ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2025, Vol. 89, No. 6, pp. 1002–1006. © Pleiades Publishing, Ltd., 2025.

SPHERE-3 Project for Primary Cosmic Rays Mass Composition Studies a 1–1000 PeV. 2024 Status

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Received December 2, 2024; revised February 14, 2025; accepted February 28, 2025

Abstract—The new SPHERE-3 detector for primary cosmic ray's mass composition studies is in development. The current version of the new SPHERE-3 detector and corresponding data analysis approaches are presented along with first estimations of their performance.

Keywords: primary cosmic rays, Cherenkov light, extensive air shower, cosmic rays mass composition

DOI: 10.1134/S1062873825711560

INTRODUCTION

Mass composition of primary cosmic rays (PCR) is crucial for the understanding of their sources, acceleration and transport processes. The composition study is complicated by extremely low PCR flux at high energy. The use of conventional calorimetric methods becomes almost impossible due to the large size of the detectors and the cost of their manufacture. There are several methods based on the extensive air showers (EAS) parameters registration: charged particles distribution, radio emission, fluorescent and Cherenkov light. All these methods use the atmosphere as a calorimeter. Despite the large number of methods, experiments implementing these methods and interpretations of their results the composition of cosmic rays in the 1–1000 PeV region remains relatively unknown [1–3].

This makes the design of new experimental techniques and approaches to data analysis one of the relevant problems of astrophysics. Widely used depth of shower maximum method provides only average PCR mass values with enormous systematic errors due to the hadron interaction model uncertainty. Some attempts were made to use not one but several methods simultaneously [4]. This approach yields somewhat better results on mass composition but is limited by Cherenkov light detectors duty factor. At the same time EAS Cherenkov light can provide detailed information on the primary particle mass. In this project an attempt at advancement of Cherenkov technique is made: the reflected Cherenkov light registration technique is enhanced by direct Cherenkov light angular properties study.

THE DETECTOR

The detector design should have high sensitivity to have low registration threshold and high spatial resolution to assess shape and form of EAS Cherenkov light spot. Also, a large field of view is required for a reasonable aperture (and, therefore, a high number of registered events). The Schmidt optical scheme meets all these requirements. Main differences of the new SPHERE-3 from its predecessor SPHERE-2 [5] are the aspherical corrector plate and aspherical main mirror. The detector is planned to be complimented by a direct Cherenkov light angular distribution detector (see [6]).

The detector exterior view is shown on Fig. 1. The current version has a 2.2 m diameter main mirror, a SiPM camera in the center consisting of 379 optical modules with lens light collectors. This optical scheme has an effective aperture of 1.9 m^2 and 40° viewing angles (0.38 sr). The optical scheme is implemented in

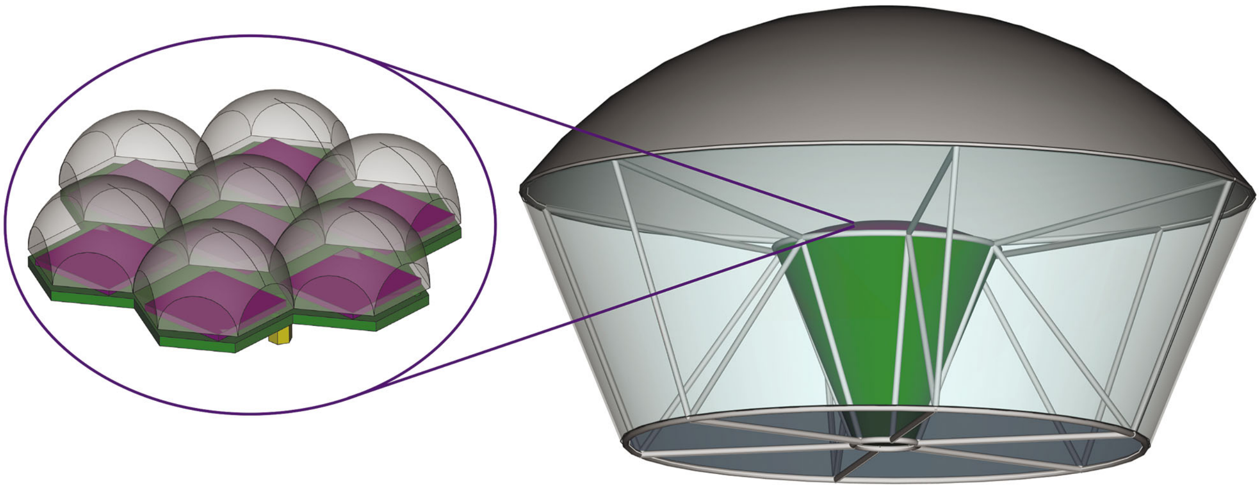

Fig. 1. Current detector with optical module design version.

Geant4 [7] to trace photons through the detector; however, it can be updated if the detector performance analysis will require this.

The camera optical modules consist of 7 pixels. In total, the SPHERE-3 will have around 2700 pixels. Each pixel consists of 6 × 6 mm SiPM with a spherical lens light collector on top of if. Distance between pixel centers is around 12 mm. General view of the optical module is given in Fig. 1. Each module houses amplifiers and 14 bits and 80 MHz fast analog-to-digital converters directly below SiPMs. Data from each pixel is stored in a buffer for the preprocessing. Each optical module is connected to the trigger board and can store a data frame (6–12 μs of signal around the trigger signal) from the buffer to the external memory (SD card) when the 'trigger' signal is received.

As an intermediate step in SPHERE-3 development a prototype construction is planned to verify design decision and performance estimations. Prototypes will have the same construction and electronics but will be smaller (about 300 pixels and 0.8 m diameter main mirror).

EAS SIMULATION

The CORSIKA 7.7500 [8] was used to simulate EAS development. Several different hadron interaction models were used: QGSJET01 [9], QGSJETII-04 [10] and SIBYLL2.3 [11]. Most of the events were obtained for QGSJETII-04. Low energy hadron interaction were simulated using GHEISHA-2002d model [12]. Since the new experiment is planned to measure Cherenkov light at several different altitudes (at snow level and above) therefore the CORSIKA was modified to output required distributions. Spatio-temporal distribution of Cherenkov light at snow level (Lake Baikal altitude) was recorded in 3.2 km by 3.2 km by 500 ns grid with 2.5 m and 5 ns steps. Additionally, combined Cherenkov photons angular-spatio-temporal distributions were recorded at 0.5, 1.0, and 1.5 km altitude in a 30° by 30° cone (with 0.2° step, centered on shower arrival direction) in 400 m by 400 m square around the shower axis (with 10 m step) within 65 ns from shower arrival (5 ns step). EAS were simulated for a set of primary parameters:

- 4 nuclei: protons, helium, nitrogen, iron;
- 3 energies: 5, 10 and 30 PeV, with 100 PeV and above planned for future:
- 6 zenith angles: 5°, 10°, 15°, 20°, 25° and 30°, azimuth was not fixed and selected randomly;
- 4 atmosphere models: atmosphere models number 1, 3, 4 and 11 in CORSIKA 7.7500 library.

Geant4 was used to trace simulated EAS photons through the detector model and form Cherenkov images both for the reflected (image on the SiPM mosaic) and the direct light (image on a photosensor of the angular lens detector).

EAS AXIS LOCATION AND ARRIVAL DIRECTION ESTIMATION

The shower axis was located as a center of mass calculated over signals in 19 pixels closest to the image maximum. If the maximum was in the penultimate pixel ring only 7 pixels were used. If the maximum was at the image edge the event was discarded. With detector at 500 m altitude, the axis location error is about 5 ± 3 m, and for 1000 m altitude, it is 10 ± 8 m. See details in [13].

Shower arrival direction was estimated by fitting EAS light arrival times (time of photon flux maximum) by a parabolic front function with respect to geometric effects (difference in optical path length between pixels). Precision of the axis location by this method is around 1°–2° with slight dependence on

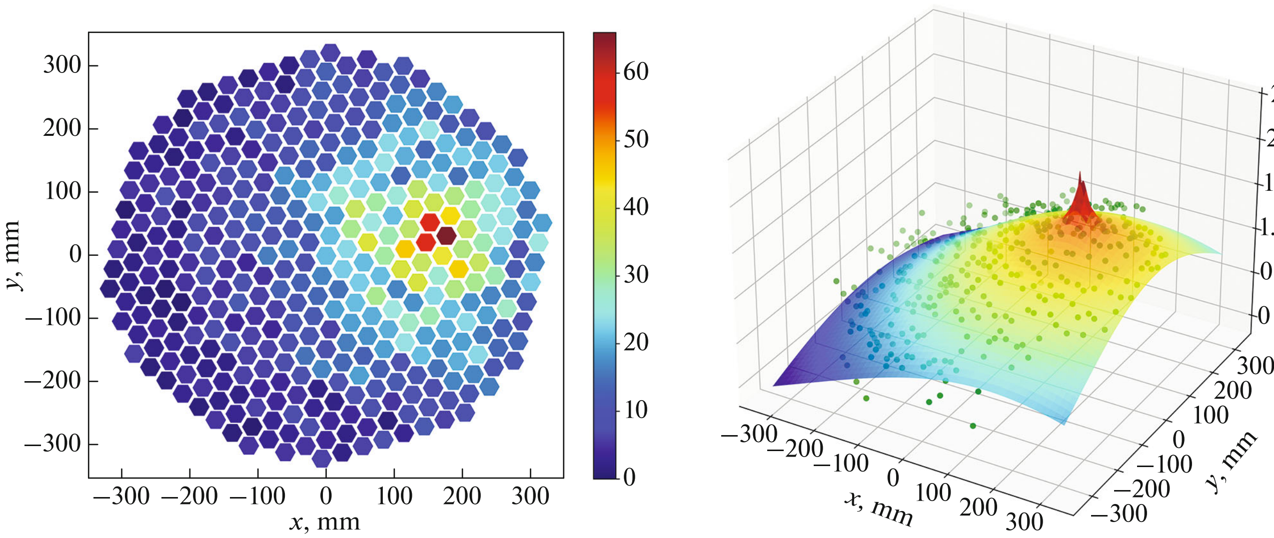

Fig. 2. (Left) An example of an EAS image on the detector mosaic. Data is shown for optical modules. (Right) Same EAS as on the left (green dots) with LDF approximation shown as surface in logarithmic scale.

the detector altitude: average error changes from 1.3° at 500 m to 1.7° at 1000 m. See details in [13].

EAS ENERGY ESTIMATION

EAS primary particle energy estimation was using total EAS Cherenkov light photon flux Q which was obtained by integrating Cherenkov light lateral distribution function (LDF) approximation (see Fig. 2). The approximation was taken from previous work [14, 15]. Simulations show that at fixed energy there is slight dependence of Q on the distance R from the shower axis to the center of the detector's field of view (due to uneven sensitivity of the optical scheme). The energy estimation is done by obtaining values Q_{exp} and R_{exp} for an event and back interpolating over simulated $Q = Q(E_0, R)$ dependence. These dependences were simulated for different primary nuclei (protons, nitrogen and iron) with 5, 10 and 30 PeV energy. In total 3300 events were simulated for each nucleus. At the current stage R_{exp} is taken from simulation directly but will be obtained from the data later.

If primary particle mass m_{exp} is known then $Q(E_0, R)$ dependences for the specific nuclei is chosen. Then the $Q(E_0, R_{\text{exp}})$ is constructed through interpolation. From this set the inverse dependence $E(Q)$ is constructed and $E_{\text{est}} = E(Q_{\text{exp}})$ is obtained. If the primary particle type is unknown the average $Q(E_0, R)$ over all nuclei is used to construct $Q(E_0, R_{\text{exp}})$ dependence.

As a test a sample of 1000 events from the primary 10 PeV helium were simulated. If primary particle mass was known the energy estimation error for these test events was 6.45%. In case if the test event mass was unknown the error was higher—6.96%.

PRIMARY PARTICLE MASS ESTIMATION

Cherenkov light LDF has a good correlation with the shower longitudinal development. If the LDF shape could be well parameterized by some value, then this value will also characterize the shower longitudinal development and correlate with primary particle mass. This shape parameter should be integral in the sense that it should account for most shower photons, not just some small parts of it. This will reduce inevitable fluctuations coming from shower development and registration procedure. Also, the parameter in question should not depend on the interaction model. Such a shape parameter – ratio of photon counts in the central circle and adjacent wide ring—and LDF approximation for this experiment is described in [14, 15].

In this study showers with small zenith angles from 10 PeV primary protons, nitrogen and iron, simulated with two different high energy interactions models, were used. No background was added, and no optical corrections were applied.

To find the best parameter, the classification into three mass groups was analyzed. In theory, showers from lighter nuclei will produce steeper LDF, therefore the higher the parameter value—the lighter the primary particle. Two class separation borders were defined: for p–N and N–Fe pairs. The maximum of two classification errors (ratio of incorrectly identified primaries) was chosen as the optimization metric. The after-shape parameter optimization (variation of circle and ring radii) the resulting distribution (see Fig. 3)

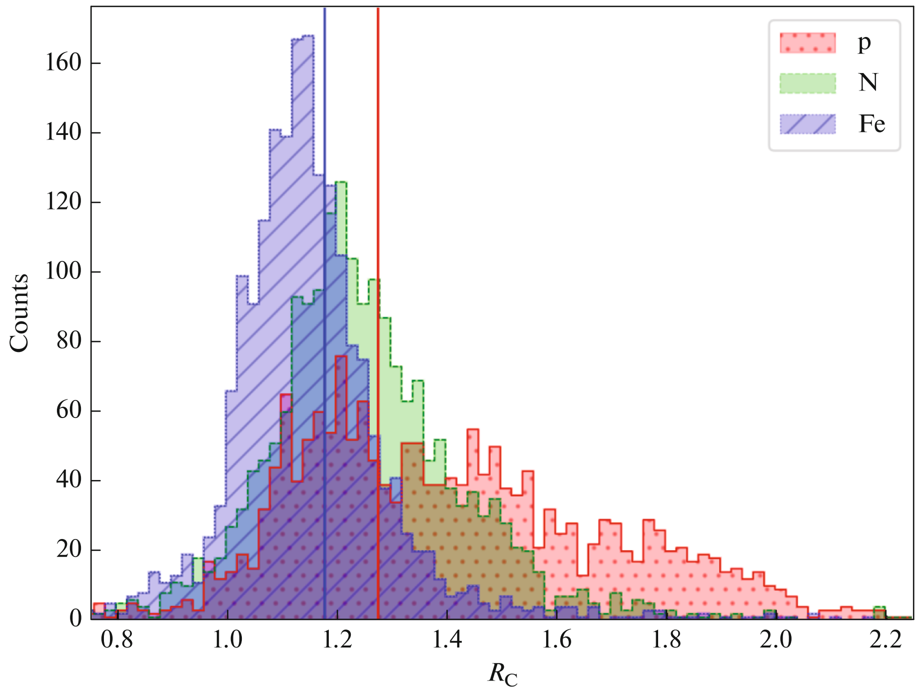

Fig. 3. The distribution of LDF shape parameter (R_C) for showers from 10 PeV protons (red with dots), nitrogen (green), and iron (blue with lines) primaries.

allowed to set class separation borders with classification errors of around 30%. Further studies and more complex parameter construction should allow better accuracy.

CONCLUSIONS

A preliminary design of the SPHERE-3 detector was developed. For this detector version Geant4 models were implemented to study the detector performance. A large bank of simulated events and their images in the detector were created to identify their mass sensitive parameters. Some preliminary results were obtained on detector performance in primary particle energy and mass reconstruction. Detector optimization is in progress to achieve detector higher sensitivity and better mass estimation precision.

FUNDING

This work is supported by the Russian Science Foundation under grant no. 23-72-00006, https://rscf.ru/project/23-72-00006/. The research was carried out using the equipment of the shared research facilities of HPC computing resources at the Moscow State University [16].

CONFLICT OF INTEREST

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

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