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Study of the primary spectrum and composition around the knee at the Andyrchy-BUST experiment

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Abstract. The experimental data of the Andyrchy-BUST experiment are presented. The three types of experimental data, taken in our experiment, have been analyzed: high energy muon number spectrum, EAS size spectrum and dependence of the mean number of high energy muons on EAS size. Joint analysis of these experimental data have been used for both studying the primary composition and testing interaction models.

1 Introduction

In the range of primary energies of $10^{14} - 10^{15}$ eV per nucleus, direct methods for studying the energy spectrum and nuclear composition of primary cosmic rays become inefficient because of a decrease in the flux of primary particles with an increase in their energy. Therefore, at these and, of course, higher energies, indirect methods based on simultaneous measurement of the characteristics of different components of extensive air showers (EASs), initiated by the primary particle in the atmosphere, are used. The interpretation of these measurements requires their comparison with EAS simulations in the atmosphere. In turn, the calculation results depend on the hadronic interaction models. But it is widely known that none of the present interaction models can completely describe a full set of experimental data for cosmic rays. Joint analysis of the various characteristics of different EAS components measured in the same experiment can be used for both studying the primary composition and testing interaction models (Apel et al., 2007; Garyaka et al., 2008). At the Andyrchy-BUST experiment the electromagnetic and high energy muon components are measured. The electromagnetic component in our experiment is measured using the "Andyrchy" EAS array (Petkov et al., 2006). High energy muon component (with 230 GeV threshold energy of muons) is measured using the Baksan Underground Scintillation Telescope (BUST) (Alekseev et al., 1998). The location of the "Andyrchy" right above the BUST gives us a possibility for simultaneous measurements of both EAS components.

In this paper three types of experimental data are analyzed: muon number spectrum, EAS size spectrum and correlation between muon number and EAS size simultaneously measured. Integral muon number spectrum (Petkov et al., 2008) has been measured using the Baksan Underground Scintillation Telescope (BUST). The EAS size spectrum (Chudakov et al., 1997a) has been measured using the "Andyrchy" EAS array. The dependence of the mean number of high energy muons on EAS size (Chudakov et al., 1997b; Petkov et al., 2003) has been measured by simultaneous operation of both devices.

2 Experimental data

2.1 EAS size spectrum

The standard definition of the shower size N_e is the total number of the charged particles (mainly $e^{\pm}$) at the level of observations. As a scintillation detector measures the energy deposition, and not the number of particles, the reconstruction of shower parameters is performed in units of relativistic particles. One relativistic particle (r.p.) is the most probable energy deposition from a single cosmic ray particle, for our detector it is 10.6 MeV (Petkov et al., 2006). The measured size $N_{r.p.}$ is the total energy deposition in allegedly continuous infinite detector. The shower size $N_{r.p.}$, the slope of the lateral distribution function and the core location are determined by a χ^2-like method, in which the logarithm of the energy deposition in each detector is compared with the one expected from the NKG lateral distribution function

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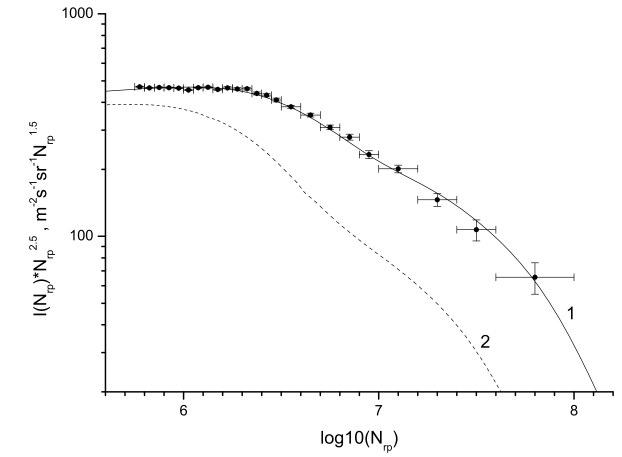

Fig. 1. EAS size spectrum. Points - experiment. Lines 1 and 2 are calculated spectra for the primary compositions 1 and 2, correspondingly.

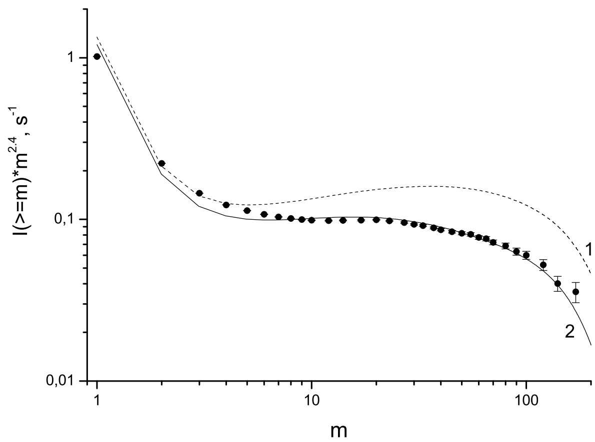

Fig. 2. Integral muon tracks number spectrum. Points - experiment. Lines 1 and 2 are calculated spectra for the primary compositions 1 and 2, correspondingly.

with $r_0 = 96$ m. This function reproduces with a good accuracy the experimental data (Chudakov et al., 1997a). In the present analysis next selection conditions were used: 1) $\sec\theta \leq 1.05$ (near vertical events); 2) ≥ 22 fired detectors; 3) ≥ 4 detectors with energy deposition $E_d \geq 10$ r.p. well inside the array; 4) reconstructed axes in central part of the array (the distance from the center is not larger than 50 m). The accuracy of reconstruction was calculated using data obtained from a simulation that includes the experimental dispersion. The size spectrum is reconstructed without distortions for showers with $5.75 \leq \lg N_{r.p.} \leq 8.0$ (Petkov et al., 2010). For these showers the accuracy of the $N_{r.p.}$ determination is better than 15% and the accuracy of the axis position determination is better than 5 m. Figure 1 shows the measured differential size spectrum taken during live time $1.297 \cdot 10^8$ s (1501.2 days), in r.p. units. The steepening of the spectrum is observed at $\lg N_{r.p.} \approx 6.35$.

2.2 Muon number spectrum

Coordinates of hit BUST detectors are used to reconstruct tracks of muons crossing the telescope. Generally the number of muon tracks m differs from the number of muons m_μ in the group (Petkov et al., 2008). In order to avoid additional uncertainty we use only experimental muon tracks number spectrum for study of primary composition. The conversion of the number of muons to the number of reconstructed muon tracks is included in the calculations. The integral spectrum of the number of muon tracks for near vertical directions ($\theta \leq 20°$, effective muon threshold energy is 230 GeV) was measured for $m = 1-250$ (Fig. 2). This spectrum was obtained using two BUST data sets. The first data set has been taken during 2001 – 2004 (live time 3.3 years) and contains information about all the BUST events. The second data set has been taken during 1984 – 1995 (live time 9.8 years) and contains information about BUST events where 100 and more detectors were fired. The latter condition corresponds to 20 or more muons crossing BUST for near vertical directions. It is to be noted that owing to muon tracks number saturation there is no sense to analyze this spectrum for $m > 170$, where the relation m_μ/m becomes more than 1.5.

2.3 The mean number of muons vs. EAS size (Fig. 3)

The size, axis position and the EAS arrival direction are determined using the Andyrchy array data; the BUST data are used to determine the number of muons crossing BUST. The underground telescope measures only a part of the total number of muons in EAS and the uncertainty in the determination of the EAS axis position at the BUST level is comparable with the size of the BUST. Therefore only mean number of muons as function of EAS size can be measured in our experiment (Chudakov et al., 1997b; Petkov et al., 2003, 2010).

3 Calculations

The development of EASs in the Earth's atmosphere have been simulated by means of the CORSIKA code (version 6.900) (Heck et al., 1998). The QGSJetII-03 and Fluka were used as the high and low energy hadronic interaction models. The CORSIKA output files were used then as input files for AndyrDet code, which performs a detector response simulation. The results of the simulations were summarized as parametrization functions of the EAS characteristics, that then was used for calculations of the observables (integral muon number spectrum, EAS size spectrum, $\overline{N}_\mu(N_{rp})$ dependence).

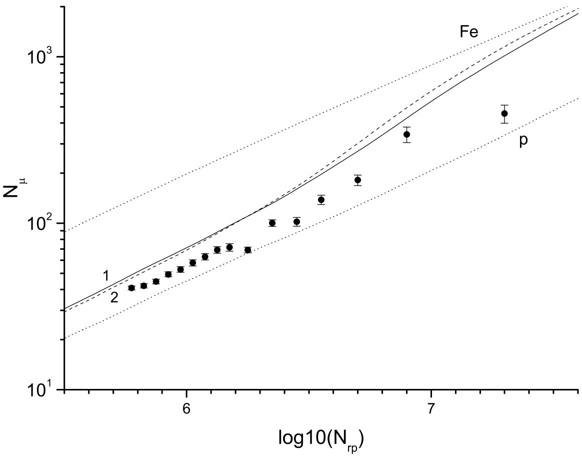

Fig. 3. $\overline{N}_\mu(N_{rp})$ dependence. Points - experiment. Solid line 1 and dashed line 2 are calculated dependencies for the primary compositions 1 and 2, correspondingly. The dotted lines are calculated dependencies for pure protons and iron nuclei.

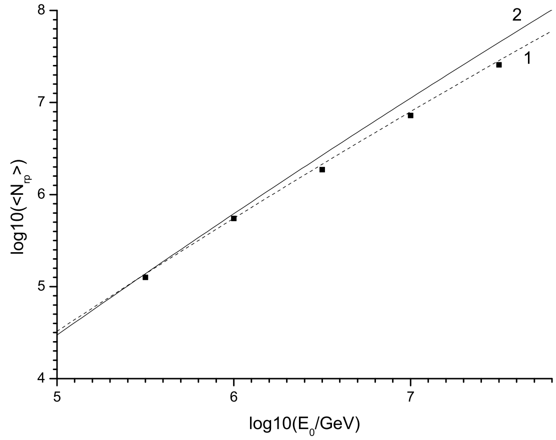

Fig. 4. Dependence of the mean EAS size on energy of primary protons. Points - CORSIKA results. Line 1 - fit to the CORSIKA results. Line 2 - changed dependence $\overline{N}_{rp}(E_0)$.

The integral muon number spectrum in BUST was calculated numerically in the same way as in Petkov et al. (2008). The EAS size spectrum can be presented as:

$$I(N_{r.p.}) = \sum_A \int_0^\infty \frac{dF_A(E_0)}{dE_0} W_A(E_0, N_{r.p.}) dE_0 \qquad (1)$$

where $dF_A(E_0)/dE_0$ is the energy spectrum of the primary nuclei and $W_A(E_0, N_{r.p.})$ is the probability for primary nucleus with energy E_0 to produce EAS with size $N_{r.p.}$ at observation level.

The dependence of the mean number of high energy muons on EAS size was calculated taking into account the energy spectra of the primaries and anticorrelation between the number of high energy muons in EAS and EAS size at fixed primary energy. The calculations of the observables were performed for two composition models with five groups of primary nuclei (see Table 1 and Table 2 in Petkov et al., 2010). Energy spectrum of every primary group is a power law with rigidity dependent knee $E_{kz} = E_{kp} \cdot Z$ (Ter-Antonyan, 2007):

$$\frac{dF_z(E_0)}{dE_0} = {F_z}^0 \cdot {E_0}^{-\gamma_z} \left[1 + \left(\frac{E_0}{E_{kz}}\right)^{\epsilon_c}\right]^{\frac{\gamma_z - \gamma_c}{\epsilon_c}} \qquad (2)$$

where E_0 is energy per particle and ${F_z}^0$ is absolute flux at 1 TeV per particle. The sharp knee was applied for both composition models: $\epsilon_c = 3.5$ and $\gamma_c = 5.2$. Both composition models do not give closest fit for the complete data set of direct measurements, but the data do not contradict these models.

For the first composition total flux at 1 TeV is $0.2677\,(\mathrm{m}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{TeV})^{-1}$ and protons knee position is $E_{kp} = 4 \cdot 10^3$ TeV. This composition gives a good fit for the EAS size spectrum (Fig. 1, line 1). But the muon number spectrum calculated for this composition is in contradiction with experiment (Fig. 2, line 1). For the second composition the protons knee position is $E_{kp} = 2 \cdot 10^3$ TeV and total flux at 1 TeV is $0.215\,(\mathrm{m}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{TeV})^{-1}$. This composition gives a satisfactory fit for the muon number spectrum (Fig. 2, line 2). But the EAS size spectrum calculated for this composition is in contradiction with experiment (Fig. 1, line 2). For both compositions the calculated $\overline{N}_\mu(N_{rp})$ dependences are very close to one another and both are in contradiction with experiment (Fig. 3). So, predictions from both considered mass composition models do not give satisfactory fits to all data set obtained from our measurements.

4 Discussion

Discrepancies between EAS size spectrum and muon data can be lessened to a considerable degree using two ways. The first one is to change muon production function (MPF, the dependence of the mean number of muons per EAS on energy) for muons with $E_\mu \geq 230$ GeV (Petkov et al., 2010). Thus changed MPF, that increases slower with energy increase in comparison with MPF fitting to the CORSIKA results, gives acceptable agreement between EAS size spectrum and muon data for the primary composition 1. But as high energy muon production is sensitive to average multiplicities of charged particle production in high energy collisions, the new data from the CERN LHC detectors might change models used in EAS simulations and predict new muon gain.

Another way is to change the dependence of the mean EAS size, $\overline{N}_{rp}(E_0)$, on energy of primary particles. The changed $\overline{N}_{rp}(E_0)$ for the primary protons is presented in Fig. 4 together with CORSIKA results. The EAS size spectrum

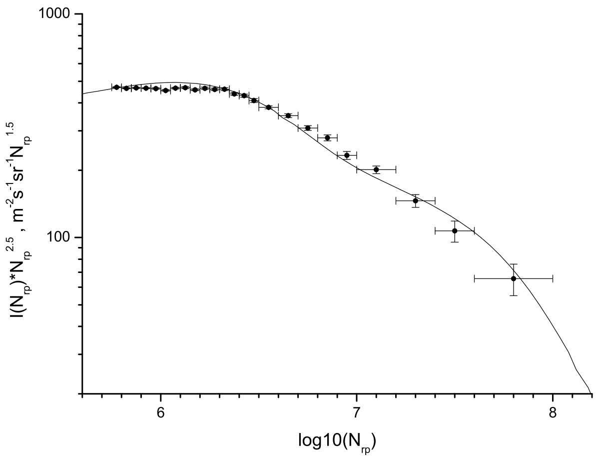

Fig. 5. EAS size spectrum. Points - experiment. Line is calculated spectrum for the primary composition 2 and changed dependence $\overline{N}_{rp}(E_0)$.

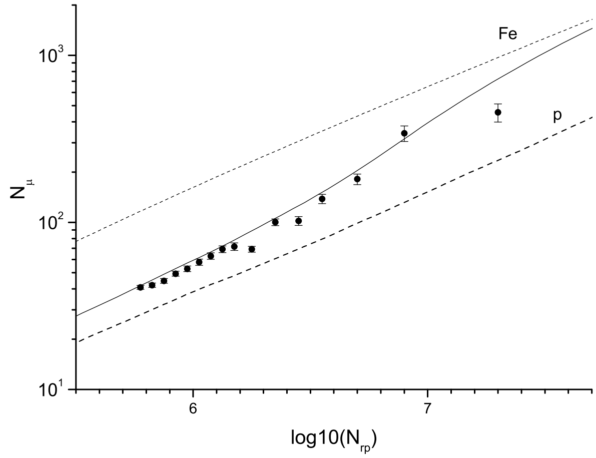

Fig. 6. $\overline{N}_{\mu}(N_{rp})$ dependence. Points - experiment. Solid line is calculated dependence for the second primary composition and changed $\overline{N}_{rp}(E_0)$. The dashed lines are calculated dependencies for pure protons and iron nuclei.

calculated for the second primary composition and changed $\overline{N}_{rp}(E_0)$ is shown in Fig. 5. The $\overline{N}_{\mu}(N_{rp})$ dependencies calculated using changed $\overline{N}_{rp}(E_0)$ are shown in Fig. 6. One can see that the dependencies calculated for the second primary composition and changed $\overline{N}_{rp}(E_0)$ gives acceptable fit to the experimental data.

5 Conclusions

Three types of experimental data taken in our experiment have been analyzed in this paper. CORSIKA code v.6.900, with QGSJetII-03 and Fluka as the high and low energy hadronic interaction models, has been used for EAS simulations. The discrepancies between EAS size spectrum and muon data can be lessened to a considerable degree by introducing changes, either related to MPF or to $\overline{N}_{rp}(E_0)$, in CORSIKA results. In any case the primary composition gets heavier across the knee.

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