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Method for Mass Analysis of Primary Cosmic Ray Particles with the SPHERE-2 System

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Abstract—The results of simulation showing the possibility of mass analysis of primary cosmic-ray particles in the energy range 10^{16}–10^{18} eV with the use of the SPHERE-2 balloon system are reported. The system is lifted by a tethered balloon at an altitude of 1 km. It has almost continuous sensitivity at an area of about 1 km^2 that is viewed by 109 photoelectron multipliers. This property makes it possible to analyze in detail the spatial distribution of Cherenkov light in extensive air showers both in the immediate vicinity of the EAS core and at large distances from it.

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INTRODUCTION

The experimental data on the nuclear composition of cosmic rays (CRs) in the energy range 10^{16}–10^{18} eV are scarce and contradictory. At the same time, these data are important for determining the nature of the sharp knee in the spectrum in the energy range $(3–5) \times 10^{15}$ eV and the possible contribution of the metagalactic component to the total CR flux. In design and fabrication of systems for detecting extensive air showers (EASs), it is necessary to take into account the possibility of reconstructing not only the energy and angle of arrival of primary particles but also the CR mass composition. Currently, the most widespread modern method for estimating the CR composition is the reconstruction of the depth $X_{\max}$ of maximum cascade development in atmosphere. The values of $X_{\max}$ are different for different types of CRs, for example, proton (p) and iron (Fe) CRs. This circumstance allows one to estimate the average change in the CR composition, i.e., decrease or increase in the "CR mass." The accuracy of this method is not sufficient to draw unambiguous conclusions about the processes of CR formation and propagation. In addition, data obtained using different systems are often contradictory.

In this study, we made an attempt to develop a method and present the preliminary results of simulation to estimate the possibility of mass analysis of primary CR particles without reconstruction of $X_{\max}$, as applied to the SPHERE-2 system. The method developed is based on the analysis of the shape of the spatial distribution of EAS Cherenkov light; it allows one to estimate the type of primary particles for individual EASs. An advantage of the SPHERE-2 system is the possibility of measuring Cherenkov light both in the immediate vicinity of the EAS core and at large distances from it.

SPHERE-2 SYSTEM

In the SPHERE experiment, we used a technique proposed by A.E. Chudakov [1] and developed in [2–5]. The SPHERE-2 balloon system includes a seven-segment spherical mirror with a diameter of 1500 mm and radius of curvature of 940 mm. A mosaic of 109 photoelectron multipliers FEU-84-3 is mounted in the focus of the mirror. To obtain maximum spatial resolution, a diaphragm 930 mm in diameter is installed before the mirror. The total angle of view of the optical system is 52°.

The instrument was lifted in the dark on a tethered balloon at an altitude of 1–3 km and operated like a camera imaging light spots formed on the snow-covered surface of the Earth upon transmission of EAS particles through the atmosphere. Each photoelectron multiplier monitors areas 70 and 210 m in diameter at altitudes of 1 and 3 km, respectively, above the snow-covered surface. The system measures the profile of light pulses with a discreteness of 25 ns in each channel; the dynamic range is 10^4.

SIMULATION

Simulation was performed in two stages using the CORSIKA 6.50 package with the QGSJET option. In the first stage, complete simulation of proton and iron showers with energies of 1 and 10 PeV was performed and the spatial and temporal distributions of Cherenkov photons at the level of light reflection (Lake Baikal, 455 m above the sea level) within a square of 1200×1200 m^2 with 2.5×2.5 m^2 cells were stored in memory differentially with respect to the time of arrival (5 ns per 100 cells). In the second stage, the recorded spatial and temporal distributions of Cherenkov light were used to simulate responses of the SPHERE-2 system and their treatment in order to reconstruct the primary parame-

Estimation of the error in reconstructing energy (disregarding fluctuations of the background and number of photoelectrons)

Particles	E_0, PeV	Q_{tot}		$Q_{0–500}$		Q_{150}	
		$\langle Q\rangle/\langle Q_{Fe}\rangle$	σ, %	$\langle Q\rangle/\langle Q_{Fe}\rangle$	σ, %	$\langle Q\rangle/\langle Q_{Fe}\rangle$	σ, %
p	1	1.32	9	1.56	12	1.45	10
Fe		1	3	1	5	1	4
p	10	1.21	3	1.30	5	1.19	4
Fe		1	0.3	1	1	1	2

ters of showers. A shower image in a detector consists of 109 light pulses (according to the number of mosaic cells) with a discreteness of 25 ns, calculated on the basis of the spatial and temporal distributions of Cherenkov light for a specified position of the system and the law of light reflection from snow. In this study, we considered the cases of system location at an altitude of 1 km and isotropic reflection. The pulse parameters in each cell were used to calculate the total light contribution and the time of arrival of a light pulse.

RESULTS OF THE SIMULATION

The main purpose of the simulation was to search for directly measurable characteristics of Cherenkov light strongly correlating with the primary parameters of a shower, first of all, with the energy and type of primary particles. To estimate the primary energy, one can use such quantities as $Q_{0–500}$ (integral of the spatial and temporal distributions of Cherenkov light in a circle of radius 500 m with the center on the shower core) or Q_{150} (light density at a distance of 150 m from the core). The table contains means and standard deviations of $Q_{0–500}$ and Q_{150}, normalized to the corresponding values for Fe showers and calculated on the existing samples of showers initiated by 1-PeV protons (12 events), 1-PeV iron nuclei (10 events), 10-PeV protons (11 events), and 10-PeV iron nuclei (4 events) with cores within a vertical circular cone with a half-opening angle of 20°. The table also contains the data on the total number of Cherenkov photons Q_{tot} in the range 310–650 nm, which reached the reflection level. Since the average values of E_0 from all indicators significantly differ for p- and Fe-induced showers, the procedure for determining the energy is intimately related to the procedure for determining the type of the primary particle. As type indicators, we considered different exponents of the slope in spatial and temporal distributions of Cherenkov light, which are traditionally used to measure the position of the shower maximum [6].

The choice of measures of energy and types of primary particles is based to a great extent of the possibilities for measuring spatial and temporal distributions of Cherenkov light in a wide range of distances from the shower core with the SPHERE-2 system. These possibilities are demonstrated in Fig. 1, which shows the density functions for transverse distribution of light at the level of reflection for characteristic showers from p and Fe with energies of 1 and 10 PeV (lines) and estimates of these densities according to the data from individual cells of the photoelectron multiplier mosaic (symbols). Quantization of the signal at the level of photoelectrons and its mixing with the star sky background were not performed. In essence, Fig. 1 indicates that the total light contributions to individual cells can be used to reconstruct the local density at the centers of the cell fields of view. For clearness, the level of light density corresponding to a signal of one photoelectron per cell is shown in Fig. 1. The procedure of drawing signal in photoelectrons will only slightly affect the results that are much above this level. Good agreement between the actual light density and its estimates gives

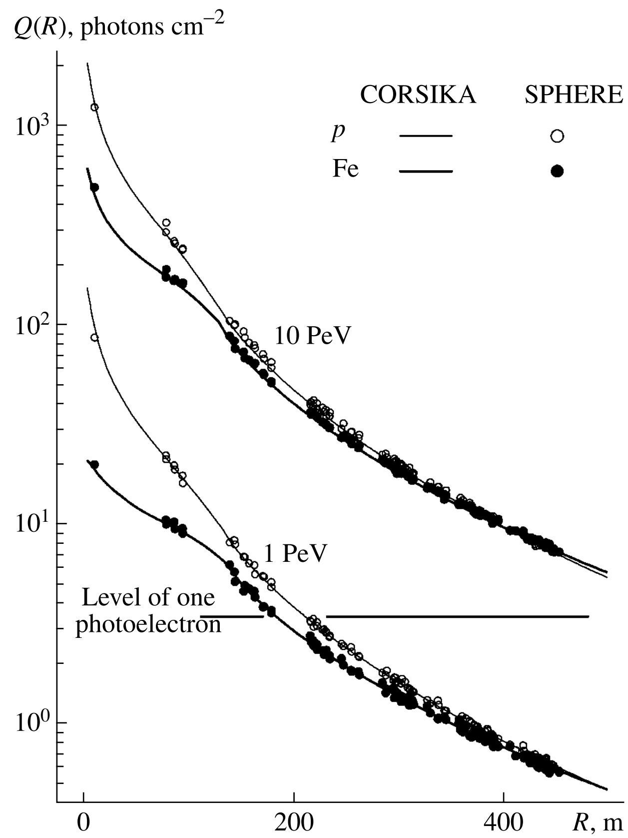

Fig. 1. Function of a Cherenkov light spatial distribution.

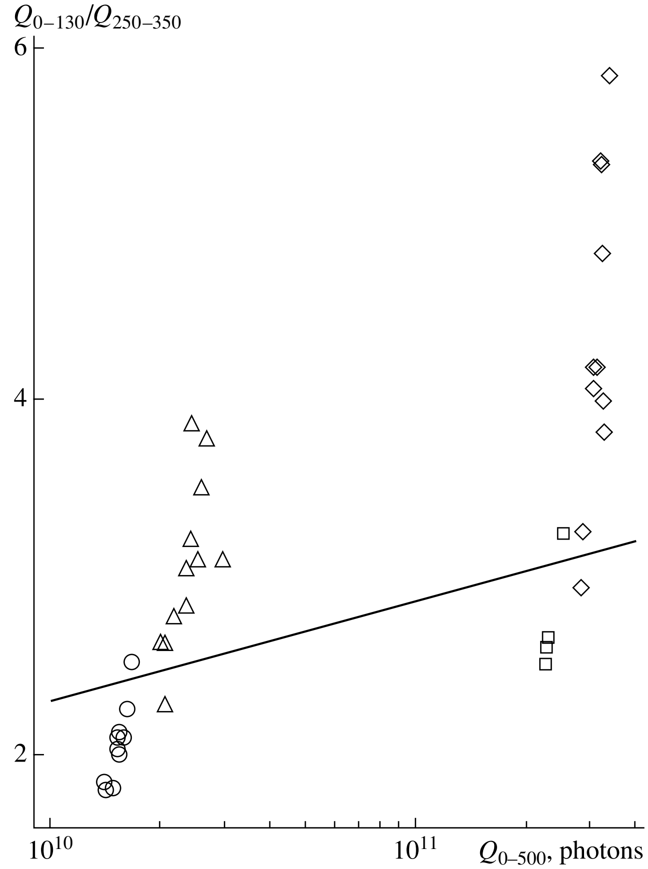

Fig. 2. Correlation dependences of the parameter η on Q_{0-500} for showers with energies 1 ((△) *p*, (○) Fe) and 10 ((◇) *p*, (□) Fe) PeV.

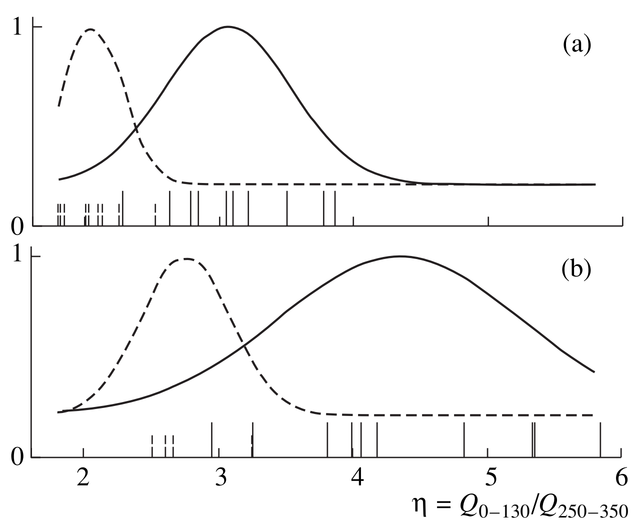

Fig. 3. Distributions of the parameter η for (solid lines) *p*- and (dashed lines) Fe-induced showers with energies (a) 1 and (b) 10 PeV. The vertical bars denote the values of η corresponding to individual showers.

grounds to believe that the energy can be determined with an error smaller than 30% in the case of correct determination of the primary particle type (90% cases).

The largest difference in the shapes of spatial and temporal distributions of Cherenkov light for protons and iron nuclei corresponds to the range of distances 0–130 m from the core and distances more than 250 m from the core. In the intermediate range, the noted difference is much smaller. For this reason, as the main directly measured parameter reflecting the shape of spatial and temporal distributions of Cherenkov light, we chose the ratio $\eta = Q_{0-130}/Q_{250-350}$ of the integrals of the spatial and temporal distributions of Cherenkov light in the rings 0–130 and 250–350 m.

Figure 2 shows the correlation map $\eta(Q_{0-500})$ for the existing statistics of artificial events, which confirms the possibility of simultaneous determination of the energy and type of a primary particle. The straight line shows the boundary between the regions of *p* and Fe events (above and below the straight line, respectively).

Figure 3 shows the distributions of the parameter η for energies of 1 and 10 PeV. At fixed E_0, the distributions over η for *p*- and Fe-induced showers intersect each other only in the wing regions. The densities of normal distributions with means and variances of real distributions (Fig. 3) only roughly illustrate the situation. The actual distributions more closely resemble γ distributions: they exhibit a falloff on the left and an exponential tail on the right. The up-to-date statistics do not make it possible to determine them more exactly. In any case, using the parameter η, one can separate *p*- and Fe-induced showers with an error less than 10%.

CONCLUSIONS

The calculations performed show that the technique for estimating the nuclear composition of primary CR by analyzing the spatial and temporal distributions of Cherenkov light can be significantly improved in the SPHERE-2 experiment. It is not inconceivable that the shape of the energy spectrum can be measured separately over groups of nuclei. The development of the method for mass analysis of primary CR particles has only begun. Due to the low statistics of simulated events, the reported results are preliminary. In the period 2007–2008, it is planned to carry out a series of measurements with the SPHERE-2 system on Lake Baikal.

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REFERENCES

1. Abstracts of Papers, *Materialy vsesoyuznogo simpoziuma po kosmofizike* (Proc. All-Union Simp. on Cosmic Physics), Yakutsk, 1972, p. 69.
2. Antonov, R.A., Ivanenko, I.P., and Rubtsov, V.I., Abstracts of Papers, *14th ICRC*, München, 1975, vol. 9, p. 3360.
3. Petrova, E.A., *Cand. Sci. (Phys.–Math.) Dissertation*, Moscow: NIIYaF MGU, 1998.
4. Antonov, R.A., Chernov, D.V., Korosteleva, E.E., et al., Abstracts of Papers, *27th ICRC*, Hamburg, 2001, vol. 1, p. 59.
5. Antonov, R.A., Kuz'michev, L.A., Panasyuk, M.I., et al., *Vestn. Mosk. Univ., Ser. 3: Fiz., Astron.*, 2001, no. 5, p. 44.
6. Belyaev, A.A., Ivanenko, I.P., Kanevskii, B.L., et al., *Elektronno-fotonnye kaskady v kosmicheskikh luchakh pri sverkhvysokikh energiyakh* (Electron–Photon Cascades in Ultrahigh-Energy Cosmic Rays), Abrosimov, A.T., Ed., Moscow: Nauka, 1980.