A Method for Primary Proton Spectrum Measurement at $E_0 \geq 10$ PeV with SPHERE-2 Telescope

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***Abstract*. A new method for selecting a certain part of the proton-induced events from the bulk of the primary nuclei events is presented. The method uses the shape of EAS Cherenkov light lateral distribution (CLLD) and is based on a few hundreds of artificial events by 10-30 PeV protons and helium nuclei simulated with CORSIKA/QGSJET-I/QGSJET-II code. Distribution of the proton CLLD steepness parameter has a long tail which is absent in helium distribution. The tail contains about 10% of the proton sample which could be distinguished from other nuclei events. The method was adapted to the geometry and conditions of SPHERE-2 telescope and proved to be capable of proton event selection.**

***Keywords*: primary composition, extensive atmospheric shower, Cherenkov light**

I. Introduction

Measurement of superhigh energy primary cosmic rays (CR) nuclear composition ($E_0 >= 10^{15}$eV= 1 PeV) is a challenging task of modern astrophysics, since the direct balloon and satellite experiments statictics is still severely limited due to the very low CR flux in this energy region. Thus, one should rely on extensive air shower (EAS) observations. However, the results found by several EAS groups are highly controversial. For instance, the measured value of mean primary CR logarithmic mass, $< lnA >$, shows dramatic discrepancy about an order of magnitude (see, e.g., [1]). Unfolding of e+μ KASKADE data [2] with QGSJET hadronic interaction model [3] leads to substantially heavier $< lnA >$ at E_0=10 PeV than the one measured by BLANCA Cherenkov array [4]. An even heavier primary composition is predicted by BASJE Collaboration [1].

In this paper we adress the question of evaluating CR proton spectrum at primary energies >10 PeV with the balloon-borne detector SPHERE-2. This Cerenkov EAS telescope detects Cherenkov light reflected from the snow surface, as suggested by [5]. In section II we describe the shower simulation process. Proton selection criteria are presented in section III. Section IV contains some results of suggested criteria application to the artifical events database. A model of Sphere-2 detector response to a shower, event parameters reconstruction procedure and the resulting proton selection criteria are described in section V. Finally, the conclusions drawn from our analysis are described in section VI.

II. Shower simulations

Simulations were carried out with CORSIKA 6.50 [6] with QGSJET-I/GHEISHA [3], [7] and QGSJET-II [8]/GHEISHA code (for the rest of paper this versions of the code are denoted as QGSJET-I and QGSJET-II, respectively). The level of observation chosen is Lake Baikal altitude (H_0= 455 m a. s. l.). We performed full direct Monte-Carlo simulations, since this technique well reproduces EAS development fluctuations. Result of simulation for each shower is a 3D histogram of Cherenkov light density function, distributed over 480 x 480 spatial cells and 100 temporal cells. The width of spatial cell is 2.5 m x 2.5 m and the width of temporal cell is 5 ns. The distribution of arrival directions of showers is isotropic.

Showers from primary protons and and helium nuclei with zenith angles $< 20^o$ were used for the proton selection criteria construction. These criteria are based on time-integrated Cherenkov light lateral distribution (CLLD) $\rho(r)$. Total statictics of artifical events is 772 showers, from which 134 showers are due to protons and helium nuclei of energy 10 PeV and QGSJET-I model, 165 protons and 152 helium nuclei for the case of QGSJET-II model and E_0=10 PeV, and 93 protons and 94 helium nuclei for E_0=30 PeV and QGSJET-II model. These showers with small zenith angles are practically axially symmetric, so the CLLD of each shower can be analysed on a set of rings with centers at the shower axis.

III. Criteria for primary proton selection

Let us introduce parameter η for CLLD shape evaluation:

$$\eta(r_1, r_2, r_3, r_4,) = \frac{\int\limits_{r_1}^{r_2} 2\pi\rho(r)dr}{\int\limits_{r_3}^{r_4} 2\pi\rho(r)dr}, \qquad (1)$$

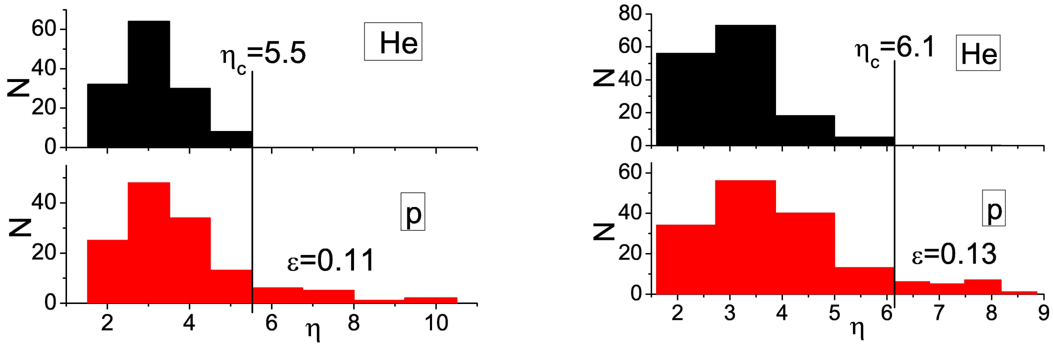

Fig. 1: Histograms of η_0 distribution for case of models QGSJET-I (left) and QGSJET-II (right) for proton primaries on top and helium primaries on bottom. Also displayed are η_0 protons selection threshold and ϵ- fraction of selected events

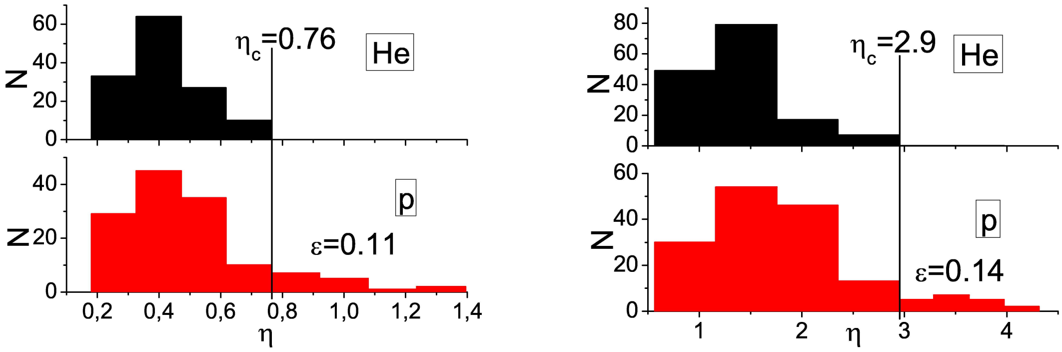

Fig. 2: The same as Fig. 1, but for optimized on number of selected events criteria. Left is $\eta_1 = \eta(0m, 80m, 80m, 320m)$, right is $\eta_2 = \eta(0m, 160m, 160m, 240m)$

where r_1,r_2,r_3,r_4 satisfy the following conditions

$$r_4 \geq r_3 + \delta r, r_3 \geq r_2, r_2 \geq r_1 + \delta r, \qquad (2)$$

Variable η has a physical meaning of CLLD steepness. Two rings are characterized by four parameters: (r_1,r_2)- interior and exterior radius of smaller ring; (r_3,r_4)- interior and exterior radius of bigger ring, respectively. Here δr denotes the characteristic spatial resolution of the EAS array.

Probability density function of random variable η for the case of proton primaries decreases with η slower than in the case of helium primaries. Therefore, it is possible to select a certain part of protons from a mixed proton+helium shower sample. The fraction of so selected protons is ruled by the shower development model and can be evaluated. For proton selection we define a value η_c such that all artifical events from helium have $\eta < \eta_c$. Then in the energy band $\approx$ 10 PeV the criterion $\eta > \eta_c$ should select primary proton events with a contamination of helium events of the order of $\approx 1/N_{He}$ or 0.75% for the case of QGSJET-I model and 0.66 % for QGSJET-II model, respectively.

IV. Results

In paper [9] the criterion $\eta_0 = \eta(0m, 130m, 250m, 350m)$ was constructed for samples of proton, nitrogen and iron primary nuclei. Histograms of η_0 random variable distributions constructed with our artifical events database are plotted in Fig. 1 for QGSJET-I (left panel) and QGSJET-II (right panel) models. Histograms of η_0 distribution are on the top and at the bottom for helium and proton primaries, respectively. η_c value and the fraction of selected proton events are also shown on the histograms. One can see that the part of selected proton events ϵ has a weak dependence on the nuclear interaction model (QGSJET-I/QGSJET-II).

Also we performed an optimization to find a criterion that allows to select the maximal number of proton events. For this purpose, a 4D grid of primary proton selection criteria was formed. Criteria in the array differ from each other by values of parameters r_1, r_2, r_3, r_4 (they vary within limits 0 m - 600 m). Then we performed a direct exhaustive search on the grid to optimize the criterion. If two criteria select the same number of proton events, we prefer the one that has the smallest r_1, if r_1 is also equal, than the smallest r_2, and so on. The reason for such a preference is that in any real experiment signal-to-noise ratio decreases with increasing distance from the shower core.

In Fig. 2 the same histograms as in Fig. 1 are plotted, but for the optimized criteria: left column, for the case of QGSJET-I, with parameters (0 m, 80 m, 80 m, 320 m) and right column, for QGSJET-II with parameters

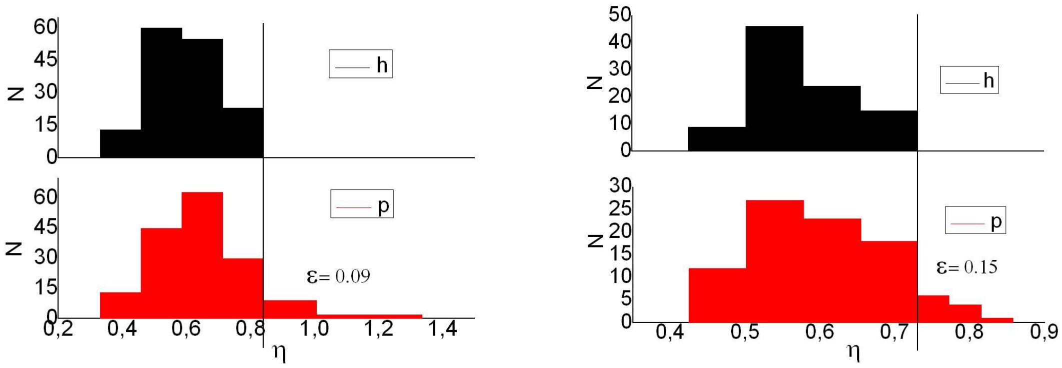

Fig. 3: Criterion for the case of model QGSJET-II and primary energy 10PeV (left) and 30PeV (right) with parameters (0,67,67,134) in the both cases. The criterion takes into account for shower parameters reconstruction uncertainties, starlight background and Cerenkov signal fluctuations Position of showers axis is equal between centers of three central fields of view

(80 m, 160 m, 160 m, 240 m). δr= 80 m for all cases, and r_4 <400 m.

We also varied δr from 10 to 300 m to find a dependence of classification performance on detector resolution. We found that in the practically important area δr= 40-280 m ϵ decreases with δr from 0.12 to 0.10 for QGSJET-I and from 0.15 to 0.10 for QGSJET-II. We also performed such operations for $E_0 = 30$ PeV and QGSJET-II hadronic interaction model. In this case $\epsilon(\eta_0)$= 0.24, the optimized criterion is $\eta(0m, 80m, 160m, 240m)$ and it ensures ϵ= 0.24. Corresponding plots are similar to those of Fig. 1, Fig. 2 (right column), so they are not presented here.

V. Fluctuations, background and detector uncertainties

Now we apply our techique to the working conditions of Sphere-2 experiment [10]. Sphere-2 is a Cherenkov telescope flying 1-3 km above the ground level and detecting the light reflected from the snow surface. The optical scheme of the telescope is Schmidt camera with spherical mirror with diameter 1500 mm, radius of curvature 940 mm and aperture diaphragm with diameter 930 mm. Sensitive mosaic of 109 photomultipliers (PMTs) is installed on the way of reflected beam. Mosaic has radius of curvature 526 mm. Radius of sensitive area of photocatode is 13 mm and the distance between the centers of nearest PMTs is 44.5 mm. This device is capable of observing $\geq$ 1/3 of EAS lightspot area. At altitude 800 m (Febraury-March 2009 working altitude) the distance between fields of view (FOV) of nearest PMTs on the snow surface was 67 m and diameter of one PMT FOV was 40 m; diameter of FOV of the telescope was about 400 m. PMTs form a hexagonal structure on surface of the mosaic and are enumerated from the central one on rings such that central PMT has a number 0, first ring contains PMTs with numbers 1-6, and so on. FOV of each PMT has the same number as PMT. A simulation of Sphere-2 detector response with account of Poissonian fluctuations of photon number reaching the diaphragm and night sky starlight background was performed.

For simulating optical system response we used the so called "ray-tracing"- a well-known method based on tracing many rays with dirrerent initial parameters (see, e.g. [11]). First, with the help of Monte-Carlo method the reflection of simulated EAS signal (section II) from the snow surface was considered. The surface was assumed to be a Lambertian optical surface with reflection factor 0.9. Then, a fraction of photons that reached the aperture Shmidt diaphragm of the telescope was traced through the optical system. Starlight and night sky background level was chosen to be $3*10^{12}$ photon/(m^2*s*ster). Background photons were traced through the optical system in the same manner as EAS Cherenkov photons. At last step the photons that hit sensitive PMT photocathodes were recorded in an array. The latter represents the so-called "detector-response event". In this section we discuss the properties of response events from proton and helium primaries. The sample of EAS is the same as in section II.

To measure the spectra of PCR we performed a reconstruction of shower parameters (θ_0, ϕ_0, x_0, y_0, E_0), here θ_0 and ϕ_0- zenith and azimuthal angles, respectively, x_0 and y_0- axis coordinates on the snow surface with respect to the center of the telescope's FOV; E_0 is the energy of a primary particle. First of all, average background was subtracted from each response event. The first two parameters (θ_0, ϕ_0) were obtained in the well-known plane-front shower approximation, while the second pair was defined with the help of a simple CLLD model function. Also it is possible to evaluate the primary particle energy, E_0. On concrete details of shower parameters evaluation method see [12]. We were able to build histograms of errors resulting from the above procedure. For instance, histogram for θ determination error is plotted in Fig. 4. Yet the shape of the error distribution is not strictly Gaussian, let us cite 67 % confidence levels for primary parameters determination: $\approx 1.5^o$ for θ_0, about 15 m for axis location error σ=

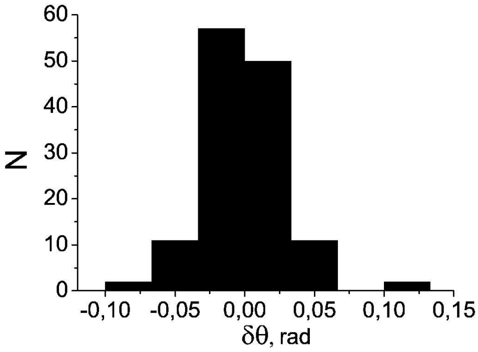

Fig. 4: Zenith angle θ determination error

$\sqrt{x_0 * x_0 + y_0 * y_0}$, and about 30 % for E_0. Error of ϕ_0 determination is about 5-10 degrees for showers with $\theta_0 \approx 8-12$ degrees. Error of ϕ_0 rises while θ_0 falls. As the last step of the event reconstruction, proton selection criteria were built in the following way. Numerator of (1) was replaced by the sum of signals in detectors, which centers are at distance $R \geq r_1$ and $R \leq r_2$ from the axis. Denominator on the equation was changed in the same way, but with parameters r_3 and r_4. It is reasonable to assign values to four parameters r_i, i= 1-4 to be multiples of the distance between the fields of view (FOV) of nearest PMTs (67 m).

Though we used not optimal primary parameter evaluation procedure it was shown that the cited primary parameter determination accuracies are sufficient to select about 10 % of primary proton events (Fig. 3). Plotted in the figure are the same histograms as in the previous figures, but the criteria are made for the artifical EAS images involving fluctuations, shower parameters reconstruction uncertainties and background effects. We set axes of all showers to be in the center of mass of the triangle with corners in centers of FOVs of PMTs with numbers 0,1,2. This is obviously the hardest case for proton selection for a shower with axis near the center of telescope's FOV. (0,67,67,134) was proven to be the best criteria to select proton-initiated EAS, since EAS signal fluctuations rise rapidly with the distance from the axis. Criteria described above allow to select about 10 % for the case of 10 PeV sample (Fig. 3, left) and about 15 % for the case of 30 PeV sample (Fig. 3, right). Axis position is also determined by the central ($R \leq 150m$ from axis) CLLD part, so all cited selection probabilities hold for distance from the center of FOV $R \leq 250m$. One can see that the main influence on criteria parameters (r_i, i= 1-4) and, in fact, on ϵ exert the signal fluctuations and the starlight contamination, since optimal criterion for 10 PeV events lies in the central ($R \leq 150m$) region of CLLD. Axis determination error is of less effect on primary proton selection criteria power.

VI. Conclusions

As a result of full Monte-Carlo simulations of EAS samples with energies 10 PeV and 30 PeV with two different nuclei-nuclei interaction routines QGSJET-I and QGSJET-II several criteria for selection of certain fraction of primary cosmic ray proton events with full supression of heavier nuclei were built. We also evaluated the fraction of selected proton events. It was shown that a selection criterion $\eta(r_1, r_2, r_3, r_4)$ may be constructed in such a manner that the proton selection threshold has a weak dependence on the interaction model (for example, η_0 criterion). All criteria considered in this paper are based on integrals over different CLLD areas. It was shown that the sensitivity to primary particle mass decreases only slightly while the area of integration expands. Event images close to reality were constructed with account of starlight background and EAS signal fluctuations. Reconstruction of such ”real” events shows that even with virtually all statistical uncertainties, which we may face, applied, the telescope is still capable to select about 10 % of primary proton events.

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References

[1] Y. Tsunesada, *et al.* (BASJE Collaboration), *Proc 30th ICRC (Merida), 4, (2007), 127*
[2] T. Antoni, *et al.* (KASKADE Collaboration), *Astropart. Phys. 24, (2005), 1*
[3] N. N. Kalmykov, *et al.* , *Nucl. Phys. B 52 (1997), 17*
[4] J. W. Fowler, *et al.* , *Astropart. Phys., 15, (2000), 49*
[5] A. E. Chudakov, *Trudy conf. po cosm. lucham (in Russian), (1972), 69*
[6] D. Heck, *et al.* , *Forschungszentrum Karlsruhe Report FZKA 6019 (1998)*
[7] H. C. Fesefeldt, *Technical Report No. PITHA 85-02 RWTH (1985)*
[8] S. Ostapchenko, *Nucl. Phys. Proc. Suppl. B151 (2006), 143*
[9] A. M. Anokhina, *et al.* , *Proc. 30th ICRC (Merida), 5, (2007), 945*
[10] R. A. Antonov, *et al.* , *Radiation Physics and Chemistry 75, (2006), 887*
[11] M. Born, E. Wolf, *Principles of Optics, Pergamon Press (1968)*
[12] R. A. Antonov, *et al.* , *Proc. 28th ICRC (Tsukuba),2, (2003), 981*