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

D.D.Krasilnikov, M.N.Dyakonov, A.A.Ivanov, V.A.Kolosov, F.F.Lischenyuk, I.Ye.Sleptsov

Institute of Cosmophysical Research & Aeronomy, Lenin Ave., 31 677891 Yakutsk, USSR

ABSTRACT

Average estimations of the shower energy components are presented and their sum gives $\langle E_0(\rho_{600})\rangle$ – an average function of the relation of E_0 with the shower size parameter ρ_{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 $15 \lesssim \lg(E_0, [\text{eV}]) \lesssim 20$ by the EAS methods is recovered.

1. Introduction. Earlier beginning from 1971 we estimated the primary energy E_0 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_0.

2. Estimation of E_0 by Energy Balance Method. The shower primary energy consists of the next components: $E_0 = E_{ei} + E_{\mu i} + E_{hi} + E_{e\gamma} + E_h + E_\mu + E_\nu = E_i + E$, 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_{ei} – a main component of the E_0 is estimated and by use of the new measurement results of the muon energy spectrum for E_μ.

E_{ei}. For $10^{17} \lesssim E_0 \lesssim 10^{19}$eV the relation of E_{ei} with the atmospheric Cerenkov light total flux Φ_H (in number of photons) and from the depth of maximum of showers X_{max} (g.cm^{-2}) is given by $E_{ei} = 2.07\cdot10^4(1.04+5.8.10^{-4}\cdot X_{max})^{-1}\cdot \mathcal{T}^{-1}\cdot \Phi_H$,eV where $\mathcal{T} = \mathcal{T}_m \cdot \mathcal{T}_a < 1$ is a light transmittance coefficient by atmosphere due to molecular (Rayleigh $\mathcal{T}_m$) and aerosol ($\mathcal{T}_a$) 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 $\mathcal{T} = 0.6$ at $E_o = 10^{16}$eV then $\mathcal{T} = 0.62$ at E_o 10^{18}eV. According to these estimations we took $\mathcal{T} = 0.60 \pm 0.04$. Then due to the experimental dependence X_{max} from ρ_{600} and the observed correlation of Φ_H with ρ_{600} [7] we found the average value $\lg(E_{ei}, [eV]) = (0.98 \pm 0.05) \cdot \lg \rho_{600} + 17.620^{+0.079}_{-0.097}$.

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

$\underline{E_{hi}}$. 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 $\varepsilon_{nd} = 0.5$ 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 ε_{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].

$\underline{E_\mu}$. When the muon component registration threshold $\varepsilon_{\mu,thr} = 1$ GeV, as it is at the Yakutsk array, then $E_\mu = \bar{\varepsilon}_\mu \cdot N_\mu (> 1 \text{ GeV})$ where the muon component energy $\bar{\varepsilon}_\mu =$

$$= [N_\mu (> 1 \text{ GeV})]^{-1} \cdot \int_0^{\varepsilon_{\mu,max}} \varepsilon_\mu \cdot dN_\mu (> \varepsilon_\mu) \simeq a \cdot (\nu - 1)^{-1} \cdot$$

$\cdot (1 + a^{-1})^\nu$ for the energy spectrum of the shower muons in form $N_\mu (> \varepsilon_\mu, \text{GeV}) \propto (\varepsilon_\mu + a)^{-\nu}$ which refers to one muon with $\varepsilon_\mu > 1$ 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 $\bar{\varepsilon}_\mu$ 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 $\bar{\varepsilon}_\mu = 18.2$ GeV. At $\varepsilon_{\mu,thr} = 1.1$ GeV [11], 5 GeV [12] and in the case $N_e = 10^6$ [13] the results confirm the mentioned approximation (Fig.1). Using $\bar{\varepsilon}_\mu = (16 \pm 3)$GeV and the observed relation $\lg N_\mu (> 1 \text{ GeV}) = (0.84 \pm 0.08) \cdot \lg \rho_{600} + 6.491^{+0.042}_{-0.046}$ [3] we obtain

$$\lg(E_\mu, [eV]) = (0.84 \pm 0.08) \cdot \lg \rho_{600} + 16.699^{+0.086}_{-0.107}$$

E_ν. 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±0.09 [8] we obtain $E_\nu = (0.64 \pm 0.18) \cdot E_\mu$.

Adding all the above components of E_0 based considerably on the experiment the average estimation is as follows:

$$\lg(E_0, [eV]) = (0.98 \pm 0.03) \cdot \lg \rho_{600} + 17.754^{+0.066}_{-0.077}.$$

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 $15 \lesssim \lg(E_0, [eV]) \lesssim 20$ 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 $J(E_0)dE_0 \propto E_0^{-\gamma-1}dE_0$ it has the following exponents:

$\Delta \lg E_0$	15.÷16.	16.÷17.5	17.5÷18.2	18.2÷18.9	18.9÷19.4	19.4÷20.
$\gamma+1$	2.59±.18	2.91±.13	2.99±.04	3.63±.05	2.47±.09	3.48±.11

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

$\lg(E_0, [eV])$	15	16	17	19
$I(>E_0)$, m.s.sr	$(2.3\pm0.6)10^{-6}$	$(5\pm1.6)10^{-8}$	$(6\pm2)10^{-12}$	$(3\pm1)10^{-14}$

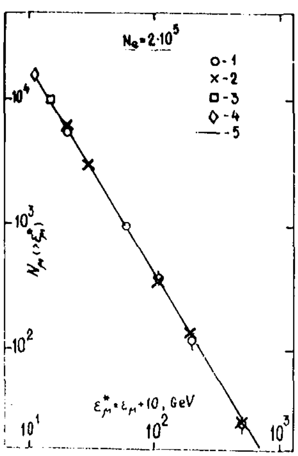

Fig.1. 1- [10], 2- [13], 3- [12], 4- [11], 5- $N_\mu(>\mathcal{E}_\mu) \propto (\mathcal{E}_\mu + 10)^{-1.64}$

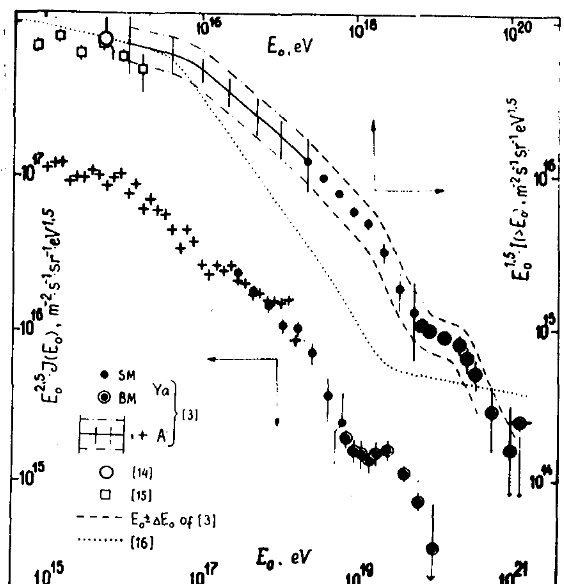

Fig.2. 1-Yakutsk and 2 - Akeno [3], 3- [14], 4 - [15], 5- at $E_0 + \Delta E_0$ (upper) and $E_0 - \Delta E_0$ (lower), 6 - [16].

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 $\lg E_0 = (0.94 \pm 0.03)(\lg N_e - 8.042) + 17.754^{+0.066}_{-0.077}$ for measurements at Akeno (920 $g.cm^{-2}$).

For $\lg(E_0, [eV]) \lesssim 19$ 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 $19 \lesssim \lg(E_0, [eV]) \lesssim 20$ 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

1. Egorov, T.A., et al., (1971), Proc.12-th ICRC, Hobart, 6, 2164.
2. Krasilnikov, D.D., i dr., (1983), Kosmicheskiye Luchi s Energiei Vyshe 10^{17}eV, Yakutsk, 117-143.
3. Krasilnikov, D.D., et al., (1985), (This Conference).
4. Diminstein, O.S., et al., (1975), Proc.14-th ICRC, München, 12, 4318.
5. Dyakonov, M.N., et al., (1983), Proc.18-th ICRC, Bangalore, 6, 210.
6. Tennekes, H., (1974), The Atmosphere Boundary Layer, Phys.Today, 52.
7. Kolosov, V.A., (1982), Thesis, FIAN SSSR.
8. Murzin, V.S., Sarycheva, L.I., (1968), Kosmicheskiye Luchi I Ikh Vzaimodeistvie, M., Atomizdat, 391.
9. McComb, T.J.L., et al., (1979), Proc.16-th ICRC, Kyoto, 9, 126.
10. Grishina, N.V., et al., (1981), Proc.17-th ICRC, Paris, 6, 3.
11. Hara, T., et al., (1983), Proc.18-th ICRC, Bangalore, 11, 281.
12. Khrenov, A.B., (1961), ZhETF SSSR, t.41, 1402.
13. Atrashkevich, V.B., et al., (1983), Proc.18-th ICRC, Bangalore, 11, 229.
14. Nikolsky, S.I., (1962), 5-th Interamer.Seminar on C.R. La Paz, 2, 18-1.
15. Grigorov, N.L., et al., (1971), Proc.12-th ICRC, Hobart, 5, 1748.
16. Greisen, K., (1965), Proc.9-th ICRC, London, 2, 609.
17. Ginzburg, V.L., Syrovatsky, S.I., (1963), Proiskhozhdeniye Kosmicheskikh Luchei, izd.AN SSSR, M., 384.
18. Krasilnikov, D.D., et al., (1983), Proc.18-th ICRC, 9, 223.