Energy spectra of primary protons and other nuclei at energies of 10–100 TeV/particle

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The energy spectra of the main components of the primary cosmic rays were measured directly in a series of ten balloon flights which began in 1975 and continued until 1987. The results found on the basis of all the data accumulated are reported in this letter. The spectrum of primary protons at energies above 10 TeV is shown to be steeper than at lower energies and also steeper than the spectra of other nuclei.

The most important experimental tasks for reaching an understanding of the mechanisms for the acceleration of cosmic rays and the nature of their sources are to measure the energy spectra of the main groups of nuclei of the primary cosmic rays at energies above 1 TeV. The first measurements of this sort were carried out on board of Proton satellites.[1] The study of this energy region was continued in two balloon experiments with x-ray emulsion chambers, JACEE[2,3] and MUBEE (Moscow University Balloon Emulsion Experiment),[4] and also in the Sokol experiment, carried out in space.[5,6] In this letter we are reporting the overall results found in the MUBEE experiment in a series of six short exposures ($T \simeq 40$ h) and four long ones ($T \simeq 150$ h).

Experimental procedure. Each x-ray emulsion chamber exposed on the balloon flights consisted of 25 layers of a lead absorber, between which there were x-ray and nuclear films for recording. The area of the chamber was ~ 0.4 m^2; the thickness of the absorber along the vertical direction was 14.7 cascade units. The x-ray film was used for a visual search for cascades and for a determination of their energy ΣE_γ. The energy resolution in terms of ΣE_γ was $\sim$ 12% and was independent of both the energy and the nature of the primary particle. The total energy of the primary particle of type j was found from the expression

$$E_j = \Sigma E_\gamma / (k_{\gamma,\mathrm{eff}})_j.$$

Values of $(k_{\gamma,\mathrm{eff}})_j$ were calculated for a spectrum with an exponent $\beta = 1.7$ and were taken to be 0.25, 0.17, 0.116, 0.106, and 0.09 for protons, helium nuclei, and the nuclear groups M ($A=14$), H ($A=26$), and VH ($A=51$), respectively. The nuclear emulsion was used to determine the trajectory of the particle, to measure its charge, and to carry out an energy calibration by the track counting method. The spatial precision in the tracing was $\sim$ 200 μm, and the angular precision $\sim$ 0.2°. The charge of the primary particles with $Z \geqslant 6$ was measured by scanning the track in a nuclear emulsion on a scanning microphotometer. The resolution in terms of Z was 1, 1.7, and

TABLE I.

	p^*		He		M		H		VH	
E, TeV	N	ΓT	N	ΓT	N	ΓT	N	ΓT	N	ΓT
10–12.6	194	90								
12.6–15.8	137	113								
15.8–20	104	113	22	50	15	93				
20–25	70	136	11	50	15	93	21	76		
25–40	61	136	8	50	24	141	27	76	3	65
40–80	27	136	4	50	17	141	21	115	2	65
80–160	7	136	5	50	7	141	9	115	2	98
160–320	2	136	0	50	4	141	2	115	0	98
>320	0	136	1	50	0	141	0	115	0	98

3 charge units for the nuclei of the M, H, and VH groups, respectively. The charge of the helium nuclei was found by the grain counting method. If no track of a primary particle with a charge $Z \geqslant 2$ was found on the trajectory of a cascade, the latter was assumed to have been generated by a proton. The background of single γ rays from the residual atmosphere amounted to $\sim$ 5% of the proton cascades.

To determine the absolute flux, we calculated a generalized exposure characteristic $\Gamma = \langle S\Omega\eta W\rangle$. This characteristic incorporates not only the geometric factor $S\Omega$ of the instrument but also the conversion of the primary flux in the residual atmosphere, η, and the probability for an interaction in the chamber under the given selection conditions, W.

Results. The statistical data on the number of primary particles detected, N, over the interval of zenith angles 25–60° are shown in Table I. Also shown here are the exposure factors ΓT (in units of $\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mathrm{h}$) for each energy interval and for each type of primary particle. The values of ΓT are smaller in certain of the smaller energy intervals because the energy thresholds in terms of the measured energy ΣE_γ were higher in the two long exposures than in others.

On the long flights we were unable to identify cascades formed by helium nuclei (we will refer to them as "α cascades") because of the high background. The spectrum of helium nuclei was therefore constructed from the data of only the six short flights. To construct a proton spectrum from the data of all exposures, we used a mixture of proton and α cascades (p^* in Table I). On the short flights, the relative number of α cascades in the $p + \alpha$ mixture was 24 ± 4%. We accordingly calculated the proton intensity from

$$i_p = p^*/\Delta E_p \Gamma_p T k_1 k_2,$$

where $k_1 = 1.24$ incorporates the admixture of α cascades, and $k_2 = 1.25$ corrects for the intensity increase due to the finite energy resolution. The intensities of the other groups of nuclei were found from

$$i_j = N_j/\Delta E_j \Gamma_j T k_2.$$

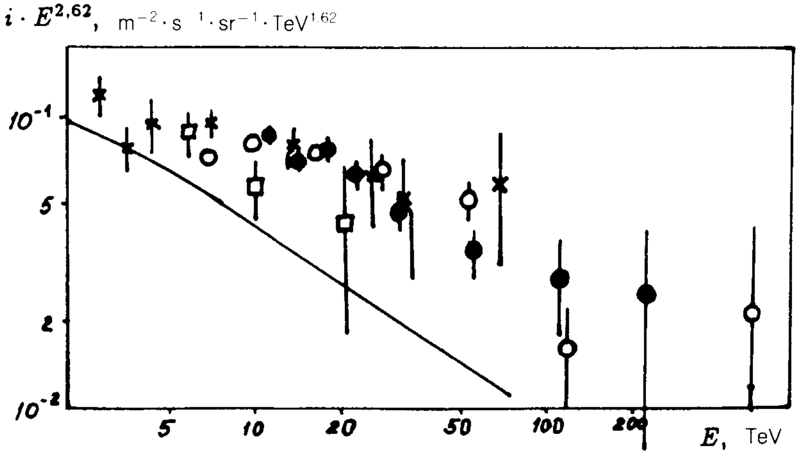

FIG. 1. Proton energy spectrum. ●—Present study; ○—Ref. 3; □—Ref. 5; × —Ref. 6; solid line—model of the spectrum from Ref. 1.

Discussion of results. We have space in this letter to discuss only the data on the proton component. The data we obtained from the proton spectrum are shown in Fig. 1. They can be described by

$$i_p = AE^{-(\beta+1)},$$

where $A = 0.3\ m^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot TeV^{-1}$, $\beta + 1 = 3.14 \pm 0.08$, and E is in TeV.

The only statistical base of proton events at > 10 TeV comparable to our own was that collected by the JACEE Collaboration.[3] It can be seen from Fig. 1 that our data and the JACEE data essentially coincide at > 10 TeV. This is the first time that such an agreement has been reached since these two groups reported their first results on the proton spectrum. Our data indicate that the proton spectrum at > 10 TeV is steeper than that at < 1 TeV,[7] while the JACEE data indicate no change in slope up to at least 100 TeV.[8] After the statistical base from the long-flights is added in, the JACEE case changes. Asakimori *et al.*[3] note some deficiency of protons at high energies and interpret that result as a possible steepening of the spectrum at > 40 TeV. To a large extent, that interpretation is a consequence of the low intensity measured at energies from 5 to 10 TeV in the JACEE study (the first JACEE point in Fig. 1). This point allows the authors to draw a spectrum with a slope of 2.62 up to 40 TeV and to state that a change in slope occurs only at higher energies. The proton spectrum measured in the Sokol experiment[6,7] confirms that the proton spectrum is steep at > 5 TeV, but the statistical accuracy of those data is not very good.

A steepening of the proton spectrum, and a difference between it and the spectra of the other nuclei of the primary cosmic rays, was first observed by Grigorov.[1] The data which we are reporting here confirm that result, but the slope changes apparently occur at an energy slightly higher than in Ref. 1. Since the assertion that there is a difference between the spectra of protons and nuclei is of fundamental importance in determining the origin and propagation of cosmic rays, further detailed measurements of the spectra of primary cosmic rays are required directly near the slope change, i.e., at energies of 1–10 TeV.

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