On the mass composition of primary cosmic rays in the energy region $10^{15} - 10^{16}$ eV

To cite this article: Yu F Novoseltsev et al 2012 J. Phys.: Conf. Ser. 375 052015

View the article online for updates and enhancements.
On the mass composition of primary cosmic rays in the energy region $10^{15} - 10^{16}$ eV

Yu.F. Novoseltsev*, R.V. Novoseltseva and G.M. Vereshkov+

Institute for Nuclear Research of RAS, Moscow, 117312, Russia
*E-mail: novoseltsev@inr.ru, +E-mail: gveresh@gmail.com

Abstract. The method of the determination of Primary Cosmic Ray mass composition is presented. Data processing is based on the theoretical model representing the EAS spectrum vs the total number of muons as the superposition of the spectra corresponding to different kinds of primary nuclei. The method consists of two stages. At the first stage, the permissible intervals of primary nuclei fractions $f_i$ are determined on the base of the EAS spectrum vs the total number of muons ($E_\mu \geq 235$ GeV). At the second stage, the permissible intervals of $f_i$ are narrowed by fitting procedure. Within the framework of three components (protons, helium and heavy nuclei), the mass composition in the region $10^{15} - 10^{16}$ eV has been defined: $f_p = 0.235 \pm 0.02$, $f_{He} = 0.290 \pm 0.02$, $f_H = 0.475 \pm 0.03$.

1. Initial conditions

We present the method of determination of CR mass composition on the base of data on the EAS spectrum vs the total number of high energy muons.

We use the data on high multiplicity muon events ($n_\mu \geq 114$) collected at the Baksan underground scintillation telescope [1]. In [2] the muon multiplicity spectrum (i.e., the number $m$ of muons hitting the facility at unknown position of EAS axis) at $m \geq 20$ was measured at zenith angles $\theta \leq 20^\circ$. The threshold energy of muons coming from this solid angle is 235 GeV. In papers [3, 4, 5] we developed the method of recalculation from the multiplicity spectrum to the EAS spectrum vs the total number of muons, $I(n_\mu)$. With the help of the method, we have combined the results reported in [2] and [5, 6] and obtained the EAS spectrum vs the total number of muons in the range $75 \leq n_\mu \leq 4000$, which corresponds to the primary energy range of $10^{15} \leq E_N \leq 10^{17}$ eV (Fig.1). It should be clarified that the data at $n_\mu > 2000$ are obtained for the muon threshold energy $E_{th} = 220$ GeV, while the points at $n_\mu < 700$ have $E_{th} = 235$ GeV which is the threshold energy in the experiment [2]. In Fig.1, the expected fluxes are calculated for $E_{th} = 235$ GeV ($n_\mu < 1000$, dotted curves) and $E_{th} = 220$ GeV ($n_\mu > 1000$, solid and dashed curves). Numbers near curves denote the mass composition variants: 1 is the low energy composition (the nuclei fractions in percentage are 39, 24, 13, 13, 11), 2 is the composition (1).

The data at $n_\mu < 700$ can be used for retrieval of information on the CR mass composition in the region $E_N = 10^{15} - 10^{16}$ eV. Let us remark here that the data at $m = 125$ ($n_\mu = 400$) and $m = 212$ ($n_\mu = 664$) in [2] were obtained with essential systematic errors: according to our estimates, the values of $m$ in these points are underestimated 4% and 10% respectively [7], therefore we restrict ourselves to the data at $m \leq 82$ ($n_\mu \leq 270$).

As initial conditions, we use the mass composition obtained by Swordy [8] with the help of
Figure 1. Squares are the EAS spectrum vs $n_\mu$ (experimental data). The muon threshold energy is $E_{th} = 235$ GeV if $n_\mu < 1000$ and $E_{th} = 220$ GeV at $n_\mu > 1000$ [3, 5]. Crosses show the muon multiplicity spectrum obtained in [2] ($m$ and $F(m)$ correspond to the multiplicity spectrum). Solid curves are expected fluxes ($E_{th} = 220$ GeV) for the case $E_k = Z \cdot 3 \cdot 10^{15}$ eV, dashed curves – the case $E_k = 3 \cdot 10^{15}$ eV/nucleus. Dotted curves show expected fluxes for the case $E_k = Z \cdot 3 \cdot 10^{15}$ eV at $E_{th} = 235$ GeV.

A compilation of results of direct measurements at energies $\approx 100$ TeV per nucleus\(^1\) ($A$ is the number of nucleons in a nucleus)

\[
\begin{array}{cccccc}
A & p & He & CNO & Ne-S & Fe \\
f, \% & 25 & 4 & 14 & 28 & 56 \\
\end{array}
\]

(1)

and the proton flux at the energy $E_p = 100$ TeV measured in the JACEE experiment [9].

\[
D_p(100 \text{ TeV}) = 2.95 \times 10^{-10} \left( m^2 \cdot s \cdot sr \cdot GeV \right)^{-1}
\]

Then the total flux of nuclei with energy of $E = 100$ TeV is equal to $D_{tot} = D_p/0.25 = 11.8 \times 10^{-10} \left( m^2 \cdot s \cdot sr \cdot GeV \right)^{-1}$, that is in a good agreement with the result obtained at Tibet array [10].

Our goal is to determine the mass composition evolution (from the composition (1)) into the region $E_N = 10^{15} - 10^{16}$ eV on the base of data on the number of high energy muons ($E_\mu \geq 235$ GeV) in EAS. To this end, we will use the measured fluxes of multiple muon events with the multiplicity into differential intervals $n_{\mu i} \leq n_\mu \leq n_{\mu(i+1)}$. At the first stage, we determine the permissible intervals of fractions $f_i$, which ensure an agreement with experimental data within the limits of one standard deviation. And then, the results are refined with the help of fitting procedure.

To obtain the more certain results we fix the CR energy spectrum, namely we adopt the conservative scenario:

i) the slope change of the spectrum occurs at the same energy per unit charge $E_k(Z) = 3$ PeV$\times Z$,

ii) the spectra of all nuclei kinds have the slope exponents $\gamma_1 = 2.7$ before the ”knee” and $\gamma_2 = 3.1$ after the ”knee”

\[
D_A(E) = I_A E^{-2.7} (1 + E/E_k(Z))^{-0.4}.
\]

This scenario is supported by experimental data well enough.

It should be emphasized, we do not attempt to use the data at $n_\mu > 2000$ because the energy spectra of nuclei at $E_N > 10^{16}$ eV are poorly understood.

\(^1\) in comparison with the composition presented in [8], in (1) the proton fraction is increased by 5\% (at the expense of helium nuclei) in accordance with data of [9]
2. Permissible domains

The flux of events with muon multiplicity \( n \geq n_{\mu} \) produced by nuclei with \( A \) nucleons can be written in the form

\[
I_A(n \geq n_{\mu}) = \int_{E_{th}(A)}^{\infty} F_A(E) D_N(E) P_A(E, n \geq n_{\mu}) dE,
\]

here \( F_A(E) \) is the fraction of nuclei with \( A \) nucleons with energy \( E \) per nucleon, \( D_N(E) \) is the total flux of nuclei with the same energy per nucleon, \( P_A(E, n \geq n_{\mu}) \) is the probability that the number of muons (with \( E_{\mu} \geq 235 \text{ GeV} \)) in EAS produced by nucleus ”A” is \( n \geq n_{\mu} \), \( E_{th}(A) \) is the threshold energy of nuclei with \( A \) nucleons.

We assume that the multiplicity of muons in EAS is described by the negative binomial distribution \( B_A(E, n) \), then

\[
P_A(E, n \geq n_{\mu}) = \sum_{n \geq n_{\mu}} B_A(E, n).
\]

The flux of events with \( n_{\mu i} \leq n_{\mu} \leq n_{\mu(i+1)} \) has the form

\[
J_A(\Delta n_{\mu i}) = I_A(n \geq n_{\mu i}) - I_A(n \geq n_{\mu(i+1)}) = \int_{E_{th}(A)}^{\infty} F_A(E) D_N(E) \times \]

\[
P_A(E, n \geq n_{\mu i}) dE - \int_{E_{th}^{i+1}(A)}^{\infty} F_A(E) D_N(E) P_A(E, n \geq n_{\mu(i+1)}) dE = F_A R_{iA},
\]

where the first index of the matrix \( R_{ij} \) points out to muon multiplicity \( (n_{\mu i}) \) and the second one pertains to a nucleus sort. \( F_A \) is the fraction of nuclei ”A” averaged over the energy region which gives the main contribution in the integral (5) (as is seen in Fig.2, the region is rather narrow). Thus we work in the approximation \( F_A(E) \simeq \bar{F}_A = \text{const} \) and will drop the symbol of averaging hereinafter.

![Figure 2. Energy distributions of protons and iron nuclei making a contribution to the flux of muon events with 114 ≤ n_µ < 151. Areas under curves (p and Fe ) are equal to 1. The widths of distributions at half-height and fractions of events in these regions are indicated.](image)

To avoid possible methodical errors, we use only 4 points in the spectrum \( I_{tot}(\geq n_{\mu}) \equiv I(\geq n_{\mu}) \): at \( n_{\mu} = 114, 151, 189, 268 \) (these points have the same exposure time). In table 1, the input data are presented: muon multiplicity intervals \( \Delta n_{\mu} \), the numbers and fluxes of events in given intervals of \( n_{\mu} \).

We will solve a direct problem and define the regions of \( F_j \) values which are compatible with equations (couplings)

\[
\sum_j R_{ij} \times F_j = J_i, \quad (i = 1, 2, ..., 4)
\]

where \( J_i \) is the observed flux of events (EAS) with muon multiplicity from \( i \)-th interval – \( n_{\mu i} \leq n_{\mu} < n_{\mu(i+1)} \).
Table 1. Integral (I) and finite-difference (J) fluxes of events (EAS) with the given number of muons \( (E_\mu \geq 235 \) GeV). The flux \( J(\Delta n_\mu) \) is defined according to (5).

| \( n_\mu \) | \( I(\geq n_\mu) \times 10^7, (m^2 \cdot s \cdot sr)^{-1} \) | \( \Delta n_\mu \) | \( N(\Delta n_\mu) \) | \( J \times 10^7, (m^2 \cdot s \cdot sr)^{-1} \) |
|-----------|-----------------|-------|----------------|----------------|
| 114       | 4.887 ± 0.209   | 114 - 151 | 277             | 2.419 ± 0.145   |
| 151       | 2.468 ± 0.150   | 151 - 189 | 106             | 0.920 ± 0.089   |
| 189       | 1.548 ± 0.121   | 189 - 268 | 98              | 0.906 ± 0.092   |
| 268       | 0.642 ± 0.079   | ≥ 268   | 66              | 0.642 ± 0.079   |

Next we will pass to the energy per nucleus and decrease the number of independent variables with the help of relations

\[
f_3(E) = f_4(E) = f_5(E), \quad \text{(model II)}\]

\[
or \quad f_3(E) = 1.5f_4(E), \quad f_4(E) = f_5(E) \quad \text{(model I)}.
\]

where \( f_j(E) \) is the fraction of nuclei of kind \( j \) at the same energy per nucleus.

The relations (7) are fulfilled at low energies \( (E_N \sim 100 \text{ GeV}) \) and the relations (8) are valid at \( E_N \simeq 100 \text{ TeV} \) (see mass composition (1)). We will find the solution of equations (6) in both cases and discuss later which variant ((7) or (8)) is more preferable.

Passing from five variables \( F_j \) to three variables \( f_k \) \( (k = 1, 2, 3) \), it is convenient to rewrite the equations (6) as follows (we multiply and divide the \( j \)-th term by \( A_j^{1.7} \) in each equation):

\[
\sum_{j=1}^{3} R3_{ij} \times B_j = J_i, \quad (i = 1, 2, ..., 4)
\]

where

\[
R3_{ij} = R_{ij}/A_j^{1.7}, \quad B_j = F_j \times A_j^{1.7}, \quad j = 1, 2, 3
\]

\[
R3_{i3} = \sum_{j=3}^{5} R_{ij}/A_j^{1.7}, \quad B_3 = \frac{1}{3} \sum_{j=3}^{5} F_j \times A_j^{1.7}
\]

In addition

\[
f_k = B_k \times \left[ \sum_{j=1}^{5} F_j \times A_j^{1.7} \right]^{-1}
\]

To determine \( B_j \) we will use independent pairs of equations (9) (for example for \( i = 1, 2 \) or \( i = 2, 3 \) etc.), and for closure of the equation system we use the normalization condition \( f_1 + f_2 + 3f_3 = 1 \), which (taking into account (9), (11)) can be read so

\[
B_1 + B_2 + 3B_3 = \sum_{j=1}^{5} F_j \times A_j^{1.7}
\]

Executing all operations mentioned above we have obtained the permissible intervals of fractions \( f_i \) which ensure an agreement with experimental data within the limits of one standard deviation\(^2\):

\[
\text{Model I} : \quad 0.182 \leq f_p \leq 0.250, \quad 0.287 \leq f_{He} \leq 0.321, \quad 0.203 \leq f_N \leq 0.211, \quad 0.135 \leq f_{Si} = f_{Fe} \leq 0.141.
\]

\(^2\) we have somewhat simplified (and reduced) the presentation. It should be explained, we have three independent pairs of equations (for \( i = 1, 2; i = 2, 3 \) and \( i = 3, 4 \)). All pairs of equations result in permissible domains of \( f_i \) very close to each other. It means that our approximation \( F_j(E) \approx \text{const} \) is valid and we obtain the ‘average’ composition for the energy interval under study; for more details see [11]
3. Fitting procedure

The second stage of data processing consists in narrowing of permissible intervals of \( f_i \). With this end in view, we carry out the simultaneous fit of 4 integral points (see table 1) and 3 finite difference points:

\[
I_{n_\mu} = I(\geq n_\mu), \quad n_\mu = 114, \quad 151, \quad 189, \quad 268, \quad J_{n_\mu} = I(\geq n_\mu) - I(\geq n_\mu'), \quad n_\mu - n_\mu' = 114 - 151, \quad 151 - 189, \quad 189 - 268.
\]  

We perform fitting of 7 points (15) requiring that:

i) all data (7 points) are satisfied within the limits of one standard deviation, 

ii) fitted parameters (\( f_i \)) are within permissible intervals.

\[
\begin{align*}
Model I: & \quad f_p = 0.236 \pm 0.003, \quad f_{He} = 0.290 \pm 0.003, \quad f_N = 0.204 \pm 0.001, \\
& \quad f_{Si} = f_{Fe} = 0.1356 \pm 0.0007.
\end{align*}
\]

The fractions of light and heavy nuclei are

\[
\begin{align*}
Model II: & \quad f_p = 0.240 \pm 0.005, \quad f_{He} = 0.299 \pm 0.015, \quad f_N = f_{Si} = f_{Fe} = 0.1535 \pm 0.004, \\
& \quad f_{light} = f_p + f_{He} = 0.526 \pm 0.005, \quad f_{heavy} = 0.474 \pm 0.003. \\
& \quad f_{light} = f_p + f_{He} = 0.539 \pm 0.019, \quad f_{heavy} = 0.461 \pm 0.010.
\end{align*}
\]

We estimate the error value about 10% [11]. In this context Model I and Model II lead to the same results

\[
f_p = 0.236 \pm 0.020, \quad f_{He} = 0.290 \pm 0.020, \quad f_H = 0.474 \pm 0.030.
\] (20)

The result (20) should be read as the estimation (rather precise) of CR mass composition in the energy region of \( 10^{15} - 10^{16} \) eV. Thus our analysis points out that CR mass composition become some more heavy in comparison with the one (1).

Acknowledgments

This work was supported by RFBR grant 11-02-12043, the ”Neutrino Physics and Neutrino Astrophysics” Program for Basic Research of the Presidium of the Russian Academy of Sciences and the Federal Targeted Program of Ministry of Science and Education of Russian Federation ”Research and Development in Priority Fields for the Development of Russia’s Science and Technology Complex for 2007-2013”, contract no.16.518.11.7072.

[1] E.N. Alexeyev et al., Proc. 16th ICRC, Kyoto, 10, 276 (1979)
[2] A.V. Voevodsky et al., Russ. J. Izvestiya of RAS, ser. phys. 58,N12, 127 (1994)
[3] V.N. Bakatanov, Yu.F. Novoseltsev, R.V. Novoseltseva. Astrop. Phys. 12, 19 (1999)
[4] Yu.F. Novoseltsev. Russ. J. Nuclear Phys. 63, 1129 (2000)
[5] V.N. Bakatanov, Yu.F. Novoseltsev, R.V. Novoseltseva. Proc. 27th ICRC, Hamburg, 1, 84 (2001)
[6] V.N. Bakatanov, Yu.F. Novoseltsev, R.V. Novoseltseva. Astrop. Phys. 8, 59 (1997)
[7] Yu.F. Novoseltsev. Doctor of Sciences Thesis, Institute for Nuclear Research of RAS, Moscow, 2003
[8] Swordy S.P. Proc. 23th ICRC, Calgary, 1993, Rapporteur Papers, p.243
[9] Asakimori K. et al. Proc. 24th ICRC, Rome, 2, 728 (1995)
[10] Amenomori M. et al. Proc. 24th ICRC, Rome, 2, 736 (1995)
[11] Yu.F. Novoseltsev, R.V. Novoseltseva, G.M. Vereshkov. arXiv:1108.4245v2