ((a), (c)) left and ((b), (d)) right columns correspond to the QGSJET-I and QGSJET-II models, respectively. The parameters of optimized criteria are $\eta_1 = \eta\,(0, 80, 80, 320\text{ m})$ and $\eta_2 = \eta\,(80, 160, 160, 240\text{ m})$ in the case of QGSJET-I and QGSJET-II, respectively. In all cases, $\delta r = 80$ m. The fraction ϵ of separated proton events beyond the boundary of the helium nuclei distribution is indicated at each histogram for protons.

Among the subset of the criteria providing the identical number of separated proton events, preference is given first to classifiers with the least r_1, second, to those with the least r_2, then to r_3 and, finally, to r_4. This additional condition is necessitated to increase the signal-to-noise ratio which is maximum on the axis of showers with zenith angle $\theta < 20°$.

It was shown that the fraction of separated proton events is approximately identical for both nucleus–nucleus interaction models and depends weakly on a specific criterion.

The physical meanings of the quantities $\delta r = r_2 - r_1$ and r_4 are close to two detector characteristics, i.e., the spatial resolution and field-of-view radius, respectively. Therefore, it is of interest to study the two-parameter set of criteria $(r_2 - r_1, r_4)$ instead of the four-dimensional parameter space. Specific values of r_1, r_2, and r_3 are chosen from the condition of the maximum fraction of separated events as described above.

We studied a simplified detector model characterized by two parameters, i.e., (i) the spatial resolution δr (does not exceed the characteristic diameter of one element of the pattern) and (ii) the effective field-of-view radius R; fluctuations and noises introduced by a real detector were disregarded. It was found that the quantity ϵ depends weakly on the parameters $(r_1 - r_2, r_4)$ in the practically important region $\delta r \geq 40$ m and decreases from 0.12 to 0.10 as δr increases from 40 to 280 m for the QGSJET-I model and from 0.15 to 0.10 for the QGSJET-II model as δr changes in the same limits for the attained statistics of model events.

The case of $\delta r = 280$ m corresponds to the extreme case when there are only two sensitive elements of the detector, signals in which are equal to the numbers of Cherenkov photons in rings with inner and outer radii (0, 280 m) and (280, 560 m), respectively. Thus, it was shown that the differences in the CL TDFs of separated proton and helium events are retained on large distance scales.

It should be noted that the probability density of η for nuclei heavier than helium more rapidly decreases with η; therefore, using the described method, criteria for separating helium nuclei and the "light component", i.e., the set of protons and helium nuclei from the mass of heavier nuclei, can also be constructed.

4. Conclusions. Based on complete statistical simulation of the transverse distribution of Cherenkov light of EASs caused by primary protons and helium nuclei with an energy of 10 PeV, criteria for separating a fixed fraction of proton events with zenith angles $< 20°$ with total (with an accuracy of available statistics) suppression of events caused by nuclei were constructed using two models of the nucleus-nucleus interaction, i.e., QGSJET-I and QGSJET-II. The separation criterion $\eta(r_1, r_2, r_3, r_4)$ can be chosen so that the proton separation threshold would also depend weakly on the interaction model (e.g., criterion η_0). It was shown that the difference between CL TDFs for separated proton and helium events is retained to distance scales of ≤ 300 m.

It was shown that installations such as the SPHERE-2 positioned at a height of 1 km over the reflection level can in principle separate no less than 10% of proton events from the total set of nuclei at energies $\approx$10 PeV. In this case, fluctuations and noises were disregarded. The results of this analysis are also urgent for other installations capable of measuring the transverse distribution of Cherenkov light of EASs in detail.

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