ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2025, Vol. 89, No. 6, pp. 1007–1010. © Pleiades Publishing, Ltd., 2025.

Estimation of Extensive Air Shower Primary Parameters Using Cherenkov Light Angular Distribution in the SPHERE-3 Experiment

E. A. Bonvech[a, *] (ORCID: 0000-0002-6878-357X), **N. O. Ovcharenko**[a, b], **O. V. Cherkesova**[a, c], **E. L. Entina**[a], **V. I. Galkin**[a, b] (ORCID: 0000-0002-2387-9156), **C. G. Azra**[a, b], **D. V. Chernov**[a] (ORCID: 0000-0001-5093-9970), **V. A. Ivanov**[a, b], **T. A. Kolodkin**[a, b], **D. A. Podgrudkov**[a, b] (ORCID: 0000-0002-0773-8185), **T. M. Roganova**[a] (ORCID: 0000-0002-6645-7543), and **M. D. Ziva**[a, d]

[a] *Skobeltsyn Institute for Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Department of Physics, Moscow State Unuiversity, Moscow, 119991 Russia*
[c] *Department of Space Research, Moscow State University, Moscow, 119991 Russia*
[d] *Department of Computational Mathematics and Cybernetics, Moscow State University, Moscow, 119991 Russia*
**e-mail: bonvech@yandex.ru*

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

Abstract—Some plans on further development of the SPHERE experiment are presented. Namely, reasons for the introduction of an additional detector of the angular distribution of Cherenkov light, pointed at zenith, are given. It can only work together with the main telescope but can yield important information on the primary particle direction and mass. Construction and capabilities of the detector are discussed, draft algorithms for direction definition are revealed, and sensitivity to the primary mass is shown.

Keywords: extensive air shower, Cherenkov light, Monte Carlo simulation, primary cosmic rays

DOI: 10.1134/S1062873825711572

INTRODUCTION

Extensive air showers (EAS) registration method using their reflected Cherenkov light was first proposed by A.E. Chudakov in 1972 [1]. This method was implemented in several experiments [2–5] with varying degrees of success. At present a new detector in the SPHERE experiments series is in design [6], aimed at primary cosmic ray mass composition estimation in the 1–1000 PeV energy range. Traditional for this series mirror telescope optical design is optimized specifically for this task and will be complemented with an additional detector to study Cherenkov light angular distribution. The first estimates show that this detector provides data on arrival direction and allows mass reconstruction with quality equal or better than that of the reflected Cherenkov light telescope. If EAS is registered by both the angular and reflected light detectors the primary particle parameters are estimated with even better accuracy.

DIRECT CHERENKOV LIGHT DETECTOR

The direct Cherenkov light detector must register the angular distribution in sufficient detail to separate the EAS events by the primary nuclei. At the same time, the data provided by it should be suitable for EAS direction estimation. Two detector options were considered. Both represent a collecting lens, and a position-sensitive sensor located in its focus. The first option had a small 100 cm^2 lens with a 10.3 cm focal distance, the second version had a larger 400 cm^2 area and lenses with a 63.5 cm focal distance. The first version had a 30 × 30° field of view with a single lens, while the second had 7 of 19 lenses in a hexagonal grid for the same field. At this stage only the first option (shown in Fig. 1) was fully analyzed.

SIMULATION

For EAS simulations CORSIKA 7.7500 was used [7] as described in [8]. All simulation runs were performed using the Lomonosov-2 supercomputer [9]. The simulated Cherenkov light from EAS was then traced through the main SPHERE-3 telescope and direct Cherenkov light detector using Geant4 [10] with implemented detector models.

SHOWER ARRIVAL DIRECTION ESTIMATION USING DIRECT CHERENKOV LIGHT

EAS arrival directions were reconstructed using Cherenkov light distributions (unmodified CORSIKA

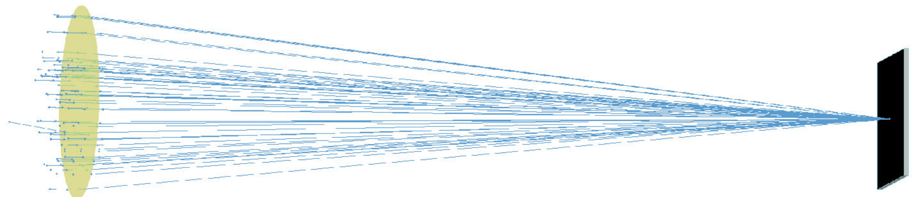

Fig. 1. A segment of the direct Cherenkov light detector with 400 cm^2 total area. The detector will have 7 or 19 such lenses with a single sensitive element in its focus.

simulations output) and Cherenkov images (an ideal detector output without electronics interference). In both cases arrival direction was estimated two ways: using light spot maximum position and using light spot center of mass. The direct Cherenkov light distribution is asymmetrical, and, therefore, the maximum and center of mass are offset from the arrival direction and from each other. However, the original EAS arrival direction projection, spot maximum and center of mass all lay along the same line in a certain order. On the one hand this introduces a systematic error in arrival direction estimation that depends on the distance from the shower core to the detector. On the other hand, this allows us to introduce a correction based on the offset between light spot maximum and center of mass. With this correction applied the arrival direction estimation can reach precision presented in Table 1.

NEURAL NETWORK APPROACH TO THE EAS ARRIVAL DIRECTION

One of the possible approaches to direct Cherenkov light registration with the SPHERE-3 detector is to use the main camera and a coded aperture introduced into the main mirror. The main mirror can have an arrangement of pinholes that will not affect the reflected light collection due to a comparably very small area. The main advantage of this approach is the use of the same light sensitive elements as for the reflected light registration therefore saving on detector electronics complexity and mass. The main drawback of this method is its limited resolution and relatively low amount of collected light.

To test this approach a toy model of coded aperture was used—a single 97 mm diameter round hole in the center of the main mirror (see Fig. 2). The incident light distribution was simulated as an artificial, gaussian in angular terms fluxes. The fluxes were traced through the main detector model using Geant4. The electronics response was modeled also as described in [8] with no background added.

The sensitivity of the proposed direct light registration method to the EAS arrival direction was done the following way:

(1) images from the detector camera were preprocessed and the geometric center of light spots was estimated in polar coordinates (r_0, φ_0) relative to the image center;

(2) values of (r_0, φ_0) were fed as training inputs to a regression model (as a test the linear regression model was used) and as engineered features to the fully connected neural network with one hidden layer;

(3) on the test set the results of two models (r_1, φ_1) and (r_2, φ_2) and preprocessed values (r_0, φ_0) were compared to the original (known) values used in the simulation (r, φ).

Linear regression model parameters were estimated using the least squares method. The neural network was trained over 5000 samples for 10 epochs with mean absolute deviation as a loss function.

Resultant arrival estimation errors Δ for all three methods are presented in Fig. 3. Feature engineering allows to achieve $2.0° \pm 0.8°$ precision. Linear regression model provides better accuracy of $0.6° \pm 0.3°$, and neural network (multilayer perceptron, MLP) had the best precision of $0.44° \pm 0.26°$.

PRIMARY MASS ESTIMATION USING DIRECT CHERENKOV LIGHT

The task of primary particle mass estimation was also approached the same way as arrival direction estimation: using angular distributions and Cherenkov images. As a numerical parameter of the light spot

Table 1. EAS arrival direction estimation errors (in degrees)

Distance to the shower core	Angular distributions		Cherenkov images	
	using maximum	using center of mass	using maximum	using center of mass
140 m	0.20	0.32	0.12	0.16
100 m	0.10	0.22	0.14	0.19

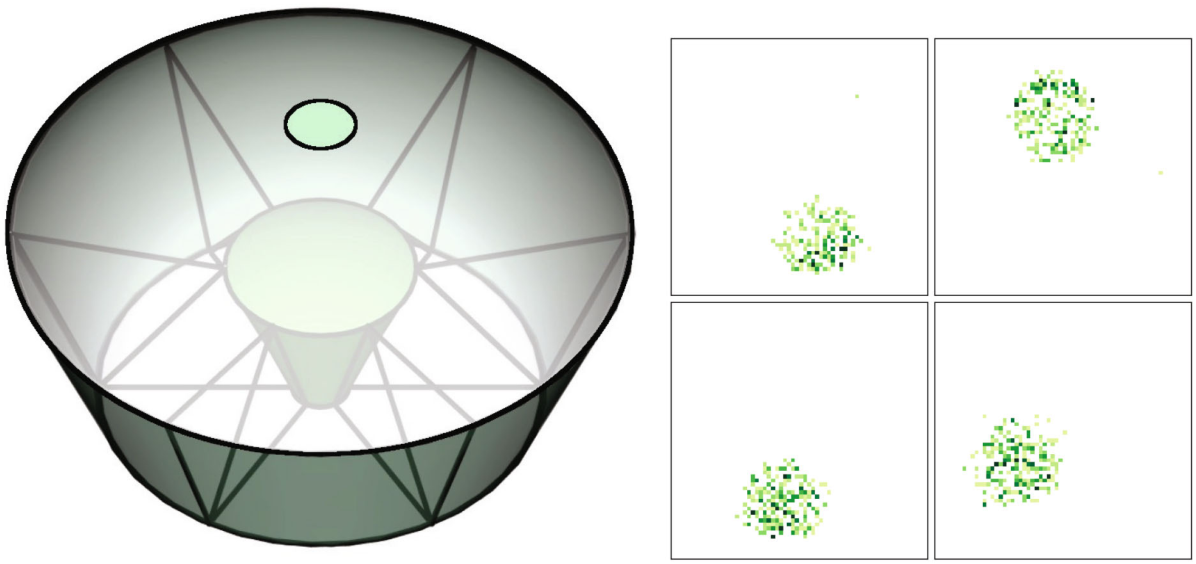

Fig. 2. (Left) Schematic representation (not to scale) of the toy-model coding aperture hole. (Right) Examples of the light spots' images on the camera from artificial events.

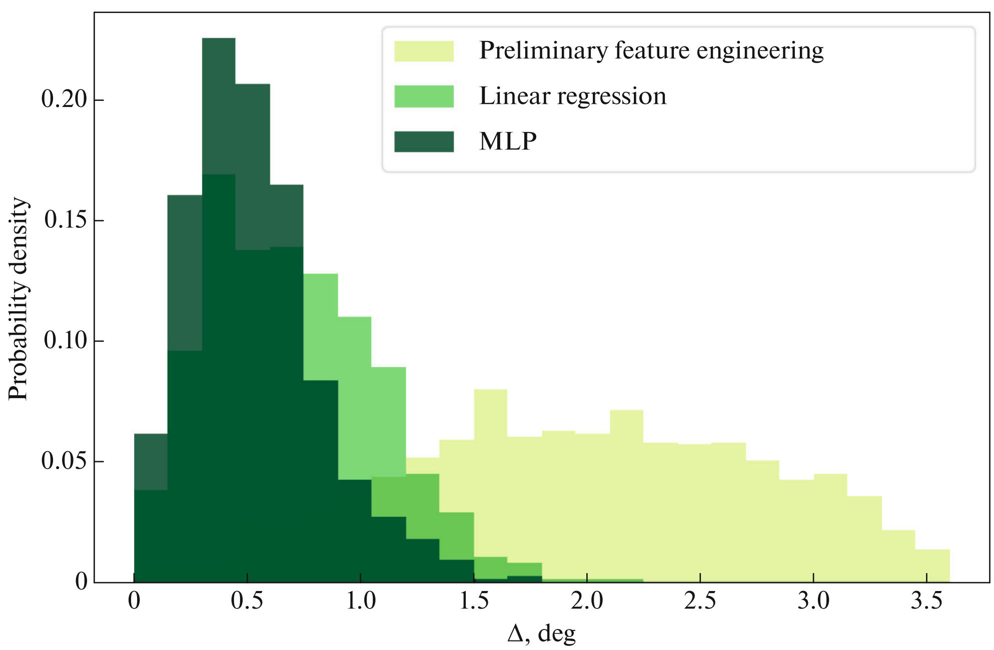

Fig. 3. Light arrival estimation error Δ distribution for different approaches (see text).

shape the length of its bigger axis was used. To lower the fluctuations the thresholds were introduced—minimum number of photons in each image cell required for the cell to be accounted in analysis. Several threshold levels allow one to study distribution at different levels. Also, the effect of Cherenkov light distribution modeling resolution was tested. Several different options were applied (1.0°, 0.5°, 0.25° and 0.2°) that significantly differed in the mass estimation results (see Table 2).

As follows from Table 2 Cherenkov light angular distribution is more sensitive to primary particle mass than to reflected light [8], which has average classification errors of around 0.3. However, for the 100 cm^2 detector version the classification errors even with the highest resolution grid (0.2° × 0.2°) were about 0.44 for both proton—nitrogen and nitrogen—iron pairs.

To solve this issue, the images were analyzed for fluctuations and thresholds were set higher to select only the areas with relative fluctuations less than 1.

Table 2. Average classification errors for different resolutions (100 cm^2 detector, 3 photons threshold, 140 m from shower core)

Resolution	1.0° × 1.0°	0.5° × 0.5°	0.25° × 0.25°	0.2° × 0.2°
p–N error	0.37	0.25	0.25	0.22
N–Fe error	0.25	0.26	0.20	0.20

Table 3. Classification errors for 400 cm^2 detector (140 m to shower core, resolution 0.2 × 0.2°)

	Threshold, photons	p–N	N–Fe
Angular distributions	15	0.270 ± 0.005	0.230 ± 0.005
	30	0.270 ± 0.005	0.240 ± 0.005
	80	0.270 ± 0.005	0.220 ± 0.005
Cherenkov images	12	0.270 ± 0.005	0.260 ± 0.005
	14	0.270 ± 0.005	0.260 ± 0.005
	16	0.270 ± 0.005	0.260 ± 0.005

This allowed to reach 0.43 and 0.39 classification errors for proton–nitrogen and nitrogen–iron pairs respectively on the 0.2° × 0.2° grid.

Since classification errors were significantly higher than in the reflected light method [8] another detector model was tested with a 400 cm^2 area lens (see Fig. 1). In contrast with the previous detector version this one has a thin lens what significantly lowers the image distortions, and, therefore, provides better classification errors (see Table 3).

Since the larger lens collects more light the thresholds for image analysis can be set higher. And with higher thresholds the best results were achieved, surpassing those of the reflected technique.

CONCLUSIONS

The development of a new experiment in the SPHERE series and the optimal design of the detector are primarily focused on the task of determining the mass composition of primary nuclei in the energy range of 1–1000 PeV. A new Cherenkov light angular distribution detector, working in conjunction with the main telescope that registers reflected Cherenkov light, can provide significant assistance in solving this problem. The article discusses the possibilities of such a detector. It can already be argued that it can solve these tasks—estimating the direction of the axis and separating the primary nuclei by mass—not worse than the main telescope.

FUNDING

The research was carried out using equipment of the shared research facilities of HPC computing resources at the Moscow State University [9]. This work is supported by the Russian Science Foundation under Grant no. 23-72-00006, https://rscf.ru/project/23-72-00006/.

CONFLICT OF INTEREST

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

REFERENCES

1. Chudakov, A.E., *Kosm. Luchi*, 1972, vol. 620, p. 69.
2. Castagnoli, C., Navarra, G., and Morello, C., *Proc. Int. Cosmic Ray Conf.*, 1981, vol. 6, p. 103.
3. Antonov, R.A., Ivanenko, I.P., and Rubtsov, V.I., *Proc. Int. Cosmic Ray Conf.*, 1975, vol. 9, p. 3360.
4. Antonov, R.A., Petrova, E.A., Sysoeva, T.I., et al., *Bull. Russ. Acad. Sci.: Phys.*, 1999, vol. 63, no. 3, p. 520.
5. Antonov, R.A., Aulova, T.V., Bonvech, E.A., et al., *Phys. Part. Nucl.*, 2015, vol. 46, p. 60. https://doi.org/10.1134/S1063779615010025
6. Bonvech, E.A., Chernov, D.V., Latypova, V.S., et al., *Bull. Russ. Acad. Sci.: Phys.*, 2024, vol. 88, no. 3, p. 435. https://doi.org/10.1134/S1062873823705676
7. Heck, D., Knapp, J., Capdevielle, J.N., et al., Forschungszentrum Karlsruhe Report FZKA no. 6019, 1998. https://www.iap.kit.edu/corsika/70.php.
8. Chernov, D.V., Kolodkin, T.A., Ivanov, V.A., et al., *Bull. Russ. Acad. Sci.: Phys.*, 2025, vol. 89, no. 6, p. 1002.
9. Voevodin, V.V., Antonov, A.S., Nikitenko, D.A., et al., *Supercomput. Front. Innovations*, 2019, vol. 6, no. 2, p. 4. https://doi.org/10.14529/jsfi190201
10. Agostinelli, S., Allison, J., Amako, K., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2003, vol. 506, p. 250. https://doi.org/10.1016/S0168-9002(03)01368-8