Measurement of the proton spectrum at energies above 1 TeV by the Sokol detector on a satellite

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The results of measurements of the energy spectra of protons and other nuclei of high-energy cosmic rays on a satellite are discussed. The spectra were measured by a detector (proposed by the present author) in which, for the first time, the return current of particles to the charge detectors does not influence the selection of protons and helium nuclei. The spectra found agree with the results measured on the Proton satellite.

Measurements on the Proton satellite in 1965–66 resulted in the first measurements by direct methods of the proton spectra in the interval $\sim 10^{10}$–2×10^{13} eV and the spectrum of all cosmic-ray particles in the energy interval $\sim 3\times 10^{10}$–10^{14} eV (Ref. 1). The results of these measurements are shown below, in Fig. 3. From that figure we see that at $E > 1$ TeV the power index of the proton spectrum is 0.5–0.7 larger than that for the nuclei.

With regard to that result, there have been suggestions in the literature that the steepening of the proton spectrum might be caused by a return current of particles from the ionization calorimeter to the charge detector. (In the SÉZ-14 instrument which carried out the measurements on the Proton satellite, the charge detector consisted of large proportional counters.)

The difference between the proton spectrum and that of the nuclei is of fundamental importance to the physics of cosmic rays. I have accordingly undertaken a measurement of the proton spectrum at $E > 1$ TeV with apparatus of such a nature that a return current of particles to the charge detectors would not affect the results of the measurements. Discussions with S. N. Vernon and A. E. Chudakov yielded the requirements which an instrument would have to meet for such measurements.

The apparatus shown schematically in Fig. 1 was developed to meet these requirements. It consists of an ionization calorimeter with 80 scintillation ionization detectors. Above the ionization calorimeter are two groups of Čerenkov counters which detect the charge of the primary particles. The upper group (DZ-2) of four counters is used to measure the charge of nuclei with $Z \gtrsim 5$. The polymethyl methacrylate radiator in them is 1 cm thick. The light scattered by the white walls of the case is detected.

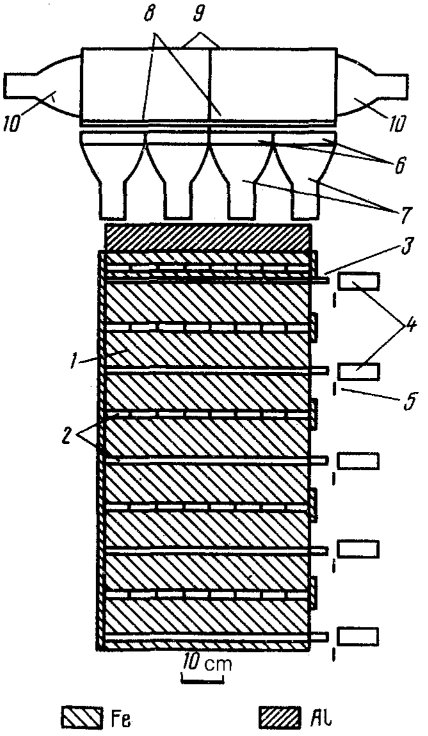

FIG. 1. Diagram of the Sokol detector. 1—Absorbers of ionization calorimeter; 2—scintillators; 3—optical fibers; 4—photomultipliers of ionization calorimeter; 5—shutters; 6—radiators of DZ-1; 7—photomultipliers of DZ-1; 8—radiators of DZ-2; 9—case of DZ-2; 10—photomultipliers of DZ-2.

Under these counters is a second group, DZ-1, of 11 counters in which the directionality of the Čerenkov radiation is exploited. In the counters of DZ-1, a polymethyl methacrylate radiator 5 cm thick is in optical contact with the photocathode of an FÉU-49 photomultiplier. The counters of DZ-1 are used for charge measurements from $Z = 1$ up to ~ 5 (in the Sokol-1 apparatus) or up to 15–20 (in the Sokol-2). The results which we will discuss in the present letter were obtained by means of the latter apparatus.

The Sokol apparatus has 95 independently operating detectors, in which the signal amplitudes are measured by 200 pulse-height analyzers upon command from a master signal. (The apparatus, its operating logic, the experimental conditions, and the selection of the detected particles are described in more detail in Ref. 2.) As a result, it was possible to reconstruct the geometry of each shower of secondary particles in the ionization calorimeter and to then use these results to determine the direction in which the primary particle is moving and the coordinate of its entrance into DZ-1, within an error ~ 1 cm.

To analyze the results of the measurements, we selected particles which passed through the detectors of DZ-1 and which were below the base of the ionization calorimeter. For them we determined the energy of the primary particle and the charge from the readings of those counters of DZ-1 and DZ-2 which were in the path of the primary particle. In addition, we determined the pulse heights (expressed as charges) in the counters of DZ-1 and DZ-2, through which the primary particle did not pass (the counters which also worked because of the return current).

To verify that a return current of particles in DZ-1 does not affect the selection of protons and helium nuclei in the Sokol apparatus, we took the following approach. We selected particles whose avalanches in the ionization calorimeter began below the first row of ionization detectors. These could be avalanches from primary particles with a

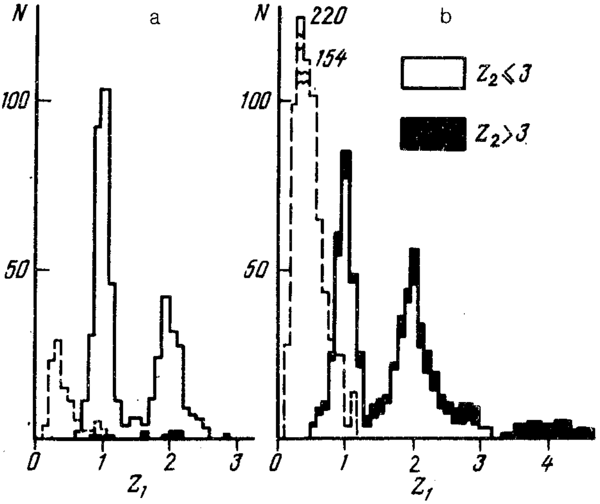

FIG. 2. Distribution with respect to Z_1 for various avalanche selection conditions. a—For avalanches which begin below the first row of the ionization calorimeter; b—for avalanches which begin in the first row.

range of more than 21 g/cm^2 (Al) + 23 g/cm^2 (Fe). Such showers could not be produced by nuclei with $Z > 5$. For the selected showers we plotted a distribution in the amount of charge in DZ-1 (Z_1). This is the white histogram in Fig. 2a in the case in which the signal in DZ-2 satisfies $Z_2 \leqslant 3$, or the black histogram in the case $Z_2 > 3$. It can be seen from Fig. 2a that the primary particles which produce the avalanches that begin in the interior of the ionization calorimeter are protons ($Z = 1$) and helium nuclei ($Z = 2$). We also see that for such showers there is no need to impose any restrictions on the value of Z_2. The dashed histogram is the distribution of pulses in the counters which additionally operated in these events. This distribution shows us that, on the average, one additional counter operates for about 10 detected particles, and the average signal in it is $Z_1 \approx 0.5$. In other words, in the showers which begin in the interior of the ionization calorimeter the return current is small and has no effect on the charge distribution of the primary particles.

For the avalanches whose beginning is detected by the first row of the ionization calorimeter, the Z_1 distribution is shown by the white histogram in Fig. 2b under the condition $Z_2 \leqslant 3$ and by the black histogram for $Z_2 > 3$. The dashed histogram is the distribution in the additionally operating counters. In these cases, an average of 1.5 counters operate additionally per event; i.e., the return current is about 15 times that in Fig. 2a. Nevertheless, the protons can be reliably distinguished from helium nuclei.

It can thus be asserted that the counters of DZ-1 identify protons in a process which is essentially unaffected by the return current of particles from the ionization calorimeter.

To verify that it is possible to use all events in detecting protons, regardless of the depth at which the first interaction occurs, we determined which fraction of the total number (N_0) of proton avalanches were avalanches which began in the various rows of the ionization calorimeter. These results are shown in Table I for two energy intervals, 1–2 and 2–10 TeV. Here N_1 is the number of avalanches which begin in the first row, $N_{2\text{-}3}$ is the number which begin in the second and third rows, and $N_{4\text{-}6}$ is the number which begin in the fourth, fifth, and sixth rows of the ionization calorimeter.

It can be seen from this table that the master signal introduces no discrimination in the number of avalanches which begin in any row of the ionization calorimeter. (Its

TABLE I.

	Experimental		Calculated
	1–2 TeV	2–10 TeV	
N_1/N_0	42 ± 4.4%	45 ± 5%	37%
N_{2-3}/N_0	35 ± 4%	36 ± 4.6%	40%
N_{4-6}/N_0	23 ± 3.3%	19 ± 3.4%	23%

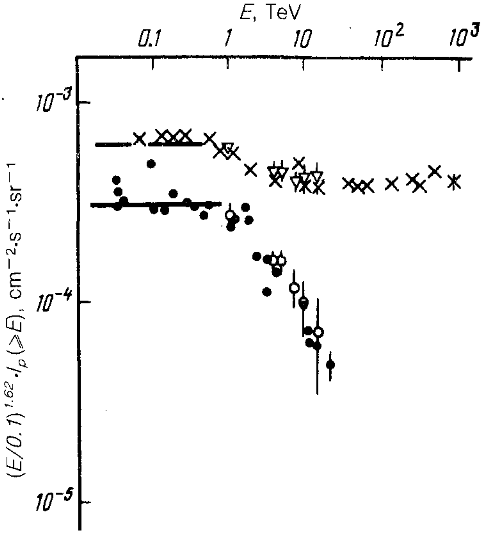

FIG. 3. Spectra of all particles (× and ∇) and of protons (● and ○) from the measurements by the SÉZ-14 detector on the Proton satellite[1,5] and the Sokol-2 detector on the KOSMOS-1713 satellite. Horizontal lines—the All-Union State Standard.[4]

effect would have been greatest at low energies, since the threshold energy of the particles which were detected was about 1 TeV.) We thus used the entire proton statistical base.

For comparison with the measurements by the SÉZ-14 detector on the Proton satellite, we corrected the measurements by the Sokol-2 detector for the fraction of the energy which was carried out of the ionization calorimeter. For this correction we used the same procedure which was used in analyzing the results of the measurements by the SÉZ-14 detector.[3] Yet a further advantage of this procedure is that the ionization calorimeters in the two detectors were nearly identical, differing only in the total thickness of the absorber.

As a result, we obtained integral spectra at energies $E \geqslant 2$ TeV for helium nuclei,

$I_\alpha(\geqslant E) = (39.6 \pm 2.8)(E/2)^{-(\gamma_\alpha - 1)}$ $m^{-2}\cdot h^{-1}\cdot sr^{-1}$ with $(\gamma_\alpha - 1) = 1.60 \pm 0.13$; for nuclei with $Z > 2$,

$I_Z(\geqslant E) = (48.0 \pm 2.8)(E/2)^{-(\gamma_Z - 1)}$ $m^{-2}\cdot h^{-1}\cdot sr^{-1}$ with $(\gamma_Z - 1) = 1.61 \pm 0.10$ and for protons at energies $E \geqslant 4$ TeV,

$I_p(\geqslant E) = (15.3 \pm 1.8)(E/4)^{-(\gamma_p - 1)}$ $m^{-2}\cdot h^{-1}\cdot sr^{-1}$ with $(\gamma_p - 1) = 2.08 \pm 0.15$.

This proton spectrum is shown in Fig. 3. The spectrum of all particles, $I_{CR} = I_p + I_\alpha + I_z$, is shown in the same figure. The points at $E = 1$ TeV on both spectra were found through an extrapolation of the corresponding spectra.

It can be seen from Fig. 3 that the proton spectrum and the spectrum of all particles measured by the Sokol-2 agree well with the corresponding data obtained by the SÉZ-14 detector on the Proton satellite. This agreement means that the steepening of the proton spectrum detected in the experiments on the Proton satellite is not a consequence of an effect of a return current of particles to the charge detector.

[1] V. V. Akimov, N. L. Grigorov, V. Nesterov *et al.*, in: Proceedings of the 11th ICRC, Budapest, 1969, OG-99.

[2] N. L. Grigorov, I. P. Ivanenko, V. Ya. Shestoperov *et al.*, in: Preprint-99-43/64, Scientific-Research Institute of Nuclear Physics, M. V. Lomonosov Moscow State University, 1988.

[3] N. L. Grigorov, V. E. Nesterov, I. D. Rapport *et al.*, Yad. Fiz. **11**, 1058 (1970) [Sov. J. Nucl. Phys. **11**, 588 (1970)].

[4] "Galactic Cosmic Rays; Energy Spectra," All-Union State Standards 25645.122-85-25645.125-85, Goskomitet SSSR po standartam, Moscow, 1986.

[5] N. L. Grigorov, V. E. Nesterov *et al.*, Space Research, XII, Akademie-Verlag, Berlin, 1972, p. 1617.

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