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Investigation of SPHERE-2 Data Sensitivity to Chemical Composition of Primary Cosmic Rays

D. V. Chernov[a], R. A. Antonov[a], T. V. Aulova[a], S. P. Besshapov[b], E. A. Bonvech[a], V. I. Galkin[c], T. A. Dzhatdoev[a], A. S. Petkun[b], D. A. Podgrudkov[c], T. M. Roganova[a], T. I. Sysoeva[b], Mir. Finger[d], Mikh. Finger[d], and S. B. Shaulov[b]

[a] *Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Lebedev Physical Institute, Russian Academy of Sciences, Moscow, 119991 Russia*
[c] *Faculty of Physics, Moscow State University, Moscow, 119991 Russia*
[d] *Charles University, 11636 Prague, Czech Republic*
e-mail: chr@dec1.sinp.msu.ru

Abstract—A new method for assessing the type of particles of primary cosmic rays in the energy range of 10–1000 PeV for individual events recorded by the SPHERE-2 facility is presented. The method is based on comparing images of recorded events and simulated events, while assuming various types of primary particles with allowance for measuring errors. The aim of the study is to find the limits of sensitivity in determining of the chemical composition of ultrahigh-energy primary cosmic rays using the detection of reflected Cherenkov light generated by extensive air showers (EASes).

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INTRODUCTION

In recent years, the composition of cosmic rays (CR) in the energy range above the so-called knee at about 3 PeV in the energy spectrum of primary CRs (PCRs) has been hotly debated in the field of studying ultrahigh-energy CRs, due primarily to a series of works on the latest results from processing experimental data obtained using the KASCADE-Grande facility [1]. A rise in the fraction of the heavy component of cosmic rays in the energy range of 2 to 20 PeV was described in [2] using data from the KASCADE facility. A reduction in the proportion of the light component was found in the same energy range. The proportion of the heavy component reached values of 50% or more above 20 PeV. A similar result was presented in [3] using the results from the Tunka-133 experiment. The data from these two papers were qualitatively consistent with one another, even though different parameters that were sensitive to the composition of a PCR were used in these experiments.

In another work of the KASCADE-Grande collaboration [4], however, it was pointed out that the applied method was highly sensitive to the model of hadron interaction. This feature in the spectrum of heavy component resulted from calculations performed using the QGSJET-II-02 model. These results coincide when using the SIBYLL 2.1model, but differ sharply from those found with the EPOS 1.99 model, since the proportion of the light component is in the latter case several times greater than that of the heavy component. The reason for this is a systematic shift in the experimental data when reconstructing the composition using EPOS 1.99. In this situation, the correctness of selecting a particular model when reconstructing the composition of a PCR from the experimental data and the validity of the obtained results come into doubt. The aim of this work is to find a way of resolving the above problem. The technique is tested using experimental data obtained at the SPHERE-2 facility.

THE SPHERE-2 FACILITY

The unique SPHERE mobile astrophysical observatory [5], which is designed to study primary cosmic radiation in the energy range of 10–1000 PeV by using a new method to record extensive air showers, was created and developed by the Skobel'tsyn Institute of Nuclear Physics at Moscow State University, and by the Lebedev Physical Institute of the Russian Academy of Sciences. The facility is lifted by a tethered balloon to an altitiude of ~1 km above the snow-covered surface of Lake Baikal on moonless and cloudless nights and records the EAS Cherenkov light reflected by the snow's surface (Fig. 1a).

The mobile observatory contains the SPHERE-2 balloon detector, the main part of which is a spherical mirror with a diameter of 1.5 m, a mosaic of 109 FEU-84-3 photomultiplier tubes (PMTs) at its focus (Fig. 1b), and electronics that record the anode signal from each PMT with a step of 12.5 ns. A Schmidt corrector diaphragm provides a viewing angle of 0.6 sr.

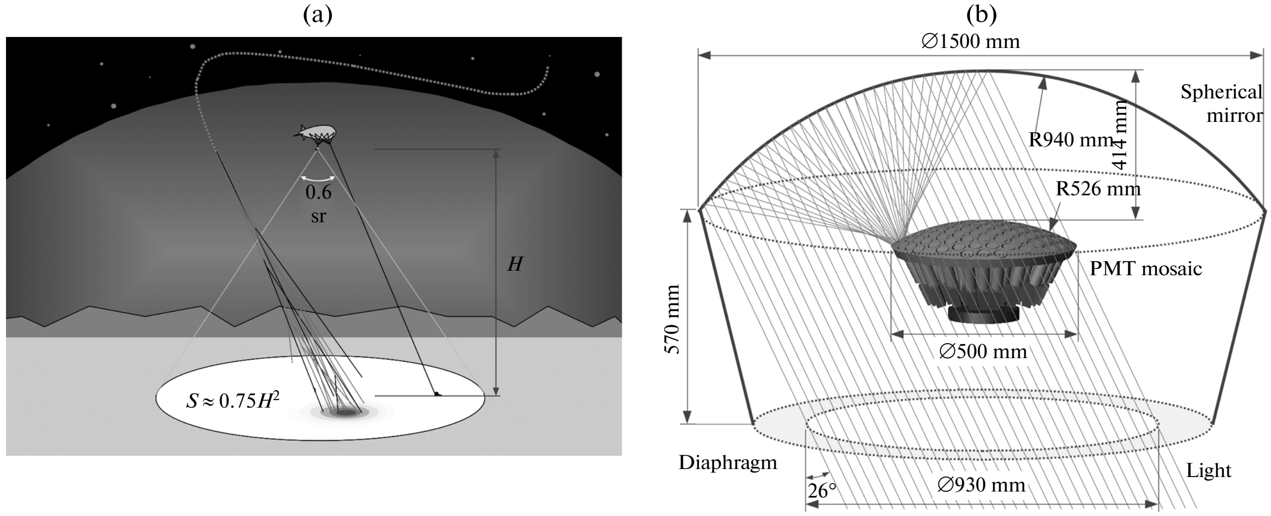

Fig. 1. (a) Design of the experiment performed on the ice of Lake Baikal using the SPHERE-2 facility; (b) optical scheme of the SPHERE-2 facility.

The facility was in operation over the period 2008 to 2013. The main data were obtained during measurements conducted in 2011–2013. More than 1000 EAS events were reconstructed, and the energy spectrum shown in Fig. 2 was plotted.

EXPERIMENTAL TECHNIQUE

To solve the problem mentioned in the introduction, we proposed comparing the images of actual experimental events and simulated images of EAS events. The image of an event consists of digital data,

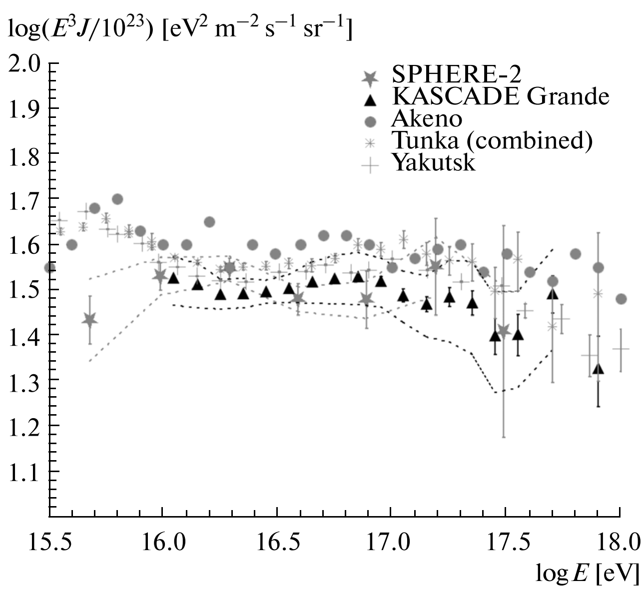

Fig. 2. Differential energy spectrum plotted using the data obtained in the period 2011–2013.

i.e., the response of the SPHERE-2 facility's electronic recording system to an EAS event.

Calibration allowances that take into account the difference between the sensitivities of some PMTs are included in the experimental data. The error in determining the relative sensitivity is 3% for any two PMTs in the mosaic of the SPHERE-2 facility. The absolute sensitivity for each PMT is determined with respect to the relative sensitivity with an error of no more than 5%. High accuracy in determining the absolute sensitivity is achieved by using a L11494-430 calibrated light source with a radiation maximum in the range of 430 nm. Relative calibration is performed directly during measurements by exposing the entire mosaic of a PMT to light using seven light-emitting diodes every 6 μs after a recorded event. The sensitivity of each PMT is thus controlled.

After considering all calibration allowances, the image data are presented in the form of a graph (Fig. 3, left). In the graph, the numbers of PMTs in the mosaic are plotted on the horizontal axis in increasing order of their indices [6]. The numbers of readings of the signal amplitude measuring time are plotted on the vertical axis. The interval between time readings is 12.5 ns.

The tilt angle of the EAS axis is reconstructed from the time of arrival for the signals from the EAS Cherenkov light at different PMTs of the facility. The shower axis is determined from the distribution of light over the mosaic of the PMT; the energy of the primary particle is determined from the total amount of light. Events having the same shower parameters are simulated using the CORSIKA program and programs for calculating the detector response. Four types of primary particles are introduced into the simulations as primary particles: protons, nuclei of helium, nitrogen, and iron. For each type of particle, a set of at least one

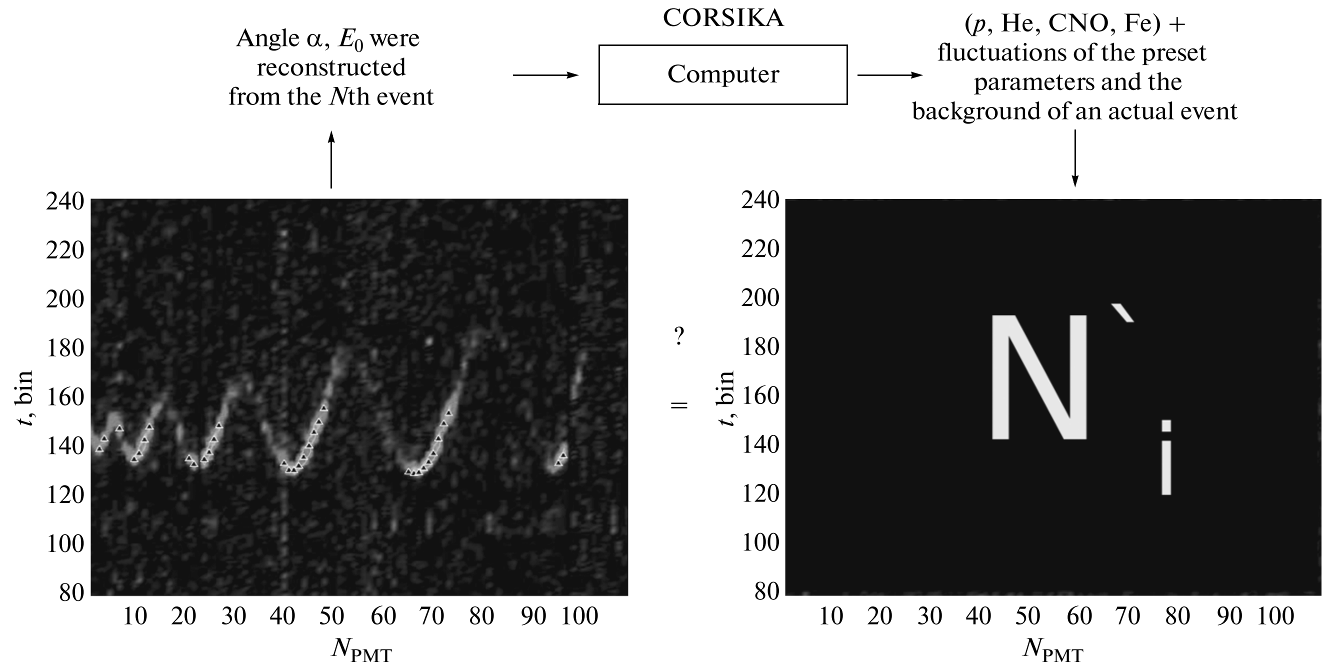

Fig. 3. Operational concept of our method.

hundred events is considered with allowance for fluctuations in known parameters: primary energy, tilt angle and coordinates of the EAS axis, and fluctuations in the development of the cascade (Fig. 3, right). This results in a set of images that are similar to the initial experimental event and can be compared to it. After the comparison, a particular type of primary particle with the specified EAS parameters is attributed to the event. Since the average shape (slope) parameters of the spatial distribution function for EAS Cherenkov light are not used in this method, there are only two factors that impede reconstructing the type of PCR: measuring instrument error and fluctuations in the light background; this method is therefore most reliable when analyzing the experimental data obtained on the SPHERE-2 facility.

In addition, the proposed method can be used to test different models of initial interaction. It is then possible that a solution to the problem of the ambiguity in determining PCR composition mentioned in the introduction will be found.

CONCLUSIONS

The high accuracy of registering EAS Cherenkov light in an experiment conducted using the SPHERE-2 facility was achieved using our calibration system. The obtained results allow us to analyze the composition of PCRs from the density of Cherenkov light in the axile region of an EAS. A method for determining the composition of PCRs based on comparing images of recorded events and simulated events was proposed.

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