ALL PARTICLE ENERGY SPECTRUM OF COSMIC RAYS
IN $10^{15}$ to $10^{20}$eV Region

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ABSTRACT

Average estimations of the shower energy components are presented and their sum gives $\langle E_o \rangle$ - an average function of the relation of $E_o$ with the shower size parameter $\rho_{600}$ measured at the Yakutsk EAS array. Using this relation to the EAS spectrum obtained at the Akeno and Yakutsk arrays the energy spectrum of the cosmic ray total flux within $15 \leq \lg(E_o\text{[eV]}) \leq 20$ by the EAS methods is recovered.

1. Introduction. Earlier beginning from 1971 we estimated the primary energy $E_o$ on the atmospheric Cerenkov light flux density on the core distance 400 m at the Yakutsk EAS array [1]. Last years the experimental data on a maximum depth, muon energy spectrum and other average characteristics of the EAS development are obtained which are important to estimate the shower energy components. By a balance of the latters one can determine the $E_o$.

2. Estimation of $E_o$ by Energy Balance Method. The shower primary energy consists of the next components: $E_o = E_{ei} + E_{hi} + E_{h} + E_{\mu} + E_{\nu} = E_i + E$, where the first three terms show the energy loss into the atmosphere ionization ($E_i$) by electrons, muons and by splitting the nuclei and the last four ones - the energy dissipated in the earth in the form of electron-photon, nuclear-active, muon and neutrino components ($E$). Our estimation [2] differs from one [4] by accounting of the atmospheric Cerenkov light losses [5] on which $E_i$ - a main component of the $E_o$ is estimated and by use of the new measurement results of the muon energy spectrum for $E_{\mu}$.

$E_{ei}$. For $10^{17} \leq E_o \leq 10^{19}$eV the relation of $E_{ei}$ with the atmospheric Cerenkov light total flux $\Phi_h$ (in number of photons) and from the depth of maximum of showers $X_{\text{max}}$ (g.cm$^{-2}$) is given by $E_{ei} = 2.07 \cdot 10^4 (1.04 + 5.8 \cdot 10^{-4} \cdot X_{\text{max}})^{-1} \cdot J^{-1} \cdot \Phi_h\text{eV}$ where $J = J_m \cdot J_a < 1$ is a light transmittance.
coefficient by atmosphere due to molecular (Rayleigh $J_m$) and aerosol ($J_a$) scatterings. According to [6 et al] a main aerosol part is in a ground layer of ~1 km thickness.

If to assume that the aerosol is concentrated at depth $>900$ g.cm$^{-2}$ and $J = 0.6$ at $E_o = 10^{16}$ eV then $J = 0.62$ at $E_o = 10^{18}$ eV. According to these estimations we took $J = 0.60 \pm 0.04$. Then due to the experimental dependence $X_{max}$ from $\rho_{600}$ and the observed correlation of $\Phi_m$ with $\rho_{600}$ [7] we found the average value $lg(E_{bl}[eV]) = (0.98 \pm 0.05) \cdot lg \rho_{600} + 17.620 \pm 0.079$.

$E_{hi}$ * Its value is small and is observed to be equal to the average meaning expected from calculations by different EAS development models, $E_{hi} = (0.12 \pm 0.09) \cdot E_{\mu}$.

$E_{hi}$ * If to suppose that the average part of hadrons on the atmosphere $P_h(X) = 0.02 \pm 0.01$ from $N_e(X)$, average energy of the nuclear splitting $\epsilon_{nd} = 0.5$ GeV[8] and adding the usual ionization losses of hadrons we found $E_{hi} = (5.6 \pm 2.2) \cdot 10^{-2} \cdot E_{ei}$. If $P_h(X)$ and $\epsilon_{nd}$ are somewhat overestimated then it is probably quite compensated in estimation of $E_{hi}$ by not accounted here the effect of photonuclear reactions [9].

$E_{\mu}$ * When the muon component registration threshold $\epsilon_{\mu,thr} = 1$ GeV, as it is at the Yakutsk array, then $E_{\mu} = \epsilon_{\mu} \cdot N_\mu (>) GeV$ where the muon component energy $\bar{\epsilon}_{\mu} =$ $[N_\mu (>) GeV]^{-1} \cdot \int_{0}^{\infty} \epsilon_{\mu} \cdot dN_\mu (\epsilon_{\mu} > \epsilon_{\mu}) = a \cdot (\sqrt[\nu]{1 - 1})^{-1}$

$\cdot (1 + a^{-1})$ for the energy spectrum of the shower muons in form $N_\mu (\epsilon_{\mu} > \epsilon_{\mu}, GeV) \propto (\epsilon_{\mu} + a)^{-\nu}$ which refers to one muon with $\epsilon_{\mu} > 1$ GeV. Calculations show that when the muons generated only due to decay of pions and kaons then the muon energy spectrum does not almost depend on the EAS development model and the $\epsilon_{\mu}$ very poorly depends on $E_o$. From unique measurement results of the muon energy spectrum in showers with $N_e = 2 \cdot 10^5$ at sea level [10] we find that $a = 10$ GeV, $\nu = 1.64$ and $\bar{\epsilon}_{\mu} = 18.2$ GeV. At $\epsilon_{\mu,thr} = 1.1$ GeV [11], $5$ GeV [12] and in the case $N_e = 10^6$ [13] the results confirm the mentioned approximation (Fig.1). Using $\bar{\epsilon}_{\mu} = (16 \pm 3)$ GeV and the observed relation $lgN_\mu (>) GeV) = (0.84 \pm 0.08) \cdot lg \rho_{600} + 6.491 \pm 0.042$ [3] we obtain
\[
\log(E_\mu, [\text{eV}]) = (0.84 \pm 0.08) \log p_{600} + 16.699 \pm 0.086 - 0.107
\]

Assuming that the neutrino carries away 27, 90 and 67\% of the muon energy due to decay of pions, kaons and muons, respectively, and the ratio of kaons to pions is 0.22 \pm 0.09 [8] we obtain \( E_\nu = (0.64 \pm 0.18) E_\mu \).

Adding all the above components of \( E \) based considerably on the experiment the average estimation is as follows:

\[
\log(E_0, [\text{eV}]) = (0.98 \pm 0.03) \log p_{600} + 17.754 \pm 0.066
\]

3. Energy Spectrum of the Primaries. Using the above estimation of \( E_0 \) for the EAS spectrum obtained on the Akeno and Yakutsk array data in a corrected form [3] the energy spectrum of all the particles at energies \( 15 \leq \log(E_0, [\text{eV}]) \leq 20 \) is recovered. It is shown in Fig.2 where the dashed lines correspond to the results at \( E_0 \pm \Delta E_0 \). As it is seen this spectrum reveals significant irregularities and being approximated by a form \( J(E_0) dE_0 \propto E_0^{-\gamma} dE_0 \) it has the following exponents:

\[
\begin{align*}
\Delta \log E_0 & = 15 \pm 16, \ 16 \pm 17.5, \ 17.5 \pm 18.2, \ 18.2 \pm 18.9, \ 18.9 \pm 19.4, \ 19.4 \pm 20, \\
\gamma & = 2.59 \pm 1.18, \ 2.91 \pm 1.4, \ 2.99 \pm 0.4, \ 3.63 \pm 0.05, \ 2.47 \pm 0.09, \ 3.48 \pm 0.11
\end{align*}
\]

Integral intensities with account of accuracy of the determination of \( E_0 \) are as follows:

\[
I(E_0, [\text{eV}]) \begin{cases} 15 & 16 \ 17 & 19 \ 10^{-6} & 10^{-8} & 10^{-12} & 10^{-14} \end{cases}
\]

\[
I(>E_0, m \cdot s \cdot sr) (2.3 \pm 0.6) \times 10^{-5} (5 \pm 1.6) \times 10^{-8} (6 \pm 2) \times 10^{-12} (3 \pm 1) \times 10^{-14}
\]

Fig.1. 1- [10], 2- [13], 3- [12], 4- [11], 5- \( N_\mu (>E_\mu) \propto (E_\mu + 10)^{-1.64} \)

Fig.2. 1- Yakutsk and 2 - Akeno [3], 3- [14], 4- [15], 5- at \( E_0 + \Delta E_0 \) (upper) and \( E_0 - \Delta E_0 \) (lower), 6- [16].
4. Discussion. A good agreement with results of energy balance of small EAS [14] and of a direct calorimetry [15] testifies a correctness of \( E_0 - \rho_{600} \) obtained by us. The latter one is \( \log E_0 = (0.94 \pm 0.03) (\log N_e - 8.042) + 17.754 + 0.066 - 0.077 \) for measurements at Akeno (920 g.cm\(^{-2}\)).

For \( \log(E_0, [eV]) \leq 19 \) the spectrum reveals a consistent steepening with energy \( E_0 \) which considerably differs from its earlier accepted form [16 et al]. It more corresponds to a picture expected at the diffusion of the mixture of the galactic origin nuclei [17]. The irregularity (rather "bump"-type) at \( 19 \leq \log(E_0, [eV]) \leq 20 \) is difficult to interpret by evidence of an extragalactic component: the particles of these energies also arrive from low galactic latitudes mainly and their anisotropy phase changes with \( E_0 \) [18 et al].

References