Energy spectrum and charge composition of primary cosmic rays with energy above 2 TeV

I. P. Ivanenko, I. D. Rapoport, V. Y. Shestoperov, Yu. V. Basina, P. V. Vakulov, Yu. Ya. Vasil'ev, R. M. Golynskaya, Yu. P. Gordeev, L. B. Grigor'eva, A. E. Kazakova, V. D. Kozlov, I. P. Kumpan, L. G. Mishchenko, V. M. Nikanorov, L. P. Papina, V. V. Platoniv, D. M. Podorozhnyĭ, G. A. Samsonov, L. G. Smolenskiĭ, V. A. Sobinyakov, G. E. Tambovtsev, Yu. V. Trigubov, I. M. Fateeva, A. N. Fedorov, L. A. Kheĭn, L. O. Chikova, V. Ya. Shiryaeva, B. M. Yakovlev, and I. V. Yashin

Scientific-Research Institute of Nuclear Physics at the M. V. Lomonosov State University, Moscow

(Submitted 20 September 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 9, 468–471 (10 November 1988)

The results of measurements of the energy spectrum and the charge composition of primary cosmic rays with an energy > 2 TeV and with a charge z ranging from 1 (for protons) to ~ 30 are presented. The experiment was carried out with the detectors "Sokol" and "Sokol-2" aboard the artificial earth satellites "Kosmos-1543" and "Kosmos-1713."

The results of measurement of the energy spectrum and charge composition of primary cosmic-ray particles with $z \geqslant 2$, carried out with the "Sokol" charged-particle detector, were reported by Ivanenko *et al.*[1] The hardware of this apparatus consisted of two sectioned Cerenkov detectors (DZ-1 and DZ-2) and a sectioned ionization calorimeter (IC) with ~ 5.5 mean-free paths for the nuclear interaction of protons. In 1985–1986, an upgraded detector "Sokol-2," aboard the artificial earth satellite "Kosmos-1713," worked continuously for 347 h. In this detector the ~ 700-fold light filters mounted in front of the photomultipliers of the ionization calorimeter were removed, two 3- and 2-cm-thick upper-layer lead absorbers of the ionization calorimeter were replaced by iron absorbers, and the measurement range of the DZ-1 detector over which it could measure the charge of light nuclei was expanded.

As a result of these modifications, the error in measuring the energy was reduced (to $\sim 15\%$) and the capability of reconstructing the particle path at the detector level was improved (to 0.5–1.0 cm). The return current of the ionization calorimeter was reduced by a factor of 1.5–2.0, improving the charge resolution of the apparatus.

In the Sokol-2 detector the vent-detecting control signal was produced when three signals were brought into coincidence: the signal in one of the sections of the DZ-1 detector, the total energy level of the ionization calorimeter, which exceeds E_{thr}, and the energy evolution in m rows of the absorber, which is greater than ϵ. The value of E_{thr}, m, and ϵ changed during the experiment. In the main regime (254 h) they were $E_{\text{thr}} = 1.2$ TeV, $m = 5$, and $\epsilon = 22$ GeV. During a 93-h period, $m = 7$, a value which is close to the first experimental regime ($m = 7$–8). The geometric factor of the apparatus differs slightly for various nuclei, ranging from 257 cm^2·sr to 275 cm^2·sr. We

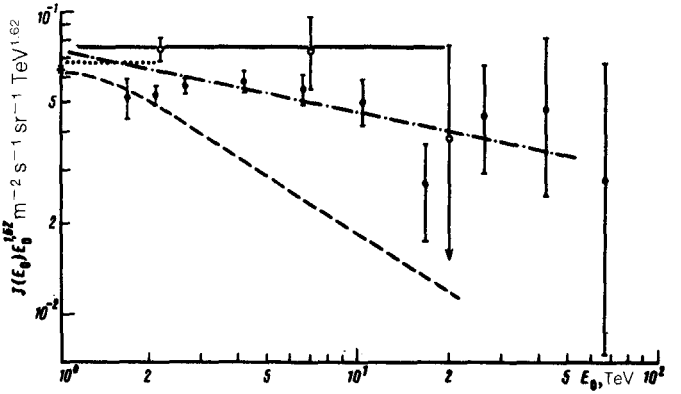

FIG. 1. Integrated proton spectrum. Filled circles—Our results; dashed line—results of Ref. 3; asterisk—results of Ref. 4; dotted line—Ref. 5; open circles—Ref. 6; dot-dashed line—Ref. 7.

detected more than 15 000 events, of which approximately 2×10^3 were within the limits of the solid angle of the apparatus (passage through the charge-particle detectors and the lower base of the ionization calorimeter). (More than 1×10^3 such events wre collected in 245 h of the first experiment).

For further analysis we selected particles which produced consistent signals in both detectors and which interacted in the three upper ionization-calorimeter absorbers. If z_1 denotes the reading of the detector for light nuclei (DZ-1) (in charge units) and z_2 denotes the reading of the detector for heavy nuclei (DZ-2), we can use the following criteria for separating particles according to charge. For protons: $0.7\leqslant z_1\leqslant 1.5$, $z_2<4$; for He nuclei: $1.5<z_1\leqslant 3.2$, $z_2<5$; for group M nuclei: $5<z_2\leqslant 9.5$, $z_1>3$; for group H: $9.5<z_2\leqslant 20.5$, $z_1>5$; for group VH: $20.5<z_2\leqslant 33$, $z_1>7$.

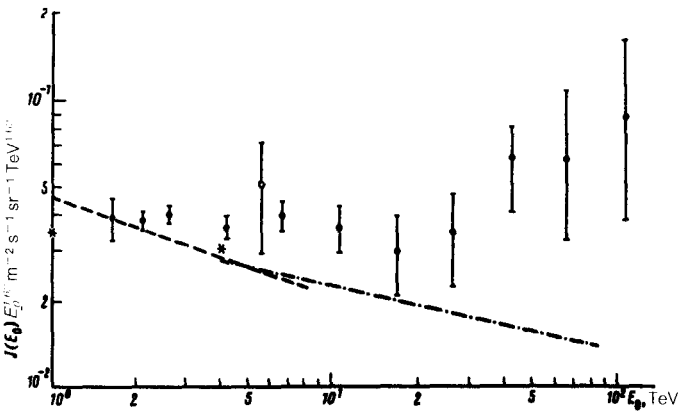

FIG. 2. Integrated spectrum of He nuclei. Filled circles—our results; asterisk—Ref. 4; dot-dashed line—Ref. 7; open circles—Ref. 8; dashed line—Ref. 9.

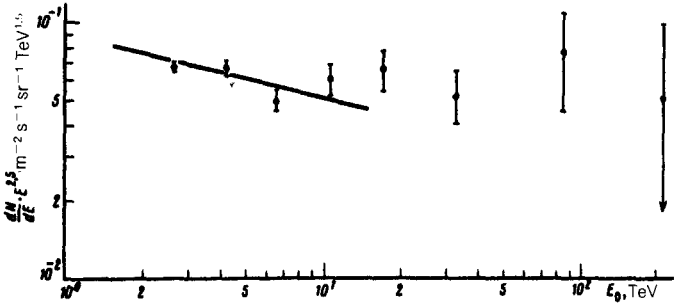

FIG. 3. Differential spectrum of nuclei with $z > 5$. Filled circles—our results; solid line—approximation of the data of Ref. 10.

To convert from the detected energy to the total energy E_0, we introduced, individually for each particle, corrections for the removal of the energy through the lower side walls of the ionization calorimeter and corrections for the energy which cannot be detected in the calorimeter. Data obtained from methodologically more sophisticated measurements of the second experiment have made it possible to refine the energy scale of the first apparatus and the particle selection criteria in comparison with those of Ref. 1 and to analyze all the data obtained.

TABLE I.

Nuclei	γ		
	$E_0 \geqslant 2$ TeV	$E_0 \geqslant 5$ TeV	$E_0 \geqslant 10$ TeV
p	1.58 ± 0.09	1.79 ± 0.18	1.99 ± 0.35
α	1.62 ± 0.10	1.60 ± 0.16	1.43 ± 0.26
$z > 5$	1.58 ± 0.06	1.41 ± 0.11	1.58 ± 0.18

TABLE II.

Nuclei	Our results			Data of Ref. 11	
E	> 2 TeV	> 10 TeV	> 20 TeV	> 1 TeV	> 10 TeV
p	38 ± 2	36 ± 7	30 ± 12	43	38
α	28 ± 2	25 ± 6	27 ± 10	19	19
M	13 ± 1	14 ± 4	12 ± 5	13.9	13
H	10 ± 1	15 ± 4	23 ± 7	15.1	16
VH	11 ± 1	10 ± 3	8 ± 4	9.6	14

Figure 1–3 show the combined energy spectra of protons, He nuclei, and nuclei with $z > 5$ (the sum of groups *M*, *H*, and *VH*) obtained from the two experiments and compare them with the results of other authors. With a statistical base of less than ten events, the errors were calculated in accordance with the procedure used in Ref. 2. In most cases there is an agreement with the published data on the index of the spectrum and on the intensity. At the same time, the measured proton spectrum is sharply at variance with the data of Ref. 3 in the energy region $E \gtrsim 2$–3 TeV. Table I gives the values of the exponents γ for the integrated energy spectra of various nuclei at energies $E_0 \geqslant E'$. Table II gives the charge composition of the primary particles (in %) at energies above 2, 10, and 20 TeV and compares it with the published data. Within the limits of statistical measurement errors, the exponent γ and the charge composition show no evidence of energy dependence.

[1]I. P. Ivanenko *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 200 (1986) [JETP Lett. **44**, 255 (1986)].
[2]O. Élen, Nuclear Technology Abroad **9**, 29 (1985).
[3]N. L. Grigorov *et al.*, Yad. Fiz. **11**, 1058 (1970) [Sov. J. Nucl. Phys. **11**, 588 (1970)].
[4]Galactic Cosmic Rays, Gosstandart SSSR, 1986.
[5]M. G. Ryan *et al.*, Phys. Rev. Lett. **28**, 985 (1972).
[6]V. V. Akimov, Dissertation, NIIYaF MGU, IKI AN SSSR, 1973.
[7]Y. W. Barnett *et al.*, Phys. Rev. Lett. **51**, 1010 (1983).
[8]P. Yain *et al.*, Phys. Rev. **115**, 654 (1959).
[9]N. L. Grigorov *et al.*, Cosmic Ray Research, Nauka, Moscow, 1975,p. 20.
[10]L. Simon *et al.*, Astrophys. J. **239**, 2, part I, 712 (1980).
[11]T. Linsley, Proc. 18 ICRC **12**,135 (1983).

Translated by S. J. Amoretty