Detector for the ultrahigh energy cosmic rays composition study in Antarctica

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Detector for the ultrahigh energy cosmic rays composition study in Antarctica

Dmitry V Chernov[1,*], Rem A Antonov[1], Elena A Bonvech[1], Leonid G Dedenko[1,2], Miroslav Finger[3,4], Michael Finger[3,4] Dmitry A Podgrudkov[1,2] and Tatiana M Roganova[1]

[1] Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, 1(2), Leninskie gory, GSP-1, Moscow, 119991, Russian Federation
[2] Department of Physics, M.V.Lomonosov Moscow State University, 1(2), Leninskie gory, GSP-1, Moscow, 119991, Russian Federation
[3] Department of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16, Praha 2, Czech Republic
[4] Joint Institute for Nuclear Research, Joliot-Curie, 6, Dubna, Moscow region, 141980, Russian Federation

E-mail: *`chr@dec1.sinp.msu.ru`

Abstract. The main purpose of the Sphere–Antarctica project is connected to the fundamental problems of the cosmic ray physics and general astrophysics - the determination of the energy and mass composition of cosmic ray particles of ultra high and extremely high energies $10^{18} - 10^{20}$ eV. In the energy region above $6 \cdot 10^{19}$ eV modern experiments (Telescope Array and Pierre Auger Observatory) observed anisotropy and the clustering of arrival directions of cosmic rays in some areas. The scientific importance of this problem stems from the lack of generally accepted acceleration mechanism of the CR particles above $3 \cdot 10^{18}$ eV, the unknown nature of the sources of such particles, the inconsistencies of the results of major experiments in the part of the mass of CR composition and the discrepancy of experimental and model data. Scientific novelty of this project is in the methodology registration of the extensive air showers over a large area ~ 600 km^2 from an altitude 30 km, that allows to measure the two optical components of the shower Vavilov–Cherenkov radiation and fluorescence light by the same SiPM sensitive elements of the detector simultaneously.

1. Introduction

Extremely high energy cosmic rays (CR) ($10^{19} - 10^{20}$ eV) carry the information about most interesting processes: their generation and acceleration mechanisms. The total flux of such particles is extremely low and the results on the primary cosmic rays (PCR) mass composition and energy spectrum are in some disagreement between main large ground detectors [1]. Therefore the search for the new and more accurate and sensitive registration methods is an important part of present day astrophysics.

The Sphere–Antarctica experiment is based on the method proposed by Alexander Chudakov. In article [2] it was offered to install on an aircraft two photo multiplier tubes (PMT) and two electron-optical converters with identical fields of view of 45 degrees. All four devices had to observe a snow-covered surface of Earth from height about 10 km and detect reflected the Vavilov–Cherenkov radiation generated by the extensive air shower (EAS). The PMTs were

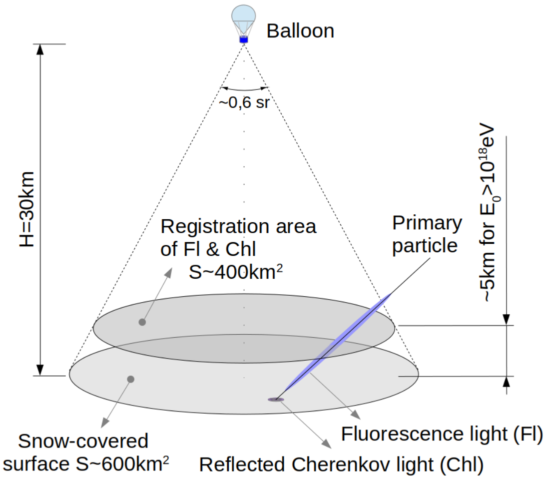

Figure 1. Scheme of Sphere-Antarctica experiment.

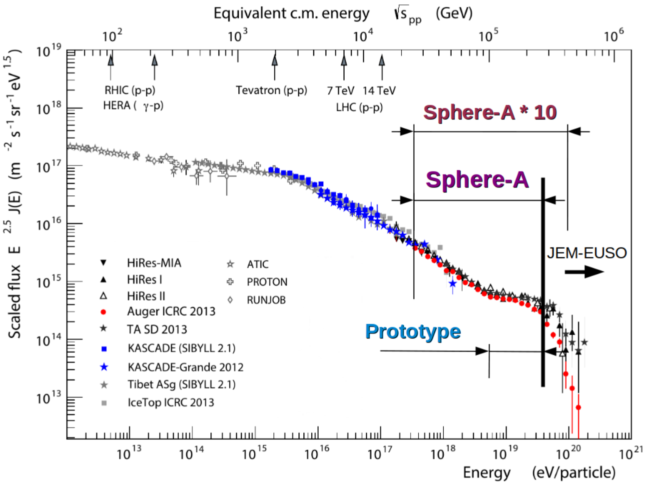

Figure 2. The energy range of the experiment Sphere–Antarctica.

proposed as a trigger system for photo registration on the electro-optical converters. The initial proposed experiment was never realized, but the works around this method were continued.

The first attempt of EAS registration using this method was conducted by Gianni Navarra in 1970–1980 in Alps at about 3500 m above sea level [3]. In early 1990s in Tian Shan the Navarra experiment was repeated by our team. The detector prototype was positioned on the mountain slope and observed the ice-covered Big Almaty Lake [4]. On the next step in 2000 from the altitude about 900 m the Spere–1 detector registered about 400 events that were used to obtain PCR spectrum in $10^{16} - 10^{17}$ eV region [5].

The more advanced detector Sphere–2 received 109 PMT mosaic with fully digital data acquisition system with 12.5 ns discretization. The main flights were performed in 2011–2013 at Baikal Lake. The analysis of the results is still going but the main result of the measurements is the sharp (down to $\sim$20%) decline of the background light component intensity at $5 \cdot 10^{16} - 10^{17}$ eV [6].

2. Sphere–Antarctica Project

The Sphere–Antarctica project [7] is aimed at using new hybrid method for ultra-high energy cosmic rays registration. The proposed new method has higher sensitivity to PCR energy and mass compared to the existing methods. Such sensitivity is achieved by registering both EAS fluorescent light track and reflected Vavilov–Cherenkov radiation flux using same elements of the same detector. The selected EAS components are at present considered to be the least model dependent and the most accurate EAS characteristics for PCR mass and energy reconstruction.

The scheme of Sphere–Antarctica experiment is presented on figure 1. A small wide-angle detector is elevated by balloon to the altitude of 30 km above snowed Antarctic surface. The project will be implemented in four stages: launch of a probe balloon with tracker, small size prototype launch, experimental launch with Sphere–Antarctica and carrying out of a series of flights for three to ten years. Figure 2 shows energy ranges for different stages of the project. The energy threshold is lower than 10^{18} eV. The maximum energy is up to 10^{20} eV. Small prototype is able to register only a few dozen events in a small range of energies.

To estimate the PCR particle energy we can use the Cherenkov and fluorescence light independently. Using this method for future orbital detectors is difficult due to changes of the reflecting surface.

During the 1000 hours of Antarctic night flight at 30 km altitude one such detector is able to record optical signals for up to 15000 EAS with energy $> 10^{18}$ eV, and up to 100 EAS with energy $> 10^{19}$ eV. A unique circumpolar air flow, as well as an absence of a strong wind in the near-polar region in the winter period makes such a long-duration flight possible. Launch of a several dozens of such a detectors would enhance the number of observed EAS.

The method of the all-nuclei spectrum measurement and composition study in the energy range of $10^{18} - 10^{20}$ eV that could be used in the Sphere–Antarctica experiment is likely the most adequate method for the above-mentioned tasks, because the integral flux of reflected Cherenkov light weakly depends from the primary nuclei type, and the Cherenkov light contamination of the fluorescent signal is very small. Therefore, the problem of Cherenkov/fluorescent light separation, that is typical for the ground-based detectors, does not exist for the balloon-borne experiment due to different arrival times of Cherenkov and fluorescent photons (see figure 4).

High accuracy of EAS zenith angle reconstruction in the Sphere–Antarctica experiment is due to registration of the signal time structure and delay between the Cherenkov and the fluorescent light pulses, and not only of the signal amplitude. Measurement of the EAS cascade curve shape allows to reconstruct the EAS cascade curve maximum position and zenith angle of the EAS. This information allows to study the CR nuclear composition, and might be helpful for reducing the all-nuclei spectrum systematic uncertainties.

3. Detector

It is proposed that the Sphere–Antarctica telescope will have the following construction: a system of acrylic lenses (PMMA) with a 480 mm diameter aperture with a spherical aberration corrector, focusing EAS light to a sensitive 440 mm diameter detector. Utilization of 3328 semiconductor sensors SensL's SiPM 6x6 mm MicroFJ 60035 with quantum efficiency 40–50% near the maximum of sensitivity (420 nm) is foreseen. All elements of the SiPM have differentiating "fast output pin", which allows to use SiPM in the photoelectron counting mode. That mode allows to forgo the complex and power-consuming analog-to-digital converters. The main elements are comparators with response time less than 5 ns and a power consumption of 7 mW. The measuring channel can correctly estimate the photoelectrons number even in the case of simultaneous arrival of several electrons.

Relatively high dark current of SiPM will be significantly reduced under measurement conditions because at the 30 km altitude the temperature is expected to be lower than -60°C. The study of the conditions will be carried out in the frames of project realization.

The field of view of the detector will be up to 0.6 sr. Each cell would observe a region on the Earth surface with optical resolution of ~ 1 degree. The energy threshold under these conditions is $3 \cdot 10^{17}$ eV. In the apparatus will be used laser lidar (0.3 W, 405 nm) for detection of aerosols, stellar orientation sensors and Iridium satellite communication system. The mass of apparatus with batteries will be less than 80 kg.

4. Calculations

The atmosphere density profile parameters were taken from the CORSIKA code for the June South pole atmosphere [8].

Optical density of the atmosphere was simulated as being proportional to the mass density with integral transparency of 0.91 at 577 nm wavelength. The atmosphere was deemed dust and aerosol free (as is expected from near polar atmosphere) hence only Rayleigh scattering was accounted for.

The background signal accounted scattered and reflected starlight, thermal noise of the SiPMs (around 1 GHz per optical module) and expected low noise of the electronics. The main source of the background is reflected starlight. Average number of the photoelectrons from background photons [9, 10, 11] in $3 \cdot 10^{-6}$ s with total reflectivity coefficient of snow surface, detector protection filter and lenses of 0.7 is $\sim 1.1 \cdot 10^2$ ph.e. with standard deviation of ~ 10.5 ph.e.

The detector was situated at 33 km above flat horizontal show surface. The sensitive element of the detector consists of 52 optical modules 52 × 52 mm each. Optical module consists of 64 SiPMs (8 by 8 square) sitting on the common base.

The optical system transparency was set at 90 %. The optical system forward window had 0.18 m^2 area. The radius of the light spot formed by the parallel beams falling on the detector was 2.5 mm (95% of all photons) for center detector area and up to 5 mm near the edge of the detector, which corresponds to the ~ 30 degrees incidence angle of the initial light beam. The detector observes solid angle about 0.45 sr.

The toy-model shower was used. No CORSIKA or other Monte Carlo codes were used to simulate shower. Instead the analytical results were used (Vavilov-Cherenkov radiation shower profile from [12] and Gaisser-Hillas curve for fluorescent light [13]). The shower was modelled as a 'falling star', no lateral distribution of the fluorescent light was used, all the fluorescent photons were generated on the shower axis. Such approximation is well justified as a single pixel (even with ideal optics) observes at shower maximum altitude the area of few kilometers whereas the half of all the charged particles of the shower are well within the 140 m distance from the axis [14].

The fluorescent yield for 1 m of the charged particle track at normal pressure was considered to be 4.8 photons and for other conditions was considered to be linearly dependent on the pressure at specific altitude. The humidity was not accounted for since the Antarctic atmosphere is considered to be dry. The pressure quenching of the different fluorescent lines was not accounted for. The Vavilov-Cherenkov radiation lateral distribution function from [15] was used with photons density at 400 m the shower axis according to [16, 17].

The shower modelling steps:

(i) the shower axis and shower arrival direction random selection;
(ii) random selection of the cascade curve parameters(according to Gaisser and Hillas [13], Dedenko [12] and TA Collaboration [18]);
(iii) from the top edge of the atmosphere with 10 ns steps (3 meters) estimation of the number of particles; at each step the number of Vavilov-Cherenkov photons were estimated in arbitrary units;
(iv) estimation of the number of fluorescent photons generated on each step by the shower particles;
(v) estimation of the mean number of fluorescent photons that fell on the detector on each step;
(vi) estimation of the number of photons that reached the SiPMs using Poisson distribution and obtained previously mean number of photons that reached the detector;
(vii) the wavelength of each photon was generated;
(viii) each photon randomly checked for scattering in atmosphere, for absorption in optical system and for photoelectron production;
(ix) each photon put on the SiPM matrix with additional distortion and smearing;
(x) estimation of the time bin of the photon arrival.

After the fluorescent light modelling the detector response for reflected and scattered Vavilov–Cherenkov photons was calculated.

The reflected and back–scattered Vavilov–Cherenkov EAS radiation the flat symmetrical shower model was used. The width of the shower was not factored as the pixel projected area (kilometers) is much greater than shower thickness. Snow reflectivity was 95 %. The calculation procedure was the same as for the fluorescent light: step by step calculation of number of photons that fell on the snow and their chance to get to the detector, estimation of the true number of photons that fell on the detector using Poisson distribution, and MC estimation of number of photoelectrons.

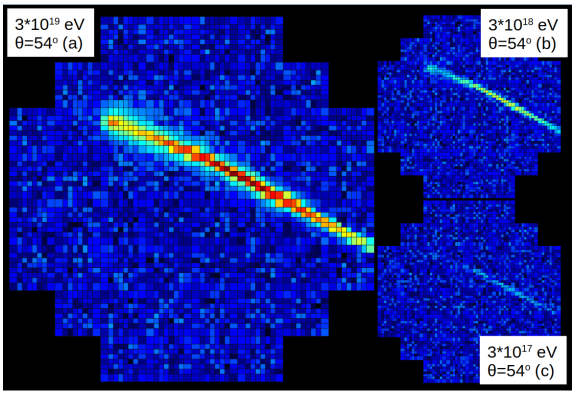

Figure 3. EAS radiation track to be viewed by Sphere–Antarctica detector.

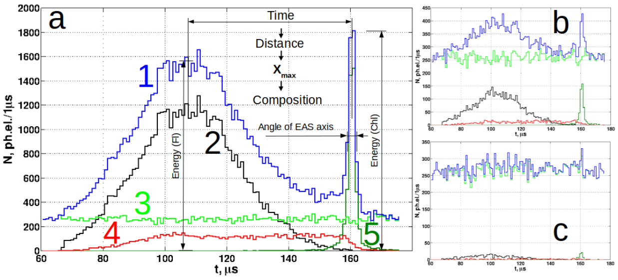

Figure 4. Time profile of EAS radiation track in Sphere–Antarctica detector. Numbers show: 1 — total light flux, 2 — fluorescent light, 3 — background and noise signal, 4 — scattered Cherenkov light, 5 — Cherenkov light reflected from snow.

Figures 3 and 4 show some results of detector simulation. Each pixel collects both fluorescent and Vavilov-Cherenkov photons but they are separated in time allowing accurate analysis.

5. Conclusions

The main advantage of the Sphere–Antarctica project is the simultaneous registration of the fluorescent light and the integrated flux of Cherenkov light of EAS. It will be realized in a new balloon experiment in Antarctica. The project increases the methodical accuracy of energy and particle type measurements and provides an opportunity to determine more precisely the direction of arrival of the primary particles of cosmic radiation. The experiment is lowcost and easy in implementation in comparison with ground or space-based detectors.

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