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# Studying the Possibility of Separation of Primary Nuclei Groups in the Energy Interval 300 TeV – 10 PeV in the **TAIGA-HiSCORE** Experiment

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Abstract. We proposed a method of discrimination between light (p+He) and heavy (C+Fe) groups of primary nuclei. It's based on parametric analysis of lateral distribution of Cherenkov light in the atmosphere with approximation by the 'knee-like' fitting function, proposed and studied earlier. Two parameters most sensitive to the depth of shower maximum were revealed and used for analysis of the bulk of experimental data obtained in the TAIGA-HiSCORE experiment in the energy range 300-3000 TeV for various incident angles of particles. It is shown that the method allows estimating the contribution of light and heavy groups of primary nuclei. In the interval 300-3000 TeV we do not see a rapid decrease of the light component flux, as it was seen in the ARGO-YBJ experiment. This result will be refined after a more detailed analysis.

#### 1. Introduction

The well-known problem of chemical composition in the range 300–3000 TeV below the knee in the cosmic-ray energy spectrum has not been solved yet due to the lack of statistics collected from direct experiment. For most extensive air shower (EAS) experiments energies lower than 1000 TeV are below threshold. In the TAIGA-HiSCORE experiment [1] due to the lower detection threshold (~100-200 TeV) we can try to distinguish showers from light and heavy groups of particles [2]. The lateral distribution functions (LDF) of Cherenkov light Q(R), emitted by EAS originated from high energy primary particles (gamma rays, protons, nuclei), can be measured in details for millions of individual events with good accuracy, if the number of hit stations is sufficiently large (greater than 7) [2]. As it was well known, a steepness of the LDF is sensitive to the depth of EAS maximum and as a result to the sort of primary particles. In this work we continue the development of a parametric method of discrimination between heavy and light groups of nuclei using the 'knee-like' fitting function of the LDF, which were proposed in [3, 4]. The experimental uncertainties, caused by the procedure of measurement, were investigated and included in Monte Carlo simulations [2]. For preliminary testing of the method, we used data (several days of exposition from season 2016–2017 observation) obtained in the TAIGA-HiSCORE experiment [1].

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### 2. Parameters of the LDF sensitive to the sort of primary particles

We developed the function, called the 'knee-like approximation', and studied its properties and applications on CORSIKA [5] simulated events in [3, 4]. It is a function of the distance to shower core R, Q(R), whereas earlier [6] this function was used for describing the knee in the CR spectrum, F(E). It depends on five parameters C,  $\gamma_1$ ,  $\gamma_2$ ,  $R_0$ , and  $\alpha$ :

$$F_{\text{fitting}} = CR^{\gamma_1} (1 + (R/R_0)^{\alpha})^{\gamma_2/\alpha}$$
(1)

where C,  $\gamma_1$ ,  $\gamma_2$ ,  $R_0$ , and  $\alpha$  are parameters of the Cherenkov light LDF,  $R_0$  is the knee position,  $\gamma_1$  is the slope of the LDF below the knee,  $\gamma_2+\gamma_1$  is the slope of the LDF above the knee, and parameter  $\alpha$  characterizes the sharpness of the knee.

We started this work using Monte Carlo simulated data and have revealed that the most sensitive parameter to the sort of primary nuclei is  $R_0$ , but it also slightly depends on energy. For the energy 300 TeV the practically linear dependence on the distance to the shower maximum:

$$dX_{max} = (X_{max} - X_{obs})/\cos\theta$$

is shown in figure 1 for four sorts of primary particles: p, He, C, Fe.



**Figure 1.** Dependence of parameter  $R_0$  (from the function (1)) on the distance to the shower maximum for primary p, He, C, Fe.

We present the distribution of the parameter  $R_0$  for two groups of showers, simulated by the CORSIKA code: the sample of light nuclei consisted of 50% protons + 50% helium nuclei, and the sample of heavy nuclei: 50% CO +50% Fe.  $R_0$  strictly depends on  $X_{max}$ . In figure 2 it's seen that using the  $R_0$  dependence one can try to separate light (p+He) and heavy (C+Fe) nuclei in Monte Carlo simulations.



**Figure 2.** Distribution of the parameter  $R_0$  for p+He (left curve) and C+Fe (right) for the energy range 300–1000 TeV and zenith angles 0–25°. MC simulations without experimental uncertainties.

However, our further study showed that the accuracy of  $R_0$  estimation depends on the accuracy of Q(R) measurement; hence, additional fluctuations of Q had to be studied and taken into account in MC simulations. We use the experimental sample of showers accumulated in the TAIGA-HiSCORE experiment during one day of 2017. The TAIGA-HiSCORE array is under development and in the season 2016–2017 it consisted of 28 stations. Each station contains 4 PMTs equipped with light-collecting Winston cones with the observation solid angle 0.6 sr and a light collection area 0.5 m<sup>2</sup>, stations are distributed over the area of 0.25 km<sup>2</sup> with the step 106 m. The *i*-th optical station records the maximum amplitude  $A_i$ , arrival time  $T_i$ , and a total number of Cherenkov photons  $Q_i$ , obtained as the integral of the pulse. Only events with more than 12 triggered stations were considered for detailed analysis of the experimental LDF shape.

The standard procedure of the core position and arrival direction ( $\theta$ ,  $\varphi$ ) reconstruction was applied for data analysis [7]. Thus, for each station we calculated the distance to the shower core, *R* (in the shower plane); obtained the experimental LDF,  $Q_{\exp}(R)$ ; approximated it by the 'knee-like' fitting function (1) and estimated 4 parameters:  $R_0$ ,  $\gamma_1$ ,  $\gamma_2$ ,  $\alpha$ . In the first stage we studied the distribution of the  $Q_{\exp}$  deviations from the fitting function value,  $Q_{\text{fit}}$ . Distributions of the value:

$$d \lg Q = \lg Q_{exp} - \lg Q_{fit}$$

were analyzed for three narrow intervals of Q. Our study showed that for narrow intervals of Q a distribution F(dlgQ) can be successfully approximated by the Gaussian normal function. However, its standard deviation, sigma, strongly decreases with increase of Q (as it was expected). The estimated experimental distortion function was added to MC simulations.

#### 3. Parametric approach to nuclei separation

After modelling the experimental uncertainties, the difference between  $R_0$  values for the two groups of particles has narrowed. For that reason, one more parameter,  $\gamma_1$ , in fitting function (1) was added to the analysis. It reflects the steepness of the LDF at the centre of the Cherenkov light spot and it is also sensitive to the sort of primary particles.



**Figure 3.** Correlation of the parameters  $\gamma_1$  and  $R_0$  for light (light circles) and heavy (dark circles) samples of nuclei with the energy 300–1000 TeV and zenith angles 0–25°. *X*2, *Y*2 – a new coordinate system for the combined parameters.

As it is seen from the two-parametric plot  $\gamma_1$ – $R_0$  in figure 3, there are two areas with a noticeable difference between two samples, light and heavy nuclei. To stress this difference we introduced a new coordinate system X2, Y2, where X2 is a combined parameter:

$$X2 = \gamma_1 - 0.013R_0, \tag{2}$$

and the lines correspond to different bins k:

$$X2(k) = -0.2 + 0.1 \cdot (k-1) - 0.013R_0$$
(3)

The combined parameter X2 distribution is shown in figure 4 for three energy intervals: around 300 TeV (200–500 TeV), around 1 PeV (800–1300 TeV), and 3–10 PeV. Black curves with errors represent experimental groups of events; histogram bars demonstrate MC simulations for light (p+He) and heavy (C+Fe) nuclei; all showers having zenith angles  $25-36^{\circ}$ . For all three intervals the difference in MC simulation between the two groups is clearly seen.

The width of the experimental distribution became noticeably narrower for the energy greater than 3 PeV, whereas for the first two energy intervals the experimental distributions cover the full region from p to Fe nuclei. In this region the ARGO-YBJ experiment reported the observation of the p+He spectrum deviation from a single power law at energies lower than 1 PeV, which looks like a new sharp knee in the p+He component [8].

For the third energy interval (beyond the main knee in the cosmic ray spectrum) the experimental curve cannot cover the region occupied by proton-induced showers. As it is widely accepted, the origin of the knee is connected with a sharp cutoff of the proton spectrum at ~3 PeV and subsequent cutoff of other nuclei with the same rigidity. Hence, our method also confirms this conclusion and indicates a sensitivity to the primary nuclei content.

The accuracy of the method is not high as is well seen in figure 5, where the  $\chi^2$  value is presented depending on the ratio of primary p+He group among primary particles. The  $\chi^2$  value was calculated for three intervals of primary energy for the experimental and MC simulation curves presented in figure 4. One can also notice a sharp change of the  $\chi^2$  dependence on the ratio of light group of particles in the interval 4–10 PeV in comparison with that dependence around 300 TeV and around 1 PeV.



**Figure 4.** The combined parameter X2 (2) distribution for three energy intervals; *k* is bin number (3). Black curves with errors – experimental groups of events. Histogram bars – MC simulations for light (p+He) and heavy (C+Fe) nuclei.



Figure 5. The  $\chi^2$  value depending on the ratio of primary p+He group among primary particles. The  $\chi^2$  was calculated for three intervals of primary energy for the experimental and MC curves presented in figure 4.

### 4. Conclusion

We proposed a method of discrimination between two groups of primary nuclei, light (p+He) and heavy (C+Fe), using two-parametric analysis of the lateral distribution of the Cherenkov light in the atmosphere. The LDF is approximated by the 'knee-like' fitting function (1), which was developed earlier [3, 4]. We used a small test sample of experimental events detected in the HiSCORE-TAIGA observatory in the energy range 300–10000 TeV and studied a sensitivity of the method by way of comparison of Monte-Carlo simulation and experiment. Our method does not reveal a rapid decrease of the light component flux up to 3 PeV in contrast to the ARGO–YBJ experiment [8], but indicates some decrease of p+He component's contribution beyond 3 PeV, thereby demonstrating the applicability of the method to mass groups study. To confirm this result, test sample size can be increased by several orders of magnitude; that will be done in the nearest future.

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