ENERGY SPECTRA OF PROTONS AND NUCLEI OF PRIMARY COSMIC RAYS IN THE ENERGY REGION ABOVE 10 TEV/PARTICLE

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ABSTRACT

Experimental data of energy spectra of the main groups of primary cosmic rays for an exposure of 110 m^2hr and preliminary results for a new exposure of 130 m^2hr are presented.

1. Results. In the previous papers /1-3/ we reported preliminary results on the proton and helium nuclei spectra. For nuclei heavier than helium the total cascade spectrum only was presented. Experimental data were obtained in exposure of 92*46*8 cm^3 emulsion chamber with lead on board balloons at a mean depth of 11 g/cm^2 in the atmosphere in six flights in 1975 and 1978. The total exposure time is 260 hours. Up to date we divided cascades produced by nuclei with $Z \geq 3$ into groups with charges 6-9 (M), 10-19 (H), $\geq$20 (VH). An accuracy of measurement of Z for these groups is 1, 1.7 and 3 charge units, respectively /4/. The results are presented in Fig.1, data on protons and helium nuclei are shown in Fig.2.

Intensities of nuclei with $Z \geq 3$ can be well described by extrapolation of data from /5/ the energy region < 1TeV/nucleon in power law with $\gamma_Z + 1 = 2.6-2.7$.

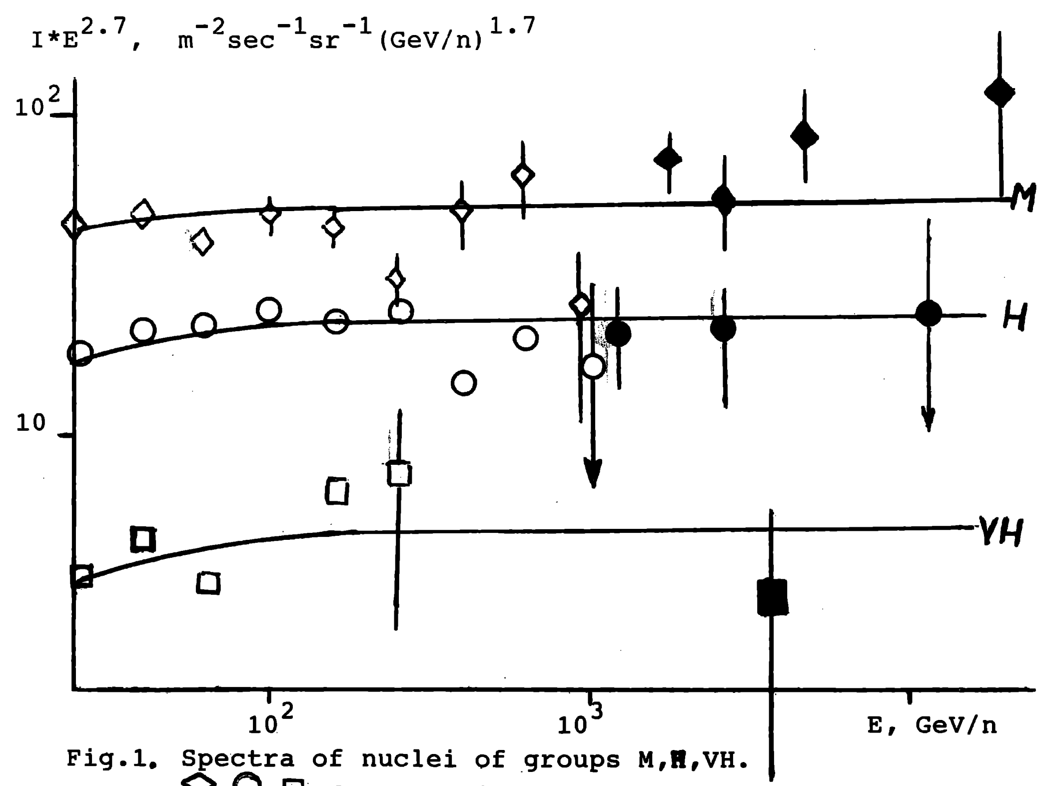

Fig.1. Spectra of nuclei of groups M, H, VH.
◇, ○, □ - data of Simon M. et al., /5/
◆, ●, ■ - the present paper data

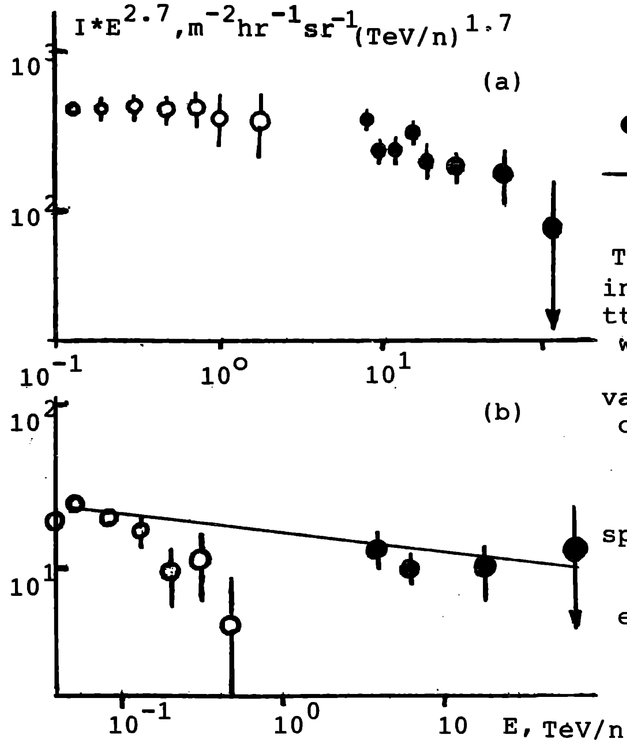

Fig.2.
Spectra of protons (a) and helium nuclei (b)
o - data of Rayan et al.,/10/
● - the present data

The spectrum of helium nuclei in a wide energy range is better described by a power law with $\gamma_{He}+1=2.8$, and the proton spectral index probably varies from 2.7 in the region of energy less than 5 TeV to $\gamma_p+1 \gtrsim 3$ at higher energies. Comparison with JACEE data on the proton and helium spectra was presented in /3/.

2. Simulation. Proton energy in the experiment was determined by the formula :

$$E_p = \varepsilon \cdot k^{-1}_{\gamma,eff}\, G^{-1}(\varepsilon),$$

where ε is the energy of e^+e^- pair which at the shower maximum gives darkness equal to that measured in X-ray film. To calculate an electromagnetic cascade, core approximation was used, and function $G(\varepsilon)$ regards the difference between hadron and electromagnetic cascades /1/. To check procedures used cascades were simulated using proton spectrum with $\gamma_p+1=2.7$. When simulating proton interaction with lead nucleus, π-mesons were assumed to result from resonance decays /6/. Electromagnetic cascade was simulated according to the scheme /7/. As a result of simulation the matrix of cascade electron density $\rho(t,r)$, where t is the depth in chamber and r is the distance from the axis, was calculated for each event. Using this matrix optical density of X-ray film in a circle was calculated and then distorted in accordance with normally distributed measurement fluctuations.

To determine the energy of artificial cascades, the same procedures as in experiment were used. Eight series of cascades were simulated with statistics in each series equal to the experimental statistics. In each series the index of proton spectrum at $E_p>7.8$ TeV ($\varepsilon>1.6$ TeV) was determined. The results obtained are listed in Table 1.

Table 1

	simulation								experiment
N	220	250	240	274	255	254	225	229	273
γ_p+1	2.89	2.63	2.82	2.68	2.60	2.62	2.87	2.59	3.09
σ_γ	0.11	0.12	0.12	0.11	0.10	0.11	0.11	0.11	0.13

The mean value of the index of restored proton spectrum at simulation proved to be equal to 2.72+0.04, the dispersion of individual values being 0.13, that does not exceed the expected value for given statistics.

The experimental value of $\gamma_p+1=3.09$ deviates by three r.m.s. from the meanvalue for simulated series. If the distribution is Gaussian the probability of this value to agree with the mean value of $\gamma_p+1=2.7$ is 0.3%.

3. Detection of gamma-quanta from the residual atmosphere

Gamma-quanta from the residual atmosphere are detected by a chamber both as individual cascades and as constituents of families. To identify these cascades, the following criteria were assumed: i) the vertex of cascade is located at depth $t<4$ c.u. from the top of the chamber; ii) the number of particles in a beam at a depth of $\lesssim 1$ c.u. from the vertex is <10, the beam width being $\Delta l<10$ mm. For $\varepsilon>1.6$ TeV the number of electromagnetic cascades was found to be $n_\gamma=35$ (21-quanta in families and 14 - individual γ-quanta). The expected ratio of the number of γ-quanta from the residual atmosphere to the number of proton-induced cascades is determined by the expression:

$$\frac{n_\gamma}{n_p}=Z_0\frac{(1-\exp(-y/\Lambda))}{W_p\cdot\exp(-y/\Lambda)}\cdot\frac{\Lambda}{\lambda}\cdot R,\quad R=\frac{1}{(\gamma+1)}\cdot\langle k^{\gamma}_{\gamma,p-Pb}\rangle^{-1}\cdot\int_0^1 x^{\gamma}\frac{dn_\pi}{dx}\cdot dx, \quad (1)$$

where y is the mean depth of exposure, x being the Feynman variable, $k_{\gamma,p-Pb}$ is the energy fraction transferred into γ-quanta in the proton interaction with lead nuclei, Z_0 is the coeffitient regarding the contribution of nuclei, γ is the integral spectrum index, W_p stands for the probability of proton registration and Λ, λ are the proton absorption and interaction paths in air. Estimation of R in (1) was made in terms of the model /8/ for various γ. For $\gamma=1.7$, (1) yields the value $n_\gamma/n_p=0.23$. The observed ratio $n_\gamma/n_p=0.13\pm0.02$ is obtained at $\gamma=2.1\pm0.14$, i.e. steeper nucleon spectrum is required.

One more evidence in favour of steep proton spectrum is given by the ratio of the numbers of γ-quanta and hadrons in families. Among 50 cascades with $\varepsilon>1.6$ TeV observed in 14 families 21 cascades are produced by γ-quanta and 29 cascades are hadron-induced ones. Simulation of family generation in the atmosphere /9/ and detection of families in chamber yielded $n_\gamma/n_h=1.7$ for the "normal" chemical composition and $\gamma+1=2.7$, while the observed value is $n_\gamma/n_h=21/29=0.72$, that deviates from calculated value by 2 r.m.s. This result can be expected if the proton fraction in the primary spectrum is smaller than in normal composition (by a factor of 2).

4. New exposure. In summer 1986 we made two flights at a mean depth of $13 g/cm^2$. The total exposure time of two flights was 310 hours. Up to date we found the origin only for high energy cascades ($\varepsilon>$ 10 TeV).

Table 2

0 - 72°			$S\Omega T=260\ m^2hr\ sr$			
ε, TeV	n_p	n_{He}	n_Z	n_{Sh}	n_F	n_γ
10-20	9	1	3	5	4	3
20-40	5	0	1	0	0	0
40-80	2	1	0	0	0	0
>80	0	0	0	0	0	0

In table 2 n_{He}, n_Z, denote numbers of cascades produced by helium and nuclei with $Z\geq3$, n_{Sh} -number of cascades which observed as a shower in the first emulsion layer just below the chamber cover. The cascades observed as members of families called F-cascades, n_γ- denotes the cascades produced by single γ- quanta. All the other cascades were attributed to p - group.

Due to long-duration flights background conditions were worse than in previous flights. Therefore now we are still not sure that each helium produced cascade was identified.

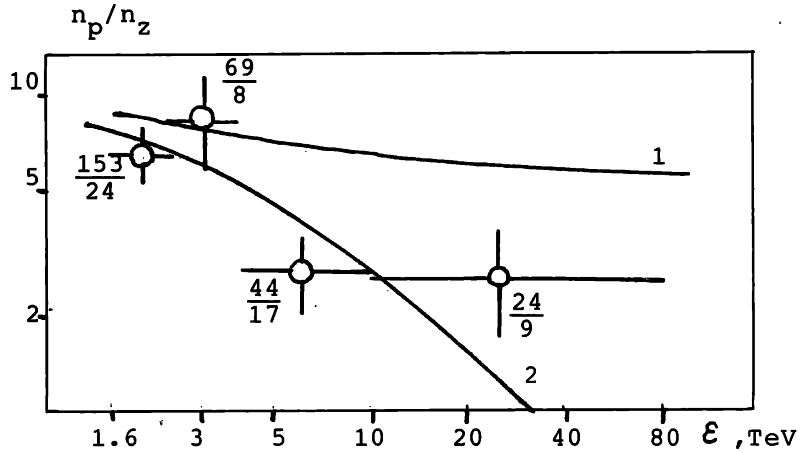

Fig.3. Energy dependence of the ratio of the number of proton cascades to the number of cascades induced by nuclei heavier than helium ones

Fig.3 shows the energy dependence of ratio n_p/n_z. This presentation decreases the effects of methodical factors. For $\varepsilon < 10$ TeV previous data were used for the angular range 25-60° ($S\Omega T$= 160 m^2 hr sr), and for $\varepsilon > 10$ TeV the angular interval was extended and the total exposure available was used (500 m^2 hr sr). Curves 1 and 2 correspond to the expected dependences for two models of the proton spectrum: curve 1 is for a model in which $\gamma_p = \gamma_z = 1.7$ and curve 2 is for a model with increasing of γ_p up to value of 2.2 at $E_p > 5$ TeV. It can be seen that experimental data are a better fit for a version with a steepening proton spectrum.

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