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# First detailed reconstruction of the primary cosmic ray energy spectrum using reflected Cherenkov light

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**Abstract:** We report on the first reasonably well systematically controlled measurement of the primary all-nuclei cosmic ray energy spectrum with a detector lifted above ground surface. The spectrum in the energy range $10^{16}$–$5 \cdot 10^{17}$ eV was reconstructed using the data of the SPHERE experiment that observes optical Vavilov-Cherenkov radiation (Cherenkov light) of extensive air showers (EAS), reflected from the snow surface of Lake Baikal. Several sources of systematic uncertainty of the spectrum were accounted for. The statistical uncertainty of the measured spectrum is still larger than for the most of the modern ground-based experiments. However, the systematic uncertainties were proved to be tolerable, and the total uncertainty of the reconstructed spectrum is comparable with that of the ground-based experiments.

**Keywords:** Reflected Cherenkov light, SPHERE-2, balloon.

## 1 Introduction

Cosmic rays (CR) are being investigated by various methods during about 100 years. Most energetic nuclei detected directly in balloon experiments have energy $E_0 \sim 10^{15}$ $eV$= 1 PeV [1]–[2]. In the "superhigh" energy domain, $E_0 > 1$ PeV, we are still bound to rely on the indirect methods only, i.e. to observe the-so-called extensive atmospheric showers (EAS) — cascades of energetic particles initiated by the primary nuclei — and to derive all physical conclusions about primary cosmic rays from these observations.

Despite several decades of the superhigh cosmic rays' energy spectrum measurements, a considerable uncertainty of the spectral shape still exists (for instance, see fig. 1, which is taken from [3]). As is evident from the figure, the shape of the spectrum reconstructed by the CASA-MIA [4], CASA-BLANCA [5] and DICE [6] experiments differs from the most of the other results. At higher energies, an anomalous peak at $8 \cdot 10^{16}$ eV exists in the spectrum measured by the GAMMA group [7].

Also, the spectrum shows some dependence of the assumed primary composition — this feature is illustrated in fig. 1 by the two ICETOP results (red squares and green circles). Red squares denote the spectrum reconstructed for the primary proton assumption, while green circles — for the two-component model in which iron fraction grows with energy from 0.3 to 0.85 while energy grows from 3 to 100 PeV. Generally, looking on fig. 1 one may conclude that the main difference between the results is due to systematic, and not statistical issues. Thus, thorough study and reduction of the systematic errors is of much more importance than just building the new detectors and observing great number of showers.

In the present paper we report on the first reasonably well systematically controlled measurement of the primary all-nuclei cosmic ray energy spectrum in the SPHERE experiment. The SPHERE-2 detector is a Cherenkov telescope lifted above the snow surface of Lake Baikal. The detector is sensitive to Vavilov-Cherenkov radiation ("Cherenkov light") of EAS, reflected from the surface. The basic idea of such an experiment was proposed in [8]. Development of the method is described in several papers [9]–[13].

The main goal of the experiment is to perform, for the first time, an event-by-event study of the PCR nuclear composition with a non-imaging Cherenkov detector in the energy region 10–200 PeV. However, the all-nuclei spectrum reconstruction is a necessary stage of any CR experiment, and it is of some general interest as the first detailed measurement of the spectrum with the detector lifted above the ground surface. First test flights on site were performed in 2008–2009, and regular experiment started in 2010. The preliminary analysis of the 2011-2012 runs data was published in [12]. In the present paper we describe analysis of the 2013 run data.

## 2 The experimental data sample

The SPHERE experiment employs a mosaic of 109 PMTs for recording the light signal reflected from the spherical mirror. For more detailed description of the SPHERE experiment see [13]. Observation level in the 2013 experimental run was from 200 m to 700 m above the snow surface. In the five flights of total effective duration about 33 hours the grand total of 3813 trigger events were registered. 458 of these events are consistent with EAS Cherenkov light reflected from the snow surface. As, in average, for the 1 km observation altitude only $\sim$1 out of each $\sim 10^6$ photons reflected from the snow surface reaches the detec-

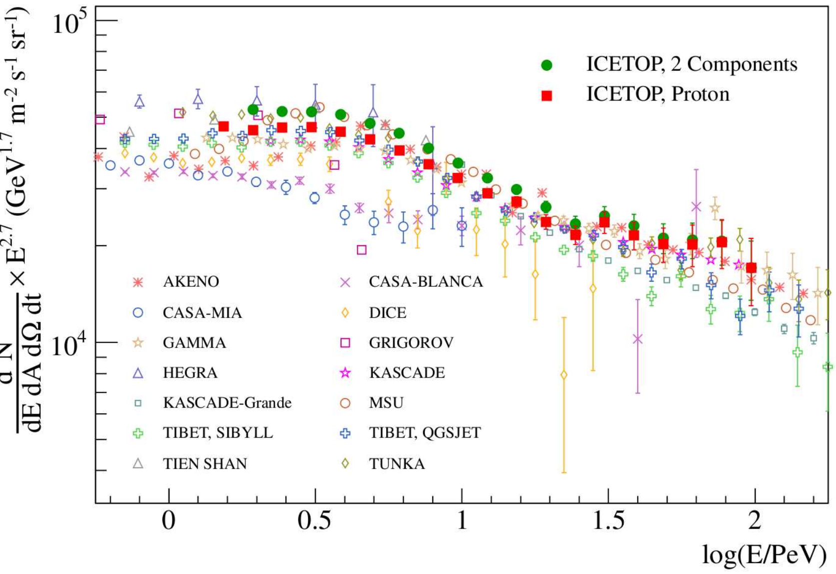


**Figure 1**: The all-nuclei CR spectrum measured by the selection of experiments [3].

tor's mirror, the effective threshold of the EAS observation is much higher than for the most of the ground-based arrays, hence the number of the EAS observed is relatively small.

## 3 Simulation of detector response and instumental acceptance

Simulation of detector response was performed by means of the full Monte Carlo method [12]. Lateral distribution function (LDF) of the EAS Cherenkov light and time structure of the shower were simulated using the CORSIKA 6.500 package [14] with the QGSJET-I high energy hadronic model [15] and the GHEISHA low energy hadronic model [16]. Then the geometrical and optical effects introduced by the SPHERE-2 detector were accounted for using the separate Geant4 [17] application. For the analysis conducted in the present paper about 500 000 response events were simulated.

After that, the simulation of the instrumental acceptance was performed [12] under the hypothesis of isotropy of the primary nuclei' arrival directions. Fiducial area was chosen to include showers with zenith angles from 0 to $40^o$ and distance of the axis to the edge of the field-of-view (FOV) not more than 100 m is allowed (part of external showers with axis outside the FOV was used in the analysis).

Several examples of the acceptance curves for different nuclei are shown in fig. 2. The simulation of acceptance was performed for 4 different primary nuclei: proton, Helium, Nitrogen and Iron, separately for each flight, and for 0-$20^o$ and 20-$40^o$ zenith angle ranges. In total, about 100 curves of acceptance vs. energy dependence were obtained and used in the subsequent analysis.

## 4 Analysis of experimental data

In order to reconstruct the primary all-nuclei CR spectrum, we have used a very simple method. Namely, we have simulated the energy distribution of EAS that would have been observed by the SPHERE-2 detector under certain assumptions about the primary CR spectral shape, and, by varying the underlying spectral shape, we have found the reconstructed spectrum as the model spectrum that best fits the data.

Strictly speaking, the only parameter of the experimental showers that must be estimated is the primary energy. To perform the energy estimation, reconstruction of experimental LDFs was performed. Relative calibration of PMTs was performed with a set of 7 LEDs installed on the mirror irradiating the mosaic. Calibration factors were calculated for each experimental event individually. Then experimental LDFs were reconstructed by subtracting the background and integrating the signal in each channel on time.

The time structure of the shower was recorded at the step of signal recognition, and reconstruction of the shower direction $(\theta_0, \phi_0)$ was performed. Then the axis position was found for each shower. Considerable effort was put in order to ensure correct reconstruction of the shower axis position, even in the "external" events, which have an axis outside the detector's FOV. Two examples of reconstructed experimental LDFs — internal and external one — are shown in fig. 3. All channels where signal was not found were assigned values of 0.1 code units. Good quality of the reconstructed LDFs ensures correctness of the above-mentioned procedures of relative calibration, pattern recognition and axis location.

At the next stage of the analysis, the energy estimation procedure was applied for each experimental LDF. The method of [18] was used, i.e. the energy estimation was performed after the axis position reconstruction by normalising of the experimental LDFs to the model LDFs with known energy.

Finally, the all-nuclei CR spectrum was reconstructed using the sample of the estimated energy values and results of the acceptance calculation. We were able to reduce the dependence of the shape of the reconstructed spectrum vs. primary composition by the following method. First of all, the LDF steepness parameter, defined as the ratio of the registered signal in the circle with the radius of 60 m to the same number in the ring with the radii of 60 m and 130 m, was estimated for the sample of reconstructed

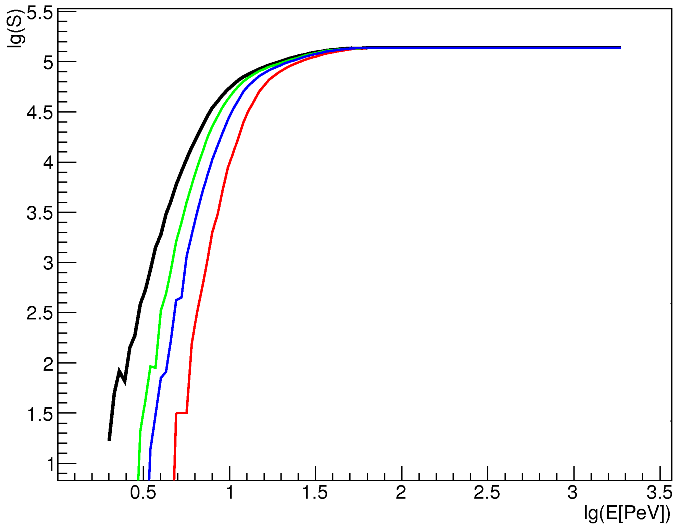


**Figure 2**: Simulated instrumental acceptance for the conditions of the 2013 experimental run, flight 3 and observation altitude 500 m for different nuclei species: proton (black), Helium (green), Nitrogen (blue) and Iron (red). Zenith angle range is from 0 to $20^o$.

LDFs, as well as for the several samples of the model LDFs with known primary nuclei mass and charge. Then the fraction $f$ of the "proton-like" (and $1-f$ of "Iron-like") experimental LDFs was determined. Finally, the "mixed-composition" acceptance was calculated using the reconstructed dependence of the $f$ parameter vs. energy, and the all-nuclei CR spectrum was reconstructed.

## 5 Results

The all-nuclei CR spectrum reconstructed using the 2013 run data of the SPHERE-2 experiment is shown in fig. 4 (right, red stars). We also present old result for the 2011-2012 experimental runs in fig. 4 (left, also red stars). Statistical (red bars) and systematic (red dashed lines) uncertainties of the spectrum are shown. The main sources of systematic uncertainty of the spectrum are: a) bin-to-bin migration due to the energy estimation error; b) statistical uncertainty of the acceptance estimation (not more than 5 %); c) the spectal shape vs. the primary composition dependence (this factor is dominant at E<20 PeV). Also the results of some other experiments are shown in fig. 4 for comparison: Akeno [19] (green circles), KASCADE-Grande [20] (black triangles), and Tunka-133 [21] (blue squares). Systematic uncertainties for the Akeno and the Tunka-133 results are not shown; systematic uncertainty of the KASCADE-Grande result is shown by black dashed lines.

## 6 Conclusions

In the present work we have reconstructed the CR all-nuclei spectrum for the 2013 experimental run of the SPHERE experiment using Cherenkov light reflected from the snow surface. Considerable effort was devoted to performing the accurate simulation of the instrumental acceptance. A dependence of the spectral shape vs. primary composition in the threshold energy region was reduced by using the information about the experimental LDF shape.

The developed approach to the all-nuclei spectrum reconstruction might be useful for the next generation of CR experiments, especially for those that are capable of observation of the EAS optical radiation reflected from the natural surfaces, like the TUS [22] and JEM-EUSO [23] orbital experiments.

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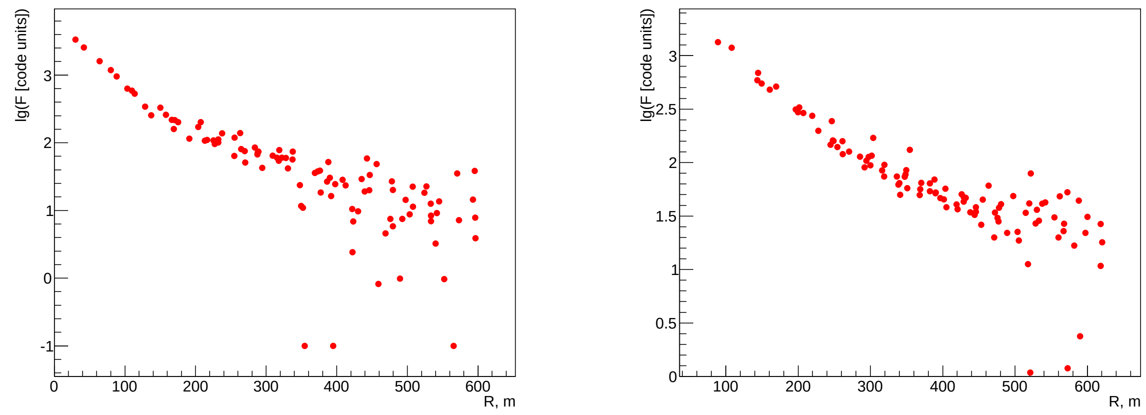


**Figure 3**: Two examples of reconstructed experimental lateral distribution functions (LDF) for a shower with an axis inside the field-of-view (FOV) of the SPHERE-2 detector (left) and for an "external" event with an axis outside the FOV.

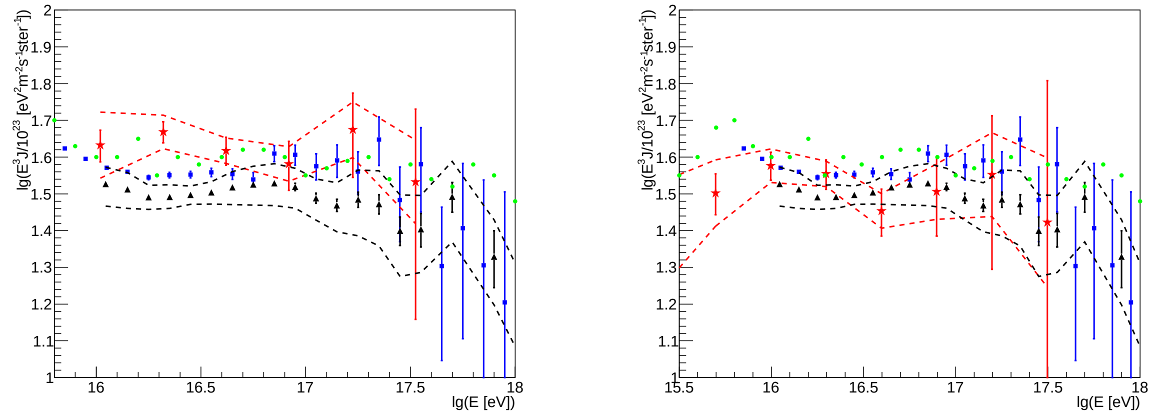


**Figure 4**: The all-nuclei CR spectrum measured in the 2011-2012 (left) and the 2013 (right) runs of the SPHERE-2 experiment (red stars) together with the statistical and the systematic uncertainties, as well as results of the Akeno [19] (green circles), KASCADE-Grande [20] (black triangles) and Tunka-133 [21] experiments (blue squares).

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