Study of lateral distribution function of charged particles in EAS at the knee region

V.B. Petkov*, **J. Sarkamo**†, **T. Raiha**†, **D.D. Dzhappuev*** **and A.S. Lidvansky***

*Institute for Nuclear Research of RAS, Russia
†University of Oulu, Centre for Underground Physics in Pyhajarvi, Finland

***Abstract*. The high-resolution measurements of the lateral distribution function (LDF) of charged EAS particles have been performed with the Carpet EAS array. The measurements were carried out for a number of shower size ranges including the knee position. We have also simulated the development of EAS in the Earth's atmosphere by means of the CORSIKA code with QGSJET 01C hadronic interaction model. The simulations have been carried out for primary protons and iron nuclei. The calculated LDF's are compared with the experimental ones.**

***Keywords*: EAS, lateral distribution, primary composition**

I. Introduction

A study of the primary composition in the PeV domain and above can be currently carried out by means of extensive air shower (EAS) measurements only. But the interpretation of these measurements requires a comparison with EAS simulations in the atmosphere. In turn, the calculation results depend on hadronic interaction models. The main problem is the extrapolation of these models into kinematical and energy regions still unexplored by present-day collider experiments. So, the measurements of different EAS components are now used for both studying the primary composition and testing interaction models [1], [2], [3], [4].

The precision measurements of the LDF's of charged EAS particles for a number of shower size ranges were performed in the past with the Carpet EAS array. The EAS development in the atmosphere have been now simulated by means of the CORSIKA code with QGSJET 01C hadronic interaction model for primary protons and iron nuclei. The experimental LDF's are compared with simulated ones. The first results of this data analysis are presented.

II. Experiment

The "Carpet" EAS array of the Baksan Neutrino Observatory INR RAS is located at the altitude of 1700 m a.s.l. (atmospheric depth $840\ g/cm^2$) [5]. Geographic coordinates: latitude - $43.28°$ N and longitude - $42.69°$ E. In this study we use two parts of this array: central part of the array (the Carpet proper) and six remote points (Fig.1). The central part of the array (the Carpet proper) consists of 400 individual liquid scintillation detectors of 0.5 m^2 area each. Six remote points have 18 scintillation detectors each. The signals from the latter are used for timing and EAS's arrival direction reconstruction. The range of energy deposition measurements for an individual detector is $10-5000$ relativistic particles (r.p.). One r.p. is the most probable energy release produced by a single cosmic ray particle crossing the detector. For our liquid scintillation detectors one r.p. is 50 MeV.

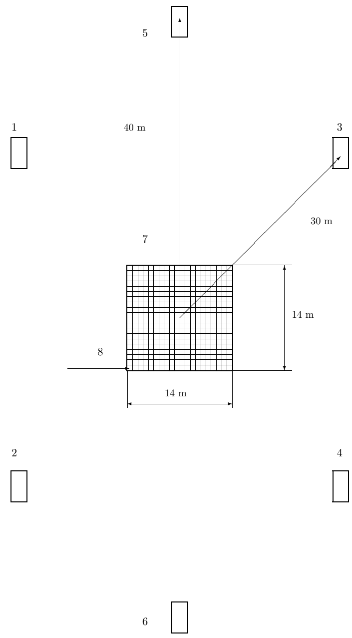

Fig. 1: Carpet EAS array. 1-6 - remote points; 7 - Carpet; 8 - individual detector.

The EASs with axes well inside the Carpet were selected, the range of zenith angles being $0° - 30°$. Due to large continuous area of the Carpet and relatively small areas of individual detectors the accuracy of axis location for such events is $\sim\ 0.2$ m. This gives a possibility to perform high-resolution measurements of the lateral distribution function (LDF) and its fluctuations near the EAS core [6]. The transition effects were taken into

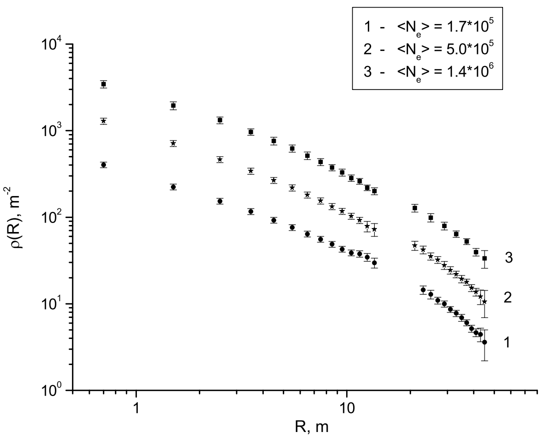

Fig. 2: Experimental dependencies of charged particles density on distance from EAS core for three shower size ranges.

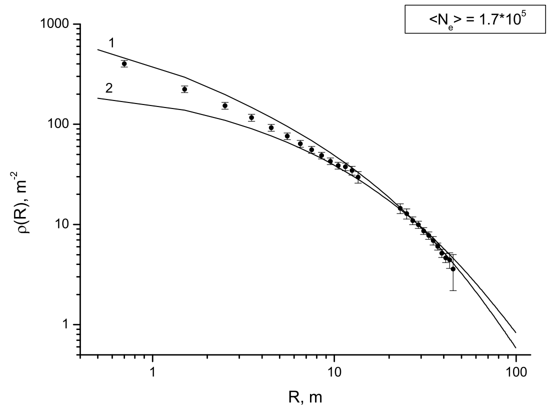

Fig. 3: Experimental data in comparison with simulated ones for shower size interval $(1.5 - 2.0) \cdot 10^5$. Points - experiment, lines: 1 - primary protons, 2 - primary iron nuclei.

consideration (both - roof effect and scintillator effect), therefore, the lateral distribution function of charged particles was measured in the experiment. Transition effects measurements were carried out by means of Geiger counters. Also, these measurements were confirmed by means of Monte-Carlo simulations with energy cutoff 2 MeV. Both are in satisfactory agreement [7], [8]. The total number of charged particles N_e for each EAS was obtained by fitting with NKG-function $s = 1.0$ and $R_M = 94$ m the remote points data (distance range 20 m - 50 m, subject to zenith angle). This can be done owing to the fact that the NKG functions with different age parameters s intersect each other in this distance range.

The average LDF's have been measured for three shower size intervals: $N_e \in (1.5 - 2.0) \cdot 10^5$, $N_e \geq 2.0 \cdot 10^5$ and $N_e \geq 8.0 \cdot 10^5$ (Fig.2). The corresponding average values of the shower size are $1.7 \cdot 10^5$, $5.0 \cdot 10^5$ and $1.4 \cdot 10^6$.

III. Calculations

The development of EAS in the Earth's atmosphere have been simulated by means of the CORSIKA code (version 6720) [9]. The QGSJET 01C and GHEISHA 2002d were used as the high and low energy hadronic interaction models. The simulations were carried out for primary protons and iron nuclei. The zenith angles are distributed isotropically in the range 0 - 30 degrees. The simulation energy range was taken from 0.3 to 30 PeV, corresponding to the N_e-range of measurements. The spectral index -2.7 was used and due to steeply falling spectrum the simulations were split into several primary energy intervals with similar statistics. Weighting of results was used to generate continous spectrum over all energy range.

The reconstruction procedure for each simulated shower was done by the following scenario:

1) the axis direction and position are assumed to be known without errors;
2) charged particles are counted and the density distribution (in shower plane) is tabulated;
3) only the densities from distance range $20 - 50$ m are used for the shower size reconstruction;
4) the shower size is derived by the NKG-function fitting with $s = 1.0$ and $R_M = 94$ m.

Each shower tabulated density distribution is ρ_{ijk} with shower label i, shower size interval j and energy interval k. The average simulated LDF for each shower size interval, $\rho_j(r)$, was then constructed as the weighted average of individual showers:

$$\bar{\rho}_j(r) = \frac{\sum_k \left(\frac{W_{jk}}{n_{jk}} \times \sum_{i=1}^{n_{jk}} \rho_{ijk} \right)}{\sum_k W_{jk}} \qquad (1)$$

where n_{jk} is the number of showers from energy interval k contributing to shower size interval j, W_{jk} is a weight which takes into account both the steeply falling energy spectrum and shower size distributions. To generate spectral index -3.1, reweighting of simulations according to energy was used.

IV. Results and discussion

The experimental data are compared with simulated ones for each shower size interval. For the size interval $(1.5 - 2.0) \cdot 10^5$ experimental densities lie between simulated ones for the primary protons and primary iron nuclei (Fig. 3), in a reasonable agreement with expectation. But for the other intervals, especially for $N_e \geq 8.0 \cdot 10^5$, a number of experimental points lie below simulated ones for the primary iron nuclei (see Fig. 4 and Fig. 5). The knee at primary energy 3.16 PeV per nucleus have a small impact on results (see dashed lines in these figures).

Discrepancies between experimental data and calculation results can have a number of reasons. Firstly, it may be due to a simplified reconstruction procedure of simulated showers as compared with experimental ones. So, we plan to include array response in simulations and to use the same reconstruction procedure.

Secondly, it may be due to an influence of hadronic interaction models on simulated showers. We used GHEISHA 2002 as low-energy interaction model. But there are some problems with this model and it is now recommended instead of this model to use FLUKA [10].

V. Conclusion

The high-precision measurement of the LDF of charged particles near the shower core gives additional information about EAS. This information can be used in the multi-component analysis to make conclusions about the composition of the primary cosmic rays [11].

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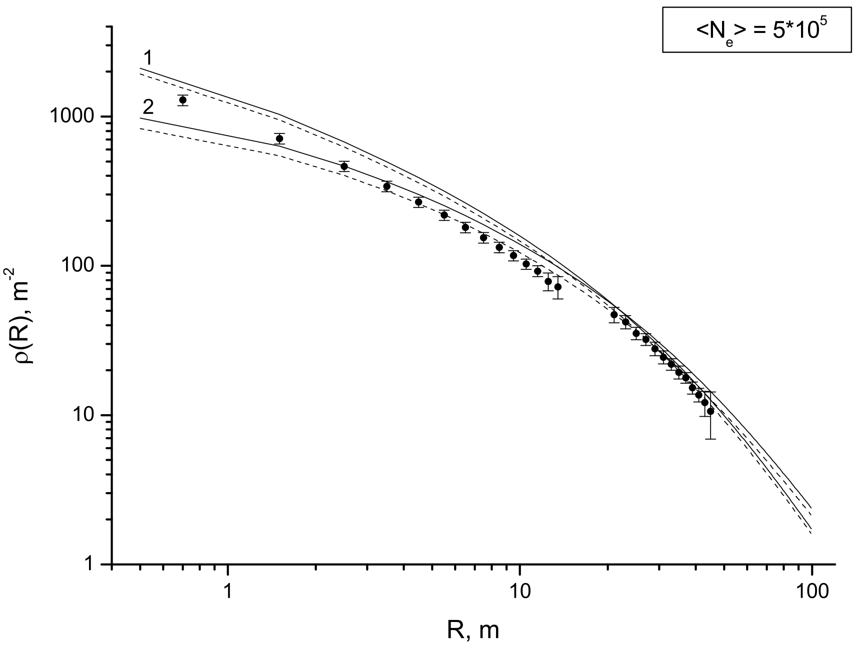

Fig. 4: Experimental data in comparison with simulated ones for $N_e \geq 2.0 \cdot 10^5$. Points - experiment, lines: 1 - primary protons, 2 - primary iron nuclei. Solid lines corresponds to primary spectrum with spectral index $\gamma = -2.7$. Dashed lines corresponds to primary spectrum with the knee: $\gamma = -2.7$ for $E_0 \leq 3.16$ PeV and $\gamma = -3.1$ for $E_0 > 3.16$ PeV.

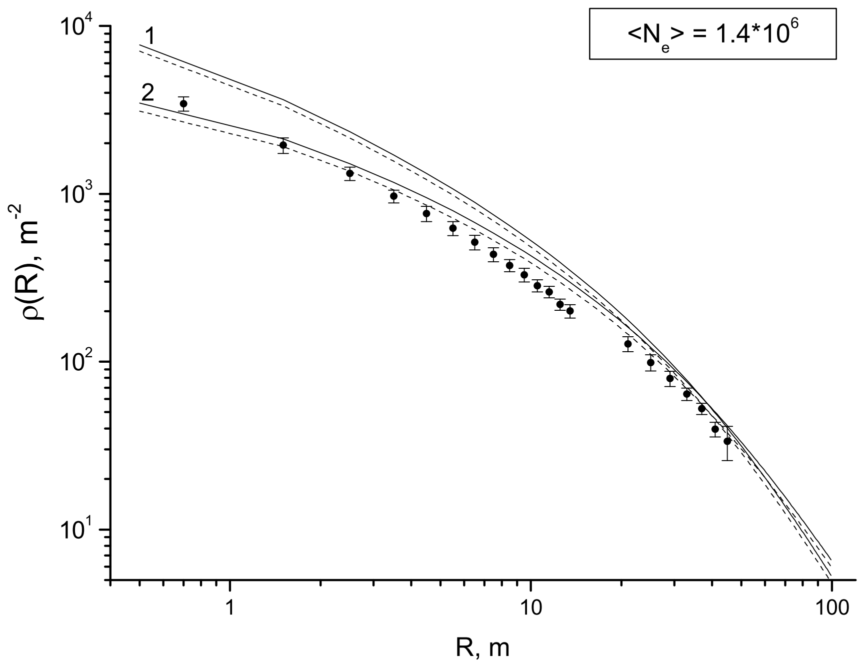

Fig. 5: Experimental data in comparison with simulated ones for $N_e \geq 8.0 \cdot 10^5$. Points - experiment, lines: 1 - primary protons, 2 - primary iron nuclei. Solid lines corresponds to primary spectrum with spectral index $\gamma = -2.7$. Dashed lines corresponds to primary spectrum with the knee: $\gamma = -2.7$ for $E_0 \leq 3.16$ PeV and $\gamma = -3.1$ for $E_0 > 3.16$ PeV.