EPJ Web of Conferences **52**, 09009 (2013)
DOI: 10.1051/epjconf/20135209009

Multiplicity spectrum of muon bundles and primary CR composition in the range 1 - 10000 TeV

V.B. Petkov[1,3,a], J.Szabelski[2,b], A.N. Gaponenko[1], and I. Alikhanov[1]

[1] *Institute for Nuclear Research of RAS, Moscow, Russia*
[2] *The National Centre for Nuclear Research, Lodz, Poland*
[3] *Institute Astronomy of RAS, Moscow, Russia*

Abstract. Multiplicity spectrum of muon bundles underground, with $E_\mu \geq few \times 100$ GeV, is an effective tool for study of primary Cosmic Ray spectrum and composition in wide range of the primary energies. In this paper we study integral muon number distribution measured at the Baksan Underground Scintillation Telescope (BUST). The analyzed range of the number of muon tracks crossing BUST (1 - 170) approximately corresponds to the primary energy range $1 - 10^4$ TeV. The analysis shows that non-power law primary spectra are preferable below the knee. Such a spectrum can be obtained as superposition of the basic power law primary spectrum and an additional component from nearby supernova remnant in the Galaxy.

1 Introduction

Despite of a number of experiments the study of muon bundles underground is an unappreciated method of investigation of the primary CR spectrum and composition. However, this method has a particular advantages which make it very useful for study of primary cosmic rays. First of all, this method gives a connection between direct measurements and EAS experiments. Direct (at satellites and balloons) measurements become unefficient at $\sim 10^{14}$ eV per nucleus because of a decrease in the flux of primary particles with an increase in their energy. Moreover, for energies $\geq 10^{13}$ eV there is an evident difference between primary spectra measured in various experiments. Most of the EAS measurements (with few exceptions) can measure primary energy from a $few \times 10^{14}$ eV and even higher. Because underground experiments begin with the energy of primary protons which is about 5 - 10 times greater than the muon threshold energy they have a good overlap with direct experiments. The range of primary energies depends on the range of registered muon multiplicity. For example, the BUST range of the number of muon tracks crossing telescope (1 - 170) approximately corresponds to the primary energy range $1 - 10^4$ TeV (fig. 1). It should be noted that the multiplicity spectrum of the muon bundles is very sensitive to the primary composition [1].

Most of the observed muons originate from particles produced in the central region of particle interaction. All models of particle production used in EAS simulations were well tuned in that region [2]. Therefore the characteristics of the EAS high energy muon component are practically the same for the different hadronic interaction models, so the analysis of the high energy muon bundles allows one to study the primary composition in a way almost independent of the interaction models.

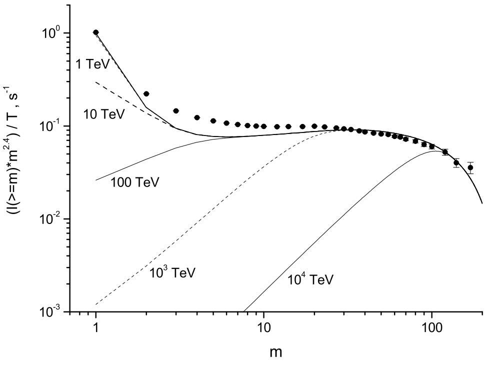

Figure 1. Integral muon number spectrum. Points - experiment. Lines - calculated muon number spectra for the light primary composition with different thresholds of primary energy.

2 Experiment

In this work we analyze the integral muon number distribution measured at the Baksan Underground Scintillation Telescope for near vertical directions ($\theta \leq 20°$, the effective depth 1020 hg/cm^2). BUST is a large installation (16.7×16.7 m^2 area and 11.1 m height), located in a cave under a mountain slope. Its four vertical sides and

---

[a] e-mail: vpetkov@inr.ru
[b] e-mail: js@zpk.u.lodz.pl

four horizontal planes are entirely covered with our standard liquid scintillation detectors [3, 4]. The standard detector consists of an aluminum tank with the dimensions $0.7 \times 0.7 \times 0.3$ m^3 and is filled with a liquid scintillator on the base of white-spirit. The total number of the detectors is 3180. Every counter is viewed with one PMT (the 15 cm diameter photocathode). The construction of BUST allows one to identify tracks of muons crossing the telescope. Coordinates of the fired detectors are the input information for determination of the muon group parameters. In general, the number of muon tracks m differs from the actual number of muons m_μ in the group passing through the telescope. In the case when 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. Muon interactions increase the number of fired detectors and in such a case the number of reconstructed muon tracks can be greater than the number of muons in the group. Furthermore there is some arbitrariness for muon track determination: for example, a track may cross two, three or four telescope planes and so on. Therefore it is necessary to convert the number of reconstructed muon tracks to the number of muons in the group taking into account all the mentioned effects. The conversion factors depend on the muon lateral distribution function which, in its turn, depends on the energy (per nucleon) of the primary nucleus. In order to avoid additional uncertainties we use only the experimental muon track number spectrum for studying the primary composition. The conversion of the number of muons to the number of reconstructed muon tracks is included in the calculations. The measured integral spectrum of the number of muon tracks for near vertical directions ($\theta \leq 20°$) is presented in the fig. 1.

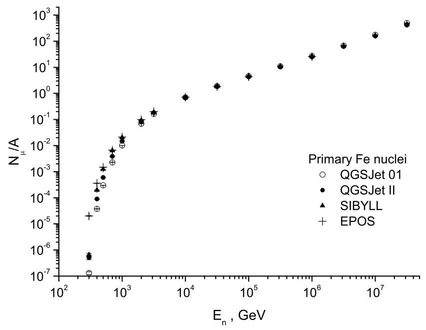

Figure 2. Dependences of the number of muons per nucleon on the energy per nucleon E_n for primary iron nuclei and four interaction models.

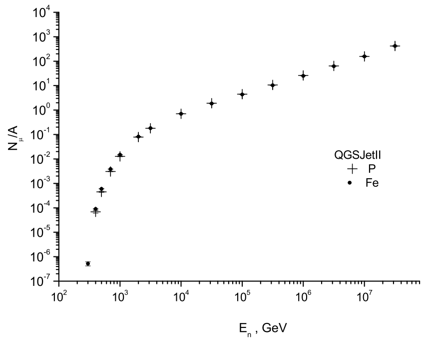

Figure 3. Dependences of the number of muons per nucleon on the energy per nucleon E_n for two primary species (interaction model QGSJet II).

3 Calculations

The integral muon number spectrum in BUST was numerically calculated in the same way as in [1]. This calculation method needs only characteristics of the high energy muon component of EAS as: 1) $\overline{N}_\mu(E_0, A)$ – the muon production function (MPF) or the mean number of muons per EAS produced by a nucleus with the atomic number A and primary energy E_0; 2) $f(\underline{r}, E_0, A)$ – the lateral distribution function (LDF); 3) $G(A, \overline{N}_\mu, N_\mu)$ – the fluctuation function (FF). It should be noted that the influence of FF on the results of calculations is smaller than those of MPF and LDF.

These characteristics have been computed for vertical direction with the corresponding effective depth 1020 hg/cm^2. The development of EAS in the Earth's atmosphere have been simulated by means of the CORSIKA code [5] with four hadron interaction models: QGSJET 01 [6, 7], QGSJET II [8], EPOS [9] and SIBYLL [10–12]. Muon propagation through the rock was performed by means of muon propagation code PROP-MU [13] (this work uses version 2.1, March 1997).

The results of simulations show that characteristics of high energy muons needed for calculation of muon number spectrum are practically the same for all interaction models mentioned above (fig. 2 as an example). Moreover, these characteristics do not depend on the kind of nuclei for the same energy per nucleon (fig. 3 as an example). The insignificant difference at the small primary energies ($E_n \leq 1$ TeV) do not impact on the muon number spectrum calculations (fig. 1).

4 Results and discussion

In our previos works we have already arrived at the conclusion that the light primary composition is preferable for explanation of measured muon number distribution [1, 14, 15]. Moreover, none of the composition models with simple power laws below the knee can fit the muon number spectrum measured at the BUST for the whole range of muon tracks. Recent measurements by the CREAM [16, 17] , ATIC [18] and TRACER [36] experiments have revealed deviations of cosmic ray spectra from the apparent power laws at TeV energies. A number of explanations of these results have been suggested (see [20–22] and the references therein). One of them is a model where a supernova explodes in some vicinity of our solar system in the recent past.

Table 1. 5-component primary composition.

Z	1	2	6-8	10-16	20-26
$\overline{Z}$	1	2	7.2	12.7	25.2
$\overline{A}$	1	4	14.4	25.5	54.2
${F_z}^0$	0.0762	0.065	0.025	0.021	0.0199
γ_z	2.75	2.70	2.64	2.73	2.66

The muon number spectrum was calculated on the assumption of the steady CR background following 5-component model of primary composition (Table 1 and figures 5 - 10) and additional p and He components from an individual supernova remnant in the Galaxy. The energy spectrum of each primary group of the CR background flux has a power law form with a rigidity dependent knee $E_{kz} = E_{kp} \cdot Z$ [23]:

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

where E_0 is the energy per particle and ${F_z}^0$ is the absolute flux ($m^{-2}\ s^{-1}\ sr^{-1}\ TeV^{-1}$) at 1 TeV per particle. The smooth knee with $E_{kp} = 3{\cdot}10^3$ TeV was applied: $\epsilon_c = 1.87$ and $\gamma_c = 3.1$.

Following [24], the energy spectrum of p and He components injected by an individual SNR was taken as:

$$I(E) = A(E)\cdot\exp\left[-C\cdot\left(\frac{E}{Z}\right)^{-\delta}\right]\cdot\exp\left[-\frac{E}{D\cdot Z}\right]\cdot\left(\frac{E}{Z}\right)^{-\beta} \tag{2}$$

The additional components parameters were adjusted to have an agreement between the calculated and experimental muon number spectra: $\delta = 0.6$, $\beta = 2.7$ and $D = 500$ TeV. Figure 4 presents comparison between measured muon number distribution and predictions of the EAS simulations. Contributions from different energy spectra of primary cosmic ray mass components are indicated.

We have noticed a satisfactory agreement between all particle cosmic ray spectrum obtained from direct experiments and the result of the sum of components used in the primary model (fig. 5). However, for the energy spectra of individual primaries, especially for primary protons and helium nuclei, there is a contradiction with the experiments.

Finally it should be noted that the experimental muon number spectrum can be fitted by different primary composition models and, therefore, there is some ambiguity in astrophysical conclusions from these experimental data interpretation.

Acknowledgements.
This work was supported in part by the Russian Foundation for Basic Research (grant 11-02-12043) and by the "Neutrino Physics and Neutrino Astrophysics" Program for Basic Research of the Presidium of the Russian Academy of Sciences.

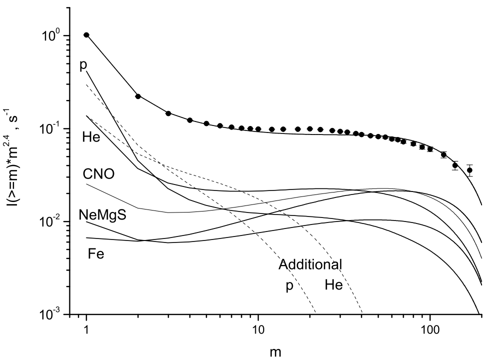

Figure 4. Integral muon number spectrum. Points - experiment. Solid lines - calculated total muon number spectrum and partial spectra for different primary species. Dotted lines - calculated muon number spectra for additional components.

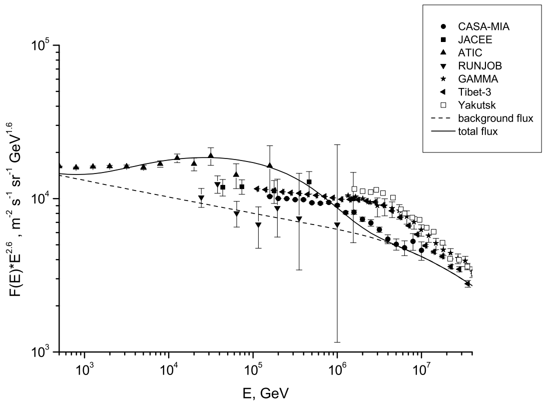

Figure 5. All particle spectrum. Points - data of direct and EAS experiments [18, 26–31]. Solid line - spectrum of used primary model, dotted line - spectrum of background cosmic ray flux.

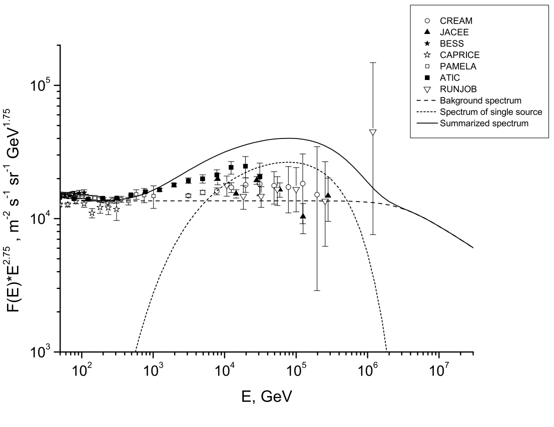

Figure 6. Proton energy spectrum. Points - data of direct experiments [17, 18, 25, 27, 32–34]. Dotted line - background spectrum, dashed line - spectrum from individual supernova remnant. Solid line - summarized proton spectrum.

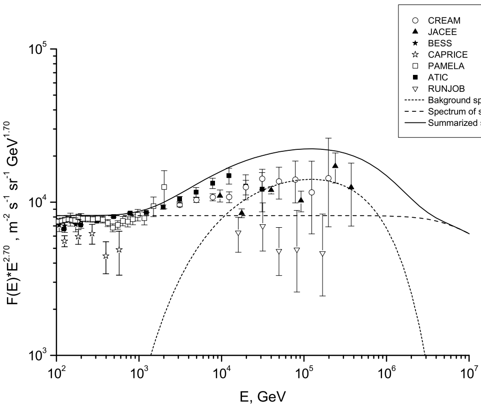

Figure 7. Energy spectrum of helium nuclei. Points - data of direct experiments [17, 18, 25, 27, 32–34]. Dotted line - background spectrum, dashed line - spectrum from individual supernova remnant. Solid line - summarized spectrum.

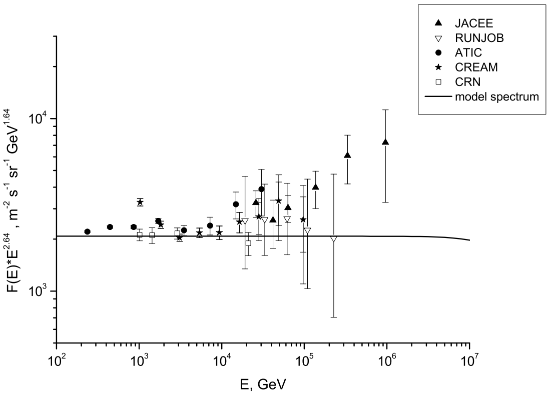

Figure 8. Energy spectrum of CNO-group. Points - data of direct experiments [16, 18, 26, 27, 35]. Solid line - model spectrum.

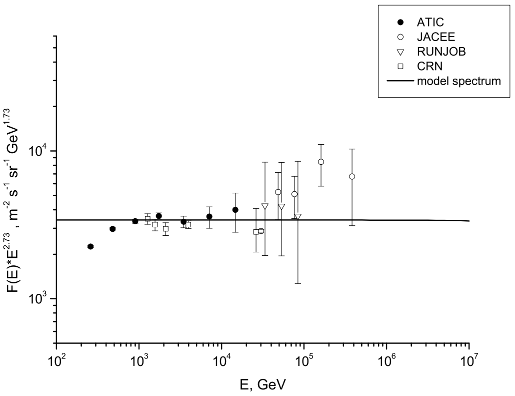

Figure 9. Energy spectrum of NeMgS-group. Points - data of direct experiments [18, 26, 27, 35]. Solid line - model spectrum.

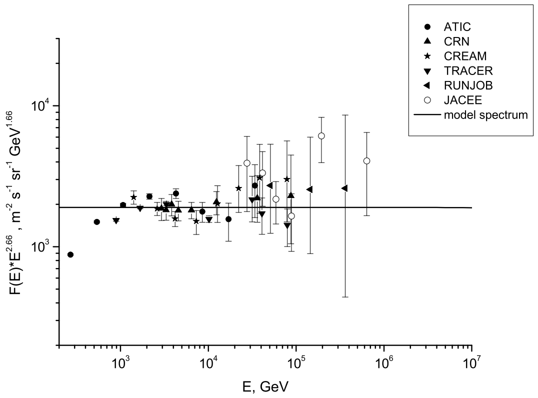

Figure 10. Energy spectrum of Fe-group. Points - data of direct experiments [16, 18, 26, 27, 35, 36]. Solid line - model spectrum.

References

[1] V.B. Petkov et al., Nucl. Phys. B (Proc. Suppl.), **175-176**, 362 (2008).

[2] David d'Enterria et al., Astroparticle Physics, **35**, 98 (2011).

[3] E.N. Alekseyev et. al., Proc.16 ICRC, **1**0, 276 (1979).

[4] E.N. Alekseyev et. al., Phys. Part. Nucl., **2**9, 254 (1998).

[5] D. Heck et al., Report FZKA 6019 (1998), Forschungszentrum, Karlsruhe.

[6] N.N. Kalmykov and S.S. Ostapchenko, Phys. Atom. Nucl., **5**6, 346 (1993).

[7] N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov, Nucl. Phys. B (Proc. Suppl.), **5**2, 17 (1997).

[8] S. Ostapchenko, Nucl. Phys. B (Proc. Suppl.), **1**51, 143 (2006).

[9] K. Werner, F.-M. Liu, and T. Pierog, Phys. Rev. C, **7**4, 044902 (2006).

[10] J. Engel et al., Phys. Rev. D, **4**6, 5013, 1992.

[11] R.S. Fletcher et al., Phys. Rev. D, **5**0, 5710 (1994).

[12] E.-J. Ahn et al., Phys. Rev. D, **8**0, 094003 (2009).

[13] P. Lipari, T. Stanev, Phys.Rev.D, **44**, 3543, (1991).

[14] V.B. Petkov, 31st International Cosmic Ray Conference. Invited, Rapporteur and Highlight Papers, p.127, Lodz, 2010. arXiv:0911.5679v1 [astro-ph.HE], 2009.

[15] V.B. Petkov and J. Szabelski, Astrophys. Space Sci. Trans., **7**, 111 (2011).

[16] H.S. Ahn et al., The Astrophysical Journal, **707**, 593 (2009).

[17] Y.S. Yoon et al., Astrophys.J., **728**, 122 (2011).

[18] A. D. Panov et al. Bulletin RAS: Physics, **73**, 564 (2009).

[19] M. Ave et al., Astrophys.J., **678**, 262 (2008).

[20] S. Thoudam and J. R. Horandel, 2012, MNRAS, **421**, 1209 (2012).

[21] V. Ptuskin, V. Zirakashvili and Eun-Suk Seo, arXiv:1212.0381v1 [astro-ph.HE] 2012.

[22] V.I. Zatsepin, A.D. Panov, N.V. Sokolskaya, arXiv:1203.6458v2 [astro-ph.HE] 2012.

[23] S.V. Ter-Antonyan, L.S. Haroyan, arXiv:hep-ex/0003006 (2000).

[24] P. Blasi and E. Amato, JCAP, **1201**, 010 (2012).

[25] K. Asakimori et al., Astrophys.J., **502**, 278 (1998).

[26] K. Asakimori et al., arXiv:astro-ph/9509091v1 (1995).

[27] A.V. Apanasenko et al., Astroparticle Physics, **16**, 13 (2001).

[28] M.A.K. Glasmacher et al., Astroparticle Physics, **10**, 291 (1999).

[29] A.P. Garyaka et al., Journal of Physics G: Nucl.Part.Phys., **35**, 115201 (2008).

[30] M. Amenomori et al., Astrophys.J., **678**, 1165 (2008).

[31] A.A. Ivanov, S.P. Knurenko and I.Ye. Sleptsov, New J.Phys., **11**, 065008 (2009).

[32] M. Boezio et al., Astropart.Phys., **19**, 583 (2003).

[33] O. Adriani et al., Science, **332**, 69 (2011).

[34] S. Haino et al., Phys.Lett.B, **594**, 35 (2004).

[35] D.Muller et al., Astrophys.J., **374**, 356 (1991).

[36] M. Ave et al., Astrophys.J., **678**, 262 (2008).