Proceedings of ICRC 2001: 84 © Copernicus Gesellschaft 2001

ICRC 2001

EAS spectrum vs $n_\mu(E > 220$ GeV) in the energy range $10^{15} - 10^{17}$ eV

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Abstract. EAS spectrum vs $n_\mu(E \geq 220$ GeV) in the range $75 \leq n_\mu \leq 4000$, obtained at Baksan Underground Scintillation Telescope, is presented. The data free of previously adopted simplifications are reported. The data agree better with the assumption that the energy of the "knee" in the energy spectrum of primary cosmic rays increases with the charge of primaries.

1 INTRODUCTION

Up to now the energy spectrum and the mass composition of primary cosmic rays (CR) have been measured by direct methods (on satellites or stratosphere balloons) up to energies of about $E_N = 10^{14}$ eV (E_N is an energy of primary nucleus). At higher energies only indirect experiments have been performed by earth bound experiments measuring extensive air showers (EAS) and muon groups deep underground.

In papers [1,2] we presented the method of detection of muon groups with multiplicity $n_\mu(E \geq 220$ GeV$) \geq 1800$ (n_μ is the total number of muons in EAS, E is a muon energy) and data obtained at the Baksan Underground Scintillation Telescope (BUST). This method is based on the use of calorimetrical propeties of the BUST and the condition of energy deposition equilibrium in some region around EAS axis (see [1,2]). The amplitude channels of the BUST have the threshold corresponding to the energy deposition density of 1 GeV/m^2 and allow us to measure an energy deposition in the muon core of EAS in the spot of some radius R. (We have 3 or 4 such spots in every event.) The events with $n_\mu > 1800$ give information about fluxes of primary nuclei with energies $> 3 \cdot 10^{16}$ eV. The threshold energy of muons is 220 GeV in this experiment.

To obtain the information about the energy spectrum and the mass composition of primary Cosmic Rays before and after the "knee" in the region $\simeq 3 \cdot 10^{15}$ eV, it was necessary to compare our data at $n_\mu > 1800$ with the results of other experiments at smaller values of n_μ. However, the hindrance to such a comparison was the fact that in all other experiments with muon groups the results were presented in the form of the multiplicity spectrum I(m) (where m is the number of muons hitting the facility at unknown position of EAS axis), whereas in our experiment [1,2] the total number of muons in EAS, n_μ, is determined.

Therefore in refs. [3,4], the method of recalculation from I(m) to the spectrum of EAS vs n_μ, F(n_μ), was developed. The formulation of the problem is following: let I(m) be the integral multiplicity spectrum obtained at a certain facility. Let us define the parameter

$$\Delta(m) = \frac{\overline{m}_1}{n_\mu}, \qquad (1)$$

which is the average fraction of muons hitting the facility in the case when the latter is crossed by $m_1 \geq m$ muons. Assuming then $n_\mu = m/\Delta(m)$, we will obtain the integral spectrum of EAS vs the total number of muons – $F(n_\mu)$:

$$F(n_\mu) = \frac{1}{G(m)} I(m) \qquad (2)$$

G(m) is the acceptance of the facility for a collection of events with muon multiplicity $\geq$ m. (It should be explained that m have to be high enough [4], for example m $>$ 20 as it is in ref. [5])

This method allowed to perform the direct comparison of data at $n_\mu > 1800$ from [1,2] and n_μ = 75 - 660 obtained with help of recalculation of multiplicity spectrum, presented in work [5] performed also at the BUST.

Thus the EAS spectrum vs n_μ was obtained in the range 75 $\leq n_\mu(E \geq 220$ GeV) $\leq$ 3500 which corresponds to primary energy range $10^{15} - 10^{17}$ eV. These results were reported in refs. [3,4].

However, we used in refs. [1-4] a number of simplifications:

1)in [3] during recalculation of I(m) to F(n_μ)

a)we did not take into account the Coulomb scattering of muons in the rock above the facility, b)the survival probability of muons was chosen in the form of

$$p(920\ hg/cm^2, E) = \begin{cases} 0,\ if\ E < 240 \\ 1,\ if\ E > 240 \end{cases} \quad (3)$$

(920 hg/cm^2 is the thickness of the rock above the BUST for a selection of events used in ref. [5], corresponding threshold energy of muons is 240 GeV)
2)in refs.[1,2] the energy losses of muons (at the passage through the rock above the BUST) were taken into account on the average. This led to that the number of muons underground in the circle with radius R (around EAS axis) was equal to the number of muons on the surface (in the same circle) with the energy greater than the threshold one for a fixed thickness H of the rock (i.e. we used the survival probability in the form (3)).

In the present work, we report the results which are free of previously adopted simplifications. The propagation of muons through the rock above the facility was taken into account with the code PROPMU (P. Lipari and T.Stanev) kindly presented to us by MACRO collaboration.

In Section 2 we recapitulate the data reported in refs. [3,4]. In Section 3 the values of $\Delta(m)$ and G(m) and the correction factor f(R,H) which takes into account (with Monte-Carlo simulation) the fluctuations of energy losses of muons during their passage through the rock above the facility are presented.

2 DATA

In Fig. 1, the EAS spectrum vs $n_\mu(E \geq 220$ GeV), represented in ref. [3], is shown with filled squares (■) and points (•). The points show our data at $n_\mu \geq 1800$, they correspond to primaries energy range of $3 \cdot 10^{16} - 3 \cdot 10^{17}$ eV. The squares are the data at $75 \leq n_\mu \leq 660$ obtained with help of recalculation of multiplicity spectrum I(m) (m $>$ 20) from ref. [5]. We show also the calculated fluxes of EAS in the region $50 \leq n_\mu \leq 10^4$:

$$F(\geq n_\mu) = \sum_{i \geq n_\mu} \sum_A \int_{E_o^{th}}^{\infty} B(i, \bar{l}, k) J_A(E_o) dE_o, \quad (4)$$

here $J_A(E_o)$ is the flux of nuclei with A nucleons with the energy E_o per nucleon, E_o^{th} depends on A; $B(i, \bar{l}, k)$ are the muon multiplicity fluctuations according to a negative binomial distribution, $\bar{l}$ is the average number of muons (with $E \geq 220$ GeV) produced by nucleus with the energy $E_N = AE_o$. For $\bar{l}$ we used the expression obtained in ref. [6] within the frame of quark-gluon strings model:

$$\bar{l}(A, E_o, \geq E) = \frac{0.0187 Y(\theta) A}{E^a} \left(\frac{E_o}{E}\right)^{0.78} \left(\frac{E_o}{E_o + E}\right)^b (5)$$

where E_o and E are in TeV,

$$a = 0.9 + 0.1 lg(E),\ \ b = E + \frac{11.3}{lg(10 + 0.5 E_o)},$$

$$Y(\theta) = \frac{1 + 0.36 ln(\cos\theta)}{\cos\theta}$$

Solid curves (in fig. 1) show the expected fluxes in the case when the change of the slope in the primary energy spectrum occurs at the same energy per nucleus, $E_c = 3 \cdot 10^{15}$ eV, dashed curves show the case $E_c = Z \cdot 3 \cdot 10^{15}$ eV (Z is the charge of the nucleus). Numbers near curves denote the variant of CR mass composition at $E_N = 10^{14}$ eV:

		P	He	CNO	Ne-S	Fe
I	%,	39	24	13	13	11
II		25	31	19	12	13

I is the standard composition observed at low energies ($E_o \sim 10$ GeV), II is the Swordy composition [7], in which the fraction of protons has been increased (at the expense of the fraction of He nuclei) in accordance with JACEE data [8]. We assume that energy spectra of nuclei have the form:

$$J_A(E_o) dE_o = K_A E_o^{-2.7} \left(1 + \frac{E_o}{E_c}\right)^{-0.4} dE_o \quad (6)$$

where E_c is the energy of the change of the slope which can depend on the charge of the nucleus. The total flux of CR at 10^{14} eV was chosen to be equal to [7,9]

$$F_{tot}(10^{14}\ eV) = 12 \cdot 10^{-10} (m^2 \cdot sr \cdot s \cdot GeV)^{-1} \quad (7)$$

It should be noticed that there is none normalization in Fig.1.

3 CORRECTIONS

The precise calculation of the propagation of muons through the rock above the facility results in that the filled squares in Fig. 1 shift to the position shown with open squares (□), and the points move to the position shown with open circles (○).

Numerical values of $\Delta(m)$ and $G(m)$ (see eqs. (1,2)) for composition II are presented in table 1. The error in calculation of $\Delta(m)$ and G(m) does not exceed 2 - 3 %. Non-integer values of m are obtained because of corrections at trajectories reconstruction (see ref. [5]). $\Delta'(m)$ and $G'(m)$ are the values obtained in ref. [3] (in approximations 1) 2), see Sect.1), $\Delta(m)$ and G(m) are the results of the present work. For the composition of the variant I, $\Delta(m)$ will be $0.7 \div 0.1\%$ greater and $G(m)$ will be 0.6% less than those for the composition II respectively.

Table 1. Values of $\Delta(m)$ and G(m) for composition II
The accuracy of calculation of $\Delta(m)$ and $G(m)$ is 3%, G(m) in $m^2 \cdot sr$ (see text).

m	$\Delta'(m)$	$G'(m)$	$\Delta(m)$	$G(m)$	n_μ
21.9	0.287	65.1	0.280	60.5	78.2
32.9	0.297	63.9	0.289	57.9	113.9
44.5	0.303	62.5	0.295	56.6	150.8
56.5	0.307	60.5	0.299	54.8	188.6
82.1	0.314	59.0	0.306	53.2	268.2
124.9	0.321	57.3	0.313	51.6	399.3
211.6	0.328	54.9	0.319	50.4	663.8

$\Delta(m)$ and $G(m)$ are used during obtaining the data at $n_\mu = 75 - 660$ (see eqs. (1,2)) and factor f(R,H) relates to the data at $n_\mu > 1800$. In table 2 the ratios $f(R,H) = N_\mu(R, \geq E_{th}(H))/N_{\mu H}(R, \geq$0.5 GeV) are shown for two depth: H_1 = 825 hg/cm^2 (the events with minimal rock thickness along the path of muon group) and H_2 = 1510 hg/cm^2 (the event with the maximal one). Here $N_{\mu H}$ being the number of muons at a depth of H (standart rock) in the circle of radius R (around EAS axis) with energy $E >$ 0.5 GeV; $N_\mu(R, \geq E_{th}(H))$ is the number of muons on the surface with the energy greater than the threshold one for a given thickness H in the same circle. As it follows from table 2 $f(R,H) > 1$ always. This means we underestimated n_μ in refs. [1.2].

The radius of the spots, where the energy deposition exceeds 1 GeV/m^2, is 1.7 $\leq R \leq$ 4 m when $n_\mu \geq$ 1800 (see [1,2] for more details). All events at $n_\mu \geq$ 1800 (30 events) were corrected by factor f(R_i, H_i) calculated for a fixed depth H_i and the spot radius R_i (R_i was determined as the average over all spots in a given event). In table 3 our data at $n_\mu \geq$ 1800 are presented before the correction by factor f(R_i, H_i) (n'_μ, and $N'(\geq n'_\mu)$) and after the one (n_μ and $N(\geq n_\mu)$). Numerical values of EAS fluxes with $n_\mu(E \geq 220 GeV) \geq$ 2000 have been shown in the last column.

Table 2.Factor f(R,H) for two thickness of standart rock. The error of f(R,H) calculation does not exceed 0.01.

$H_1 = $825hg/cm^2

R, m	$f(R,H_1)$
1	1,272
2	1.142
3	1.110
4	1.091

$H_2 = $1510hg/cm^2

R, m	$f(R,H_2)$
1	1,400
2	1.265
3	1.204
4	1.172

Table 3. Data at $n_\mu(E \geq$ 220) $\geq$ 2000 before and after the correction with factor $f(R_i, H_i)$

n'_μ	$N'(\geq n'_\mu)$	n_μ	$N(\geq n_\mu)$	$F(\geq n_\mu) \cdot n_\mu^{2.5}$ $(m^2 \cdot s \cdot sr)^{-1}$
1800	28	2000	28	0.068 ± 0.013
2500	15	2800	17	0.089 ± 0.022
3500	7	4000	7	0.085 ± 0.032

Note that the boxes (□) show the data for muon threshold energy E_{th} = 240 GeV, whereas the points and the curves relate to E_{th} = 220 GeV. It means the boxes shift up by 15-20$\%$ for E_{th} = 220 GeV.

4 CONCLUSION

We have presented the Baksan data on high energy muons ($E \geq$ 220 GeV) in EAS for primary energy range of $10^{15} - 10^{17}$ eV. The method developed in [1,2] allowed us to obtain the information about the muon content of EAS up to primaries energies of 10^{17} eV. The error in the determination of n_μ in individual event does not exceed 15 $\%$ at n_μ = 2000 and decrease with increasing n_μ. The poor statistics is connected with insufficient acceptance of the BUST for this task (the ”live time” of detection is 69220 hours).

Because of poor statistics after the ”knee” our results can feel only the trend in a behaviour of the energy spectrum. Therefore we do not present the quantitative estimate. The EAS spectrum vs n_μ at 75 $\leq n_\mu \leq$ 4000, shown in Fig. 1 with open boxes and circles, is more flat than the one presented in [3,4]. This is an indication that the energy of the ”knee”, E_c (see eq.(6)), appears to increase with the charge of primary nucleus. The latter means that the mass composition at $E_N > 10^{15}$ eV becomes gradually more heavy. So our data favour to some heavying of the mass composition and (withih the errors) do not contradict the constant one.

These conclusions agree qualitatively (at least do not contradict) with the results obtained at EAS - TOP [10], HEGRA [11], CASA - MIA [12], KASCADE [13]. At the same time the interesting analisys in the DICE [14] shows more light composition in the region around the ”knee”. A similar result was obtained in CASA-BLANCA experiment [15].

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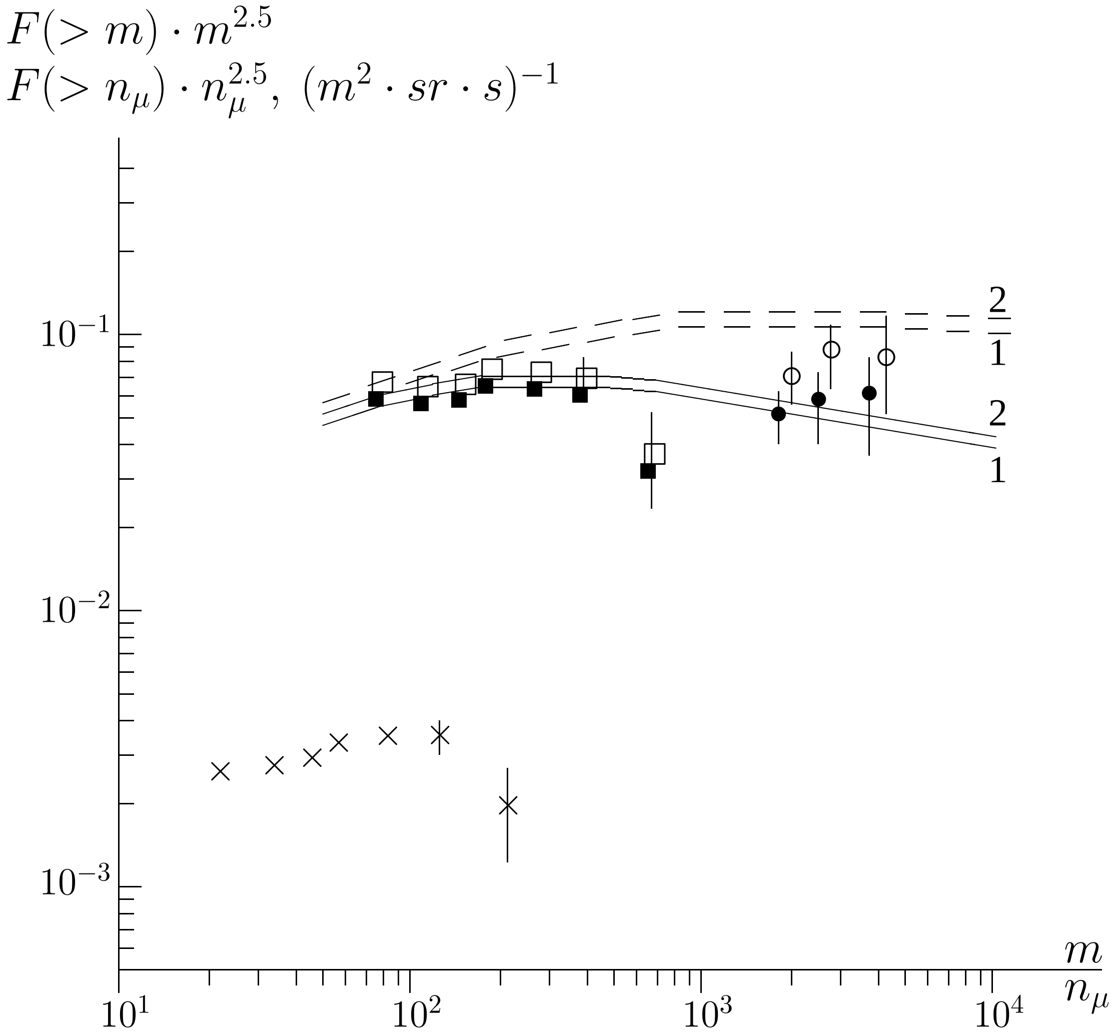

Fig. 1. Filled circles are the data obtained in [1,2]; crosses show the muon multiplicity spectrum obtained in ref. [5] (m and F(m) correspond to the multiplicity spectrum); filled squares represent the data from [5] recalculated to $F(n_\mu)$ using the survival probability in the form (3). Open circles and squares are the present work data (see text). Solid curves are expected fluxes for the case $E_c = 3 \cdot 10^{15}$ eV/nucleus, dashed curves – the case $E_c = Z \cdot 3 \cdot 10^{15}$ eV. Numbers near curves denote the composition variants.