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Method for Isolating the Light Component of CR Using Cherenkov Telescope Data in the TAIGA Experiment

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Abstract—This paper proposes a method for separation the light component of cosmic rays in the energy range of 200 TeV–20 PeV (the knee region in the PCR spectrum) from hybrid events detected by two Cherenkov setups IACT + HiSCORE in TAIGA experiment. The possibility of such separation is demonstrated using Monte Carlo calculations and the first experimental estimates are made.

Keywords: primary cosmic radiation, extensive air showers (EAS), Cherenkov light, chemical composition of cosmic radiation

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INTRODUCTION

The study of spectrum and composition of primary cosmic rays (PCR) in the energy range of 100 TeV–10 PeV continues to be a very urgent task, since the final solution to the problem of the “knee” origin in the PCR spectrum at an energy of several PeV requires knowledge of the spectrum of various mass components in the knee region. At the same time, direct experiments on satellites, in which the particle charge is determined, reach several hundred TeV, and in experiments with extensive air showers (EAS), the mass of primary particle is determined starting from ~1 PeV. It is in the knee energy range that it is possible

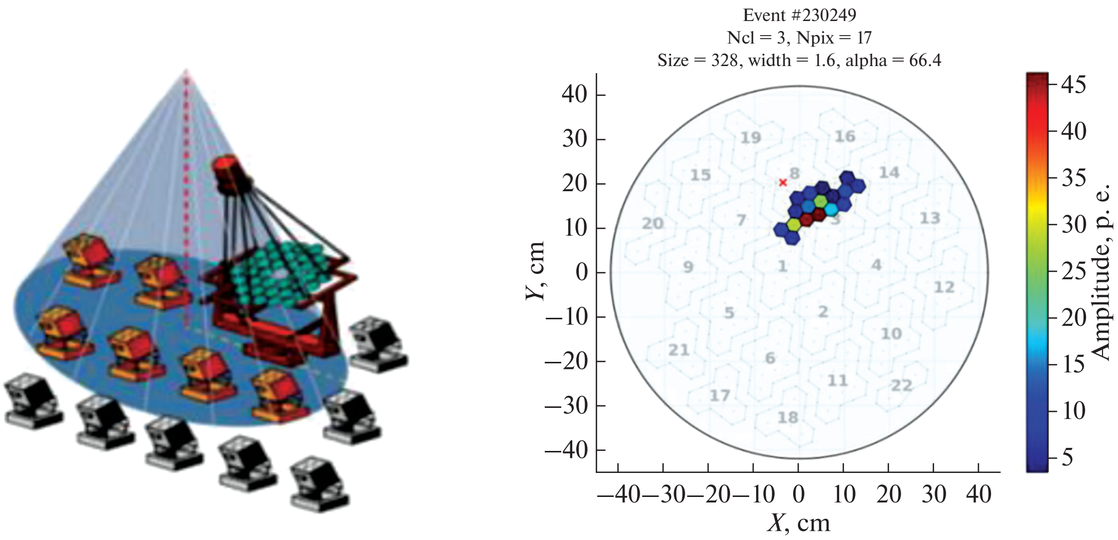

Fig. 1 Hybrid registration of EAS in the TAIGA experiment (HiSCORE stations + ACT) (a) left; image of EAS registered by the telescope (b) right.

and proposed to use a new method for isolating the light component of PCR in the TAIGA experiment, based on the application of a hybrid method for registering extensive air showers. This article describes the TAIGA facility, the basics of method for isolating the light component and the first test results obtained from a small sample of events.

TAIGA ASTROPHYSICAL COMPLEX

TAIGA astrophysical complex [1, 2] consists of the TAIGA-HiSCORE Cherenkov array with an area of 1 km^2, covered by 122 wide angle (0°–30°) detectors and several (three at present) atmospheric Cherenkov telescopes (ACT or in English connotation IACT). Such an array makes it possible to register EAS from gamma quanta with an energy of more than 50 TeV and a charged component of CR with a threshold of about 100–200 TeV using the HiSCORE method [2]. For some showers that are registered by both HISCORE stations and at least one telescope, Fig. 1, the concept of a hybrid registration method has been introduced, which has so far been used to isolate and analyze high-energy gamma quanta [3, 4]. In this paper, we analyze the possibility of using these data to isolate the light component of cosmic rays (CR).

In the hybrid method [3], the primary particle energy, the direction, and position of EAS axis are reconstructed using the TAIGA-HiSCORE data, and the TAIGA-IACT data are used to determine the primary particle type that generated the EAS [3, 4]. Shower image recorded in the IACT chamber and close in shape to an ellipse (Fig. 1, right panel) reflects the EAS longitudinal and transverse development in the atmosphere, and the ellipse's direction is the direction to the source position in the chamber. Many years of positive experience in using various image parameters (including in the TAIGA experiment [5]) to isolate EAS from gamma quanta above the hadron background (thousands of times exceeding the background of charged CRs) stimulated the development of a similar method for isolating EAS from protons and helium from showers formed by heavy and medium nuclei. This method is essentially based on Monte Carlo calculations. We will rely on the MC calculations developed in the TAIGA experiment, the scheme of which is described in [6].

METHOD OF SEPARATION OF LIGHT COMPONENT

To develop the method for selecting the light component, we used an algorithm that has proven itself well in gamma-ray astronomy for reconstructing the gamma-quanta spectrum. Namely: **Stage 1**: identifying the parameters of images sensitive to the primary nucleus mass and finding the optimal criteria for selecting the light component based on the Monte Carlo simulation data; **Stage 2**: the spectra of all hybrid events and the spectra of events selected as Pr + He, i.e., those obtained after the selection criteria introduction, are calculated from MC data; **Stage 3**: the effective area of all hybrid events S_{Hyb} and events selected by the light component criteria S_{PrHe} is calculated. An effective area also includes an efficiency of registering showers after selection according to the given criteria. It is calculated as the ratio of showers that passed the selection criteria $N_{\mathrm{PrHe}}(E)$, $N_{\mathrm{Hyb}}(E)$, to the showers directed to the setup in Monte Carlo calculations, $N_{\mathrm{primary}}(E)$, on the S_{MC} area, which is 3 km^2:

$$S_{\mathrm{Hyb}}(E) = N_{\mathrm{Hyb}}(E)/N_{\mathrm{primary}}(E) * S_{\mathrm{MC}};$$
$$S_{\mathrm{PrHe}}(E) = N_{\mathrm{PrHe}}(E)/N_{\mathrm{primary}}(E) * S_{\mathrm{MC}}. \quad (1)$$

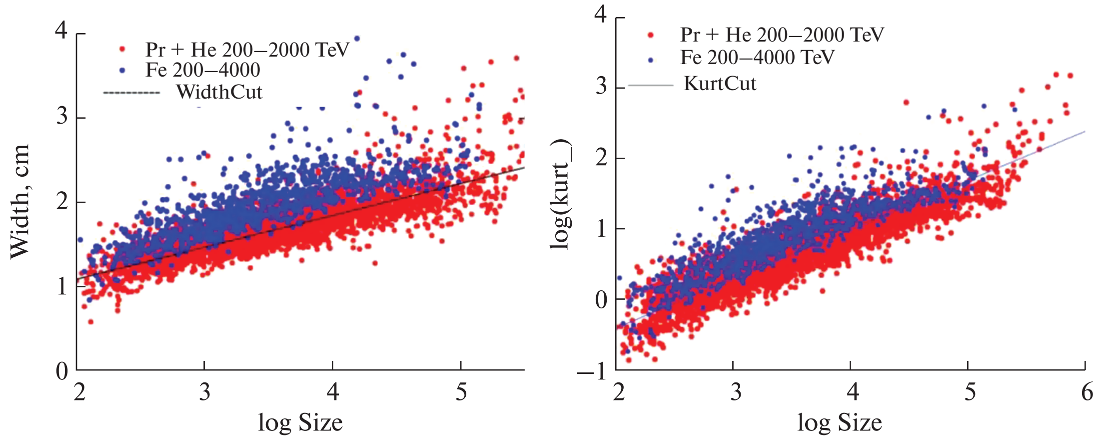

Fig. 2. Dependence of *width(Size)* and *kurtosis(Size)* for Pr + He nuclei (red dots) and for iron nuclei (blue dots).

Stage 4: from the experimental data $F_{\mathrm{Hyb}}(E)$, $F_{\mathrm{Pr+He}}(E)$ the absolute intensity of total primary flux of all particles and light component is reconstructed considering the effective area, solid angle, and observation time. The criterion for the correctness of the used technique is the correct reconstruction of the total particle flux from the data of hybrid events.

The study showed that the most effective parameter, as and in gamma-ray astronomy, was the width of the ellipse of the image depending on Size (the total number of photoelectrons in chamber—*Size*: *width(Size)*, as well as the third moment—kurtosis—characterizing the image peak's sharpness, since events from nuclei are flatter *kurt(Size)*. Figure 2 shows examples of such dependences for the interval of 200–4000 TeV. It should be noted that these dependences are linear in log(Size), and the type of dependence does not change at high energies, which allows choosing as selection criteria dependences of the type: $width < widthCut = a + b\log(\mathrm{Size})$. Events satisfying this condition belong to the group of Pr + He-like events. The choice of criteria is optimized by the condition of the maximum fraction (Pr + He) and the minimum admixture of heavy and medium nuclei.

The Monte Carlo spectra of all hybrid events and the spectra of events selected as Pr + He have a power-law character, and no sharp change in the slope of spectra is observed at high energies up to 20 PeV. The effective areas above 100 TeV change from 0.2 km^2 at 200 TeV and increase to 0.6 km^2 TeV for all hybrid events, and for Pr + He the components are from 0.1 to 0.3 km^2.

TEST EXPERIMENTAL ESTIMATES OF THE LIGHT COMPONENT SPECTRUM

To test the proposed method, we used data containing hybrid events selected during IACT01 tracking for the Boomerang source in the zenith angle range of 0–25° in the 2022–2023 observing season. The total observation time was 40 h. We passed from the measured $F_{\mathrm{meas}}(E)$ spectra to the reconstructed spectra above the atmosphere $F_{\mathrm{reco}}(E)$ using the formula $F_{\mathrm{meas}}(E)/S_{\mathrm{eff}}(E)/\mathrm{dOm}/\mathrm{dTime}$ (see Section 1). The $F_{\mathrm{reco}}(E)$ spectrum of all particles reconstructed from hybrid events is shown in Fig. 3. For comparison, the spectra of all particles obtained from the HiSCORE data in [2] and the spectra obtained in the LHAASO experiment [7] are shown. Since the proportion of hybrid events registered by one IACT is no more than 5% of the events registered at the HiSCORE facility, then the correctly reconstructed spectrum of all particles indicates the adequacy of Monte Carlo simulations to the experiment, which is necessary when studying the light component (Pr + He).

The spectrum of the light component of events selected by the criterion *width* < *widthCut(Size)* (see Fig. 2) and the reconstructed one inside the effective area, solid angle and observation time is also shown in Fig. 3. For comparison, the data of the direct DAMPE experiment on the spectra of Pr, He, Pr + HE from the work [8] and the data of the Grapes3 experiment [9] are shown.

CONCLUSIONS

(1) The spectrum of all particles, reconstructed from the data on hybrid events registered by the HiSCORE + IACT setups, demonstrates a classical break “knee” at an energy of ~3 PeV in the CR spectrum and does not differ much from the HiSCORE data [2]. This indicates the adequacy of the Monte Carlo simulations used. (2) The Pr + He spectrum preliminary estimate does not contradict the direct DAMPE experiment data extrapolation intensity [8]. A pronounced knee is observed at 3 PeV, which confirms the old hypothesis that the knee of various CR components occur according to the particle rigidity and is determined by the light component, as the most repre-

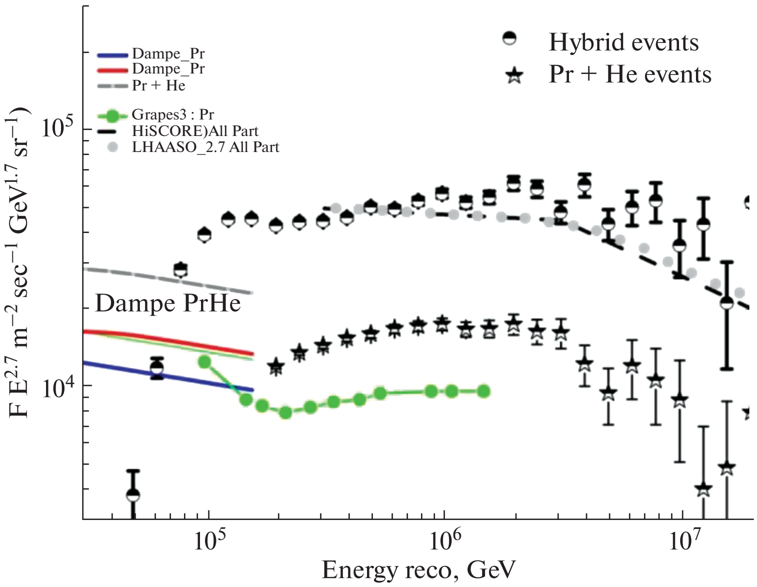

Fig. 3. Reconstructed spectrum of all particles from hybrid events—black circles. Light component spectrum—black stars (conditionally Pr + He), reconstructed from events with *width* < *widthCut(Size)*. Red and blue lines—direct measurements of the Dampe satellite experiment of protons and helium [8]. Black dotted line—spectrum of all particles, obtained only from data in the HiSCORE work [2], gray dots—in the LHAASO experiment [7]. Green dots—proton spectrum estimate in the GRAPES3 experiment [9].

sented in the spectrum before the knee energy. Until the contribution of medium nuclei to the obtained spectrum is estimated, MC simulations in this direction are ongoing, so the obtained estimate should be considered as an upper limit. (3) Estimated data were obtained from hybrid events with one telescope for 40 h of observation. In the TAIGA experiment, the total accumulated statistics is an order of magnitude greater, which will allow us to significantly refine the result. (4) The proposed method for identifying the light component spectrum of CR based on hybrid event data should be developed further.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

SPELL: 1. ok

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