MUON GROUPS AND PRIMARY COMPOSITION AT $10^{13}$-$10^{15}$ EV


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ABSTRACT

The data on muon groups observed at Baksan underground scintillation telescope is analysed. In this analysis we compare the experimental data with calculations, based on a superposition model in order to obtain the effective atomic number of primary cosmic rays in the energy range $10^{13}$-$10^{15}$ ev.

1. Introduction. Our general approach to the problem was presented in Kyoto (1), and the first experimental data from Baksan in (2). The first attempt to analyse Baksan multiplicity spectrum in terms of primary composition was made in Bangalore (3). Now we have to correct one of conclusions made in (3) concerning effective atomic number. The change came for two reasons: 1) now a smaller zenith angle interval was accepted $0^\circ \leq \theta < 30^\circ$, corrections for individual events inside this interval were made. This affected the obtained decoherence curve, making it 20% narrower; 2) the second reason is the choice of more reliable function $N_u = F(E_0)$ which represents the mean number of muons from primary nucleon of energy $E_0$.

2. Experiment. The observed multiplicity or muon number spectrum is shown in fig. 1. It is practically the same as in (3) the difference $m^{-3.4}$ or $m^{-3.3}$ being not significant. All the difference with (3) is in calculated curves. The experimental decoherence curve is shown in fig. 2. It deviates slightly from pure exponential one with parameter $(12 \pm 1)$ m. The decoherence curve is used to choose the parameters of assumed lateral distribution functions (LDF) in such a way as to fit the experimental curve. $D(R) F_1(r) + F_4(r)$: examples of tried LDF.

Then the important function $\Delta(R)$ (see below) does not depend much on the choice of the type of LDF.

3. Calculations of expected muon number spectra for a given primary atomic number $A$. To do this following assumption have been made:

1. the muon group from $A$ is a superposition of $A$ independent groups from constituent nucleons,
2. LDF does not depend on $A$ and energy per nucleon $E_0$,
3. fluctuations of the muon numbers are pure Poissonian,
4. the power law energy spectrum of primaries of a given $A$,
5. the mean number of muons of energy $E_u \geq E_{th}$ from primary nucleon of energy $E_0$ was taken as $f(E_0) = 0.355(E_0^{0.42} - 0.55)^{1.55}$.
for \( E_{th} = 0.22 \text{ TeV} \), \( E_0 \) in TeV on the basis of numerous Monte-Carlo simulations of cascades in atmosphere (5,6).

The problem is presented by a system of equations:

\[
\frac{dN}{dE_0} \propto E_0^{-\gamma} \quad \text{Eq. 1}
\]

\[
\frac{dN}{dE_0} = A \cdot f(E_0) \quad \text{Eq. 2}
\]

\[
\psi(N') \sim N'^{\gamma} \quad \text{Eq. 3}
\]

\[
\psi(N') \int_{N'}^{N} dN' = \frac{\psi(N') - \psi(N')} {\psi(N')} \quad \text{Eq. 4}
\]

\[
\psi(N') = \int_{N'}^{\infty} \frac{\psi(N')}{\psi(N')} dN' \quad \text{Eq. 5}
\]

Here: \( N \) is the mean number of muons \( E \geq E_{th} \) from nucleus \( A \) with total energy \( A \cdot E_0 \); \( \Delta(R) \) is the fraction of \( N \) which is expected to be inside detecting area when the core of group is at the distance \( R \) from telescope centre (\( \Delta(R) \) is calculated using assumed LDF); \( \psi(A(N')) \) is distribution of \( N' \) (expected numbers inside area), which is obtained by solving eqs. 1-3; \( \psi(A(m)) \) is the intensity of multiplicities \( m \) for a given \( A \); \( \psi(A(m)) \) the same, but normalized to the total muon flux through detecting area. The resulting from these calculations \( \psi(A(m)) \) are shown in Fig. 1 for several \( A \) and mixed composition. Obviously, these results depend on \( \gamma = 1.7 \) (which is in agreement with experiment) and on functions \( f(E_0) \) and \( \Delta(R) \).

Discussion. To demonstrate the sensitivity of \( A_{eff} \) to assumed functions \( f(E_0) \) and \( \Delta(R) \) let us use "\( N_0 \)-approximation", introduced in (1), valid for \( m \gg 1 \); which consists of following:

1. at large \( N \) \( f(E_0) \approx E_0 \), then \( \psi_i(N') \approx C \cdot (N')^{-\gamma' - 1} \) at large \( N' \),

2. suppose this power law distribution is valid for \( N' > N_0 \) and is cut to zero for \( N' < N_0 \); determine \( N_0 \) by

\[
\int_{N_0}^{\infty} \psi_i(N') dN' = \int_{N_0}^{\infty} C \cdot (N')^{-\gamma' - 1} \quad \text{Eq. 6}
\]

so providing the correct total number of muons.

In a similar way we determine \( N_0 \) which corresponds to the
case \( \Delta(R)=1 \). Fig. 3 shows the original \( f(E_0) \) (5) — the dependence of number of muons \( N \), \( E_\mu \gg 220 \) Gev on the primary nucleon energy \( E_0 \) and its power law version in "\( N_0 \) - approximation". The total number of muons after integrating over primary spectrum should be the same for both versions. Substituting the functions \( f(E_0) \) and \( \psi_{\Delta}(N') \) in /1/ and /4/ by power law versions using the mentioned procedure we obtain a simple solution of eqs. /1-5/:

\[
I(m) = \frac{E_0}{E_{\text{th}}} \left( \frac{N_0}{A} \right) \frac{K_\Delta}{E_{\Delta}} \int_{N'}^{N_0} \frac{N'^{ m-\frac{k}{E_{\Delta}} - 1}}{N'} dN'
\]

where \( N_0 = N_0 \cdot A \cdot \Delta \), \( \Delta = \left[ \frac{1}{E_\mu} \int_0^{E_{\text{th}}} R dR (\Delta(R))^{\gamma/\delta} \right]^{\delta/\gamma} \) is the "effective fraction" of total number of muons in the group expected in detection area. For \( m \gg N_0 \) and \( m \gg 1 \)

\[
I(m) = \frac{E_0}{E_{\text{th}}} \left( \frac{N_0}{A} \cdot \Delta \right) \frac{1}{m} \left[ \frac{E_{\text{th}}}{E_\mu} \right]^{\gamma/\delta - 1} \cdot \lambda(m)
\]

where \( \lambda(m) \rightarrow 1 \) if \( m \rightarrow \infty \). When \( \gamma \) and \( \delta \) are fixed the results depend only on the product \( N_0 \cdot A \cdot \Delta \). The eq. /7/ describes the asymptotic behavior of expression /5/ shown as solid curves on fig.1. By definition the effective atomic number for a mixed composition is:

\[
A_{\text{eff}} = \left[ \frac{E_{\text{th}}}{E_\mu} \int_{N_0}^{N_0} R dR \right]^{\delta/\gamma}
\]

which we can evaluate comparing /7/ with experimental data. For \( \gamma = 1.7, \delta = 0.73, N_0 = 0.43 \pm 0.12, \Delta = 0.15 \pm 0.02 \) (of them only \( N_0 \) is model dependent (5,6)) the new value of \( A_{\text{eff}} \) is \( A_{\text{eff}} = 3.9 \pm 1.5 \) (using experimental value of \( I(m) \) at \( m = 10 \)).

Table 1

<table>
<thead>
<tr>
<th>( \xi ) (Gev/n)</th>
<th>1</th>
<th>4</th>
<th>9</th>
<th>14</th>
<th>28</th>
<th>56</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \xi_1 )</td>
<td>0.399</td>
<td>0.055</td>
<td>0.009</td>
<td>0.0035</td>
<td>0.011</td>
<td>0.003</td>
</tr>
<tr>
<td>( \xi_2 )</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>( \xi_3 )</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 1 shows two suggested examples of chemical composition, \( \xi_1 \) — fraction of nuclei \( A_1 \) with a given energy per nucleon (at 1 Gev/n). Number spectra for these two cases calculated using eqs. /1-5/ shown in fig.1 by dashed lines. A good fit to
experimental data is provided by CC1 which corresponds to the case of a constant chemical composition (a standard one) in all energy range from 1 Gev/n. The $A_{\text{eff}}$ for CC1 according to /8/ is $A_{\text{eff}}=4.8$, which is about 20% bigger than obtained using "$N_0$-approximation" at $m=10$; this is because $f(E_0)$ did not reach asymptotic behavior at $m=10$ for heavy primaries. Different multiplicities $m$ represent different primary energies but also different selection of $A$. Table 2 shows, assuming CC1 and eqs. /1-5/, relative contributions of different $A$, also their mean energy, to different $m$, $q$ is relative contribution.

Table 2

<table>
<thead>
<tr>
<th>$m$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A=1$</td>
<td>$E$ =</td>
<td>6.1</td>
<td>25</td>
<td>86</td>
<td>240</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td>$q$ =</td>
<td>.83</td>
<td>.64</td>
<td>.47</td>
<td>.32</td>
<td>.22</td>
</tr>
<tr>
<td>$A=4$</td>
<td>$E$ =</td>
<td>20</td>
<td>44</td>
<td>94</td>
<td>170</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>$q$ =</td>
<td>.14</td>
<td>.26</td>
<td>.33</td>
<td>.33</td>
<td>.26</td>
</tr>
<tr>
<td>$A=14$</td>
<td>$E$ =</td>
<td>53</td>
<td>78</td>
<td>106</td>
<td>160</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>$q$ =</td>
<td>.02</td>
<td>.07</td>
<td>.13</td>
<td>.2</td>
<td>.23</td>
</tr>
<tr>
<td>$A=56$</td>
<td>$E$ =</td>
<td>170</td>
<td>200</td>
<td>210</td>
<td>220</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td>$q$ =</td>
<td>.005</td>
<td>.03</td>
<td>.07</td>
<td>.15</td>
<td>.3</td>
</tr>
</tbody>
</table>

4. Conclusions. The Baksan muon number spectrum at $E_{\mu}>E_{th}=220$ Gev is well explained suggesting a constant chemical composition (the same as at $1\text{Gev/n}$) till $\sim 20$ Tev/n.

The integral exponent of the heavy primaries power law spectrum should be $\gamma = 1.7 \pm 0.1$ till $10^{15}$ ev/nucleus.

References

5. A.D.Erlykin Private communication.