The Andyrchy-BUST experiment: primary spectrum and composition around the knee

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Abstract. The main goal of the Andyrchy-BUST experiment is to study the primary cosmic rays spectrum and composition around the knee. The experimental data on the knee, as observed in the electromagnetic and high energy muon components, are presented. The electromagnetic component in our experiment is measured using the "Andyrchy" EAS array. High energy muon component (with 230 GeV threshold energy of muons) is measured using the Baksan Underground Scintillation Telescope (BUST). The location of the "Andyrchy" right above the BUST gives us a possibility for simultaneous measurements of both EAS components.

Keywords: EAS, primary spectrum, primary composition

I. 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), which are initiated by the primary particle in the atmosphere, are used. But 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. 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] - [7].

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 has been measured using the Baksan Underground Scintillation Telescope (BUST) [8]. The EAS size spectrum has been measured using the "Andyrchy" EAS array [9]. The dependence of the mean number of high energy muons on EAS size has been measured by simultaneous operation of both devices [10], [11].

II. FACILITIES

The "Andyrchy" EAS array is located on the slope of the Andyrchy mountain above BUST (43.3° N, 42.7° E) and consists of 37 plastic scintillation detectors. A plastic scintillator of the 5 cm thickness has an area of 1 m² and is viewed with a single PMT. The detectors are designed for both timing measurements (for EAS arrival direction) and evaluation of primary energy (via EAS core localization and determination of total number of particles in shower). The distance between the detectors is about 40 m in projection to the horizontal plane and the overall area of the installation is $5 \cdot 10^4$ m²; the solid angle at which the array is viewed from the BUST is 0.35 sr. The central detector of the array is above the
BUST's center at a vertical distance of about 360 m and at 2060 m above the sea level. The difference between the heights of the upper and lower rows of detectors is \( \sim 150 \) m.

The energy deposition measurement is performed in natural units, so called 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 \[12\]. The range of the energy deposition is from 0.5 r.p. (the threshold of the Charge-to-Time Converter) up to more than 1000 r.p.

Trigger formation and all measurements are performed in a registration room, which is placed near the center of the array (length of connection cables is up to 280 m). The shower trigger condition requires signals from 4 detectors within 3 microseconds. The trigger's rate is about 9 s\(^{-1}\). The array and its characteristics are described in more details in \[12\].

BUST \[13\] is a large device \(16.7 \times 16.7 \text{ m}^2\) area and 11.1 m height, located in a cave under mountain slope. The four vertical sides and four horizontal planes are completely covered with standard liquid scintillation detectors. The standard detector consists of an aluminium tank with \(0.7 \times 0.7 \times 0.3 \text{ m}^3\) dimensions and is filled with liquid scintillator on the base of white-spirit. Total number of the detectors is 3180. Every counter is viewed with one PMT. The construction of BUST allows one to reconstruct tracks of muons crossing the telescope. Coordinates of hit detectors is used as input information for muon group parameters determination. The telescope allows one to determine the number of passing muons, their coordinates (with 0.7 m accuracy) and the arrival direction (with 1.5 degree accuracy).

The coincidence trigger between "Andrychy" and BUST is produced when one or more muons crossing the telescope (\(\approx 12 \text{s}^{-1}\)) coincide with the shower trigger within 51.2 microseconds; the coincidence rate is about 0.1 s\(^{-1}\).

III. 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 (r.p.). 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 \(\chi^2\)-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

\[
\rho(r) = N_{r.p.} \frac{C(s)}{r_0^s} \left( \frac{r}{r_0} \right)^{(s-2)} \left( 1 + \frac{r}{r_0} \right)^{(s-4.5)}
\]

with \(r_0 = 96\) m. The NKG function reproduces with a good accuracy the experimental data \[9\].

In the present analysis, only the showers with:
1) \(\sec \theta \leq 1.05\) (near vertical events);
2) \(\geq 22\) fired detectors;
3) \(\geq 4\) 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) were taken into account.

The accuracy of reconstruction was calculated using data obtained from a simulation that includes the experimental dispersion. Figure 2 shows the reconstructed size spectrum together with the simulated one, the size spectrum is reconstructed without distortions for showers with \(5.75 \leq \log N_{r.p.} \leq 8.0\). 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 3 shows the measured differential size spectrum taken during live time 1.297\times 10^8\ s (1501.2

Fig. 2: Simulated and reconstructed size spectra.

Fig. 3: EAS size spectrum. Points - experiment. Lines 1 and 2 are calculated spectra for the primary compositions 1 and 2, correspondingly.
Fig. 4: Integral muon tracks number spectrum. Points - experiment. Lines 1 and 2 are calculated spectra for the primary compositions 1 and 2, correspondingly.

The steepening of the spectrum is observed at \( \lg N_{r.p.} \approx 6.35 \).

IV. 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 \( m_\mu \) in the group. In the case where the distance between muons is small enough (compared to the individual detector size) the number of reconstructed muon tracks is smaller than the number of muons in the group. Opposite effect is also present since interacting muons can produce particles which might increase the number of hit detectors, therefore the number of reconstructed muon tracks in such a case can be larger than the number of muons in the group. Furthermore there is some arbitrariness in muon track determination: for example, a track may cross two, three or four telescope planes and so on. Hence it is necessary to convert the number of reconstructed muon tracks to the number of muons in the group taking into account all mentioned effects. Conversion factors depend on muon lateral distribution function. Lateral distribution might depend on muon energy distribution in EAS and on primary nucleus energy (per nucleon) etc. 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 in such a case is calculated as

\[
\frac{m_\mu}{m} \leq 1.5.
\]

V. THE MEAN NUMBER OF MUONS VS. EAS SIZE

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. The mean number of muons in BUST is determined as follows. Events within a given range of \( N_{e} \) are grouped according to the distance to the BUST’s center with step \( \delta R = 10 \) m. For each group, the number of muons is

\[
M(R_i) = \frac{K_i}{K_i} \sum_{j=1}^{K_i} m_{ij}.
\]

where \( K_i = K(R_i) \) is the number of EAS in the \( i \)-th group, and \( m_{ij} \) is the total number of muons in the BUST in the \( i \)-th group for the \( j \)-th EAS.

Thus, the mean number of muons for a given range of \( N_{r.p.} \) can be written as

\[
\bar{\mu}(R_i) = \frac{M(R_i)}{K_i} = \frac{1}{K_i} \sum_{j=1}^{K_i} m_{ij}.
\]

The mean number of muons in a shower is then calculated as
TABLE I: Primary composition 1.

| Z     | 1   | 2   | 6-8 | 10-16 | 20-26 |
|-------|-----|-----|-----|-------|-------|
| $F_z^0$ ($m^2 \cdot sr \cdot TeV^{-1}$) | 0.12 | 0.056 | 0.03 | 0.035 | 0.0267 |
| $\gamma_z$ | 2.75 | 2.64 | 2.66 | 2.70 | 2.62 |

\[
\overline{N}_\mu = \frac{1}{S_t} \cdot \sum_i \overline{n}(R_i) \cdot S_r(R_i),
\]

(3)

where $S_t = 200 \text{ m}^2$ is the effective area of the telescope, $S_r(R_i)$ is the area of the ring of radius $R_i$ with $\delta R = 10 \text{ m}$.

The fraction of muons in the telescope $\Delta(R)$ was measured as a function of the distance $R$ between the center of the telescope and the EAS axis for a set of showers with a given value of $N_{r,p}$. This fraction for a given range of $N_{r,p}$ is defined by

\[
\Delta(R) = \frac{\overline{n}(R)}{\overline{N}_\mu(N_{r,p})},
\]

(4)

where $\overline{n}(R)$ is the mean number of muons in the telescope at the distance $R$, $\overline{N}_\mu(N_{r,p})$ is the mean number of muons in EAS. Because $\Delta(R)$ depends on the lateral distribution function (LDF) of high energy muons and BUST geometry only, LDF can be recovered from these measurements. Preliminary results on high energy muons’ LDF can be found in [14].

VI. CALCULATIONS

The development of EAS in the Earth’s atmosphere have been simulated by means of the CORSIKA code (version 6900) [15]. 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, $\overline{N}_\mu(N_{r,p})$ dependence). Vertically arriving CR particles were used as primary CR particles. Simulations were performed for nuclei with atomic number $A = 1, 4, 14, 28, 56$. Primary energy per particle $E_0$ was taken from the range $10^4 \text{ GeV} - 10^{7.5} \text{ GeV}$ with a step of 0.5 of energy decade.

The integral muon number spectrum in BUST was calculated numerically in the same way as in [8]. This calculation method needs only such characteristics of high energy muon component of EAS as: 1) $\overline{N}_\mu(E_0, A)$ - muon production function (MPF) or mean number of muons per EAS produced by nucleus with atomic number $A$ and primary energy $E_0$; 2) $f(r, E_0, A)$ - lateral distribution function (LDF); 3) $G(A, \overline{N}_\mu, N_p)$ - fluctuation function (FF).

Fig. 6: The number $N_\mu$ of high energy muons (with $E_{\text{min}} \geq 230 \text{ GeV}$) as function of $N_{r,p}$ for the different primary energies of the primary protons and iron nuclei.

The EAS size spectrum can be presented as:

\[
I(N_{r,p}) = \sum_A \int_0^\infty \frac{dF_A(E_0)}{dE_0} \cdot W_A(E_0, N_{r,p})dE_0
\]

(5)

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 taken 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 (Fig. 6). The calculations of the observables were performed for two composition models with five groups of primary nuclei. Energy spectrum of every primary group is a power law with rigidity dependent knee $E_{kp} = E_{kp} \cdot Z$:

\[
\frac{dF_z(E_0)}{dE_0} = F_z^0 \cdot E_0^{-\gamma_c} \left[ 1 + \left( \frac{E_0}{E_{kp}} \right)^{c} \right]^{-\frac{\gamma_c - 2}{c}}
\]

(6)

where $E_0$ is energy per particle and $F_z^0$ is absolute flux at 1 TeV per particle [16], [17]. The sharp knee was applied for both composition models: $c_c = 3.5$ 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. All-particle energy spectra for these composition are shown in Fig. 7 together with averaged spectrum from air shower experiments [17].
TABLE II: Primary composition 2.

|   | 1  | 2  | 6-8 | 10-16 | 20-26 |
|---|----|----|-----|-------|-------|
| $Z$ | 1  | 2  | 7.2 | 12.7  | 25.2  |
| $\bar{Z}$ | 1  | 4  | 14.4| 25.5  | 54.2  |
| $A$  | 4  | 4  | 0.102| 0.079 | 0.018 | 0.018 | 0.02 |
| $F_{Z}(m^2 s sr TeV)^{-1}$ | 2.77 | 2.65 | 2.70 | 2.70 | 2.64 |

Fig. 7: All-particle energy spectra: lines 1 and 2 - for compositions described in Tables 1 and 2, correspondingly. Points - averaged all-particle energy spectrum from air shower experiments [17].

The first composition is presented in Table 1, for this composition total flux at 1 TeV is $0.2677 \left(m^2 s sr TeV \right)^{-1}$ and protons knee position is $E_{kp} = 4 \cdot 10^3$ TeV. This composition gives a good fit for the EAS size spectrum (Fig. 3, line 1). But the muon number spectrum calculated for this composition is in contradiction with experiment (Fig. 4, line 1). For the second composition (Table 2) the protons knee position is $E_{kp} = 2 \cdot 10^3$ TeV and total flux at 1 TeV is $0.215 \left(m^2 s sr TeV \right)^{-1}$. This composition gives a satisfactory fit for the muon number spectrum (Fig. 4, line 2). But the EAS size spectrum calculated for this composition is in contradiction with experiment (Fig. 3, line 2). For both compositions the calculated $N_{\mu}(N_{rp})$ dependences are very close to one another and both are in contradiction with experiment (Fig. 5).

So, predictions from both considered mass composition models do not give satisfactory fits to all data set obtained from our measurements (see Fig. 3 and 4).

VII. HIGH ENERGY MUON PRODUCTION FUNCTION

Discrepancies between EAS size spectrum and muon data can be lessened to a considerable degree if we use another muon production function for muons with $E_{\mu} \geq 230$ GeV. The MPF can be expressed by next formula:

$$\overline{N}_{\mu}/A = b \left( \left( \frac{E_{\mu}}{A} \right)^{\alpha} - c \right)^{\beta} \quad (7)$$

Fit of the CORSIKA (QGSJetII-03) results was obtained for parameters: $b = 0.0018$, $c = 13.5$, $\alpha = 0.43$ and $\beta = 1.675$ (line 1 in Fig. 8). It gives asymptotic behavior for $\overline{N}_{\mu} \sim E_{0}^{0.720}$.

The agreement between EAS size spectrum and muon data can be obtained for MPF with parameters: $b = 0.0035$, $c = 14$, $\alpha = 0.42$ and $\beta = 1.54$ (line 2 in Fig. 8). The asymptotic behavior of the mean number of muons for this MPF is: $\overline{N}_{\mu} \sim E_{0}^{0.647}$. The integral muon number spectrum calculated for the first primary composition and both MPF’s is shown in Fig. 9.

The $\overline{N}_{\mu}(N_{rp})$ dependences calculated using changed...
MPF are in Fig. 10. One can see that the dependence calculated for the first primary composition and changed MPF gives acceptable fit with experimental data.

VIII. CONCLUSION

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, especially measured in one and the same experiment, can be used for both studying the primary composition and testing interaction models.

In this paper three types of experimental data, taken in our experiment, were analyzed: high energy \( (E_\mu \geq 230 \text{ GeV}) \) muon number spectrum, EAS size spectrum and dependence of the mean number of high energy muons on EAS size. CORSIKA code v.6900, with QGSJetII-03 and Fluka as the high and low energy hadronic interaction models, has been used for EAS simulations. As it was mentioned above, the calculations of these observables need only the following characteristics of EAS:

1) \( W_A(E_0, N_{r.p}, N_\mu) \) - the probability for primary nucleus with atomic number \( A \) and energy \( E_0 \) to produce EAS with size \( N_{r.p} \) and total number of high energy muons \( N_\mu \) at the observation level;

2) \( W_A(E_0, N_{r.p}) \) - the probability to produce EAS with size \( N_{r.p} \) at the observation level;

3) \( N_\mu(E_0, A) \) - high energy MPF;

4) \( G(A, N_\mu, N_\mu) \) - high energy muons fluctuation function;

5) \( f(r, E_0, A) \) - high energy muons LDF.

It should be noted that characteristics 2 - 4 can be derived from 1.

The analysis has shown that:

1) our experimental data can be brought into good enough agreement using changed MPF (Fig. 8);

2) in both cases the primary composition gets heavier across the knee.

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