Energy spectrum of primary cosmic-ray particles at 1–100 TeV from data from the Sokol package

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This letter reports data on the spectrum of particles of the primary cosmic rays and on the ratio of the proton flux to the flux of nuclei with $z \geqslant 2$ over the energy interval 1–100 TeV obtained from experiments carried out on the Kosmos-1543 and Kosmos-1713 satellites.

One of the basic problems in cosmic-ray physics is that of experimentally determining the energy spectrum of the primary particles at high energies. At the moment, the spectrum of primary cosmic rays with energies $E \lesssim 1$ TeV has been studied by various methods,[1,2] while the energy range 1–1000 TeV has not been studied adequately by direct experimental methods. In this range, the only experiment in which the spectrum of all the particles, in terms of the energy per particle, has been measured directly was that carried out on the satellites of the Proton series.[7–10] On the Proton satellites, the spectrum of all particles was measured through a measurement of the global flux of primary cosmic rays, without charge separation, by a calorimetric apparatus of relatively small thickness (between 1.7 and 3.1 times the proton interaction range λ).

In an effort to study the energy spectrum and charge composition of the primary cosmic rays at energies of 1–100 TeV, experiments have been carried out with the Sokol scientific package on the Kosmos-1543 and Kosmos-1713 satellites.[3,4] The package consisted of two types of Cerenkov charge detectors, which separated the primary particles into charge groups: protons, α particles, M, H, and VH. The energy was measured by an ionization calorimeter with an absorber 5.5λ thick. The apparatus and the criteria for selecting particles by charge within the solid angle are described in detail in Refs. 4–6.

Figure 1 shows differential energy spectra of all the particles detected in both experiments. These spectra were generated by summing the intensities of the various charge groups. For energies above 0.1 TeV, Fig. 1 also shows data on the spectrum of all particles from some reviews,[1,2] in differential form. In these results, the data on the intensities of the various charge groups which have been studied separately in various experiments by various methods have been summed. Also shown here are indirect data

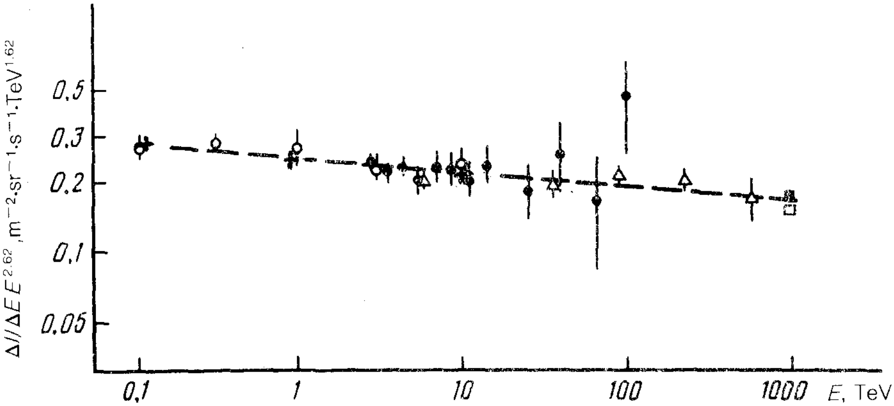

FIG. 1. Differential spectrum of all particles. ●—Present study; +—Ref. 1; ○—Ref. 2; △—small extensive air showers[2]; □—Moscow State University[12]; ■—Akeno[12]; dashed line—Ref. 2.

from small extensive air showers which were found in Ref. 2 on the basis of a model which retained scaling. The dashed line is an approximation of the differential spectrum of all particles found in this study. The χ^2 criterion for the agreement of our experimental data with this approximation is $\chi^2 = 0.61$ per degree of freedom.

Figure 2 shows an integral energy spectrum of all particles from the Sokol data. Over the energy interval 2–70 TeV this spectrum can be described by a power function with an argument $\gamma - 1 = 1.60 \pm 0.04$; the intensity of the particles with energies $E \gtrsim 2.5$ TeV is $(3.26 \pm 0.11) \times 10^{-2}$ m^{-2}·cr^{-1}·s^{-1}. Shown for comparison are experimental data obtained from the Proton satellites, data from Refs. 7–10, and an approximation of this spectrum proposed in Ref. 10. The energy scales in these experiments were reconciled on the basis of the geomagnetic effect at an energy of 12 GeV (Ref.

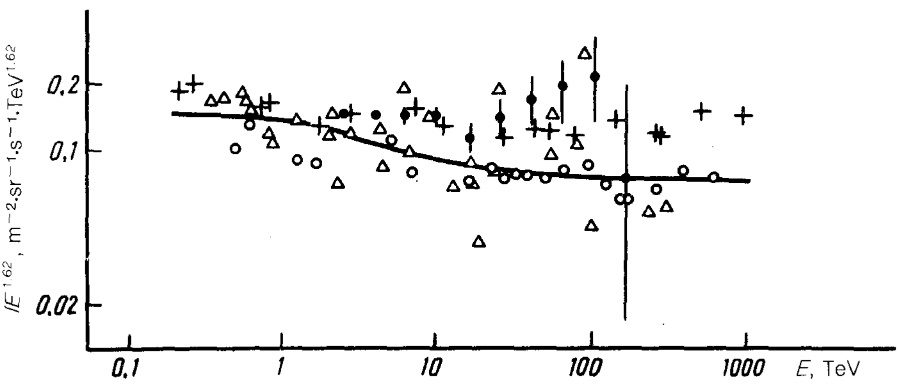

FIG. 2. Integral spectrum of all particles. ●—Present study; +—Refs. 8 and 9; ○—Ref. 7; △—Ref. 10.

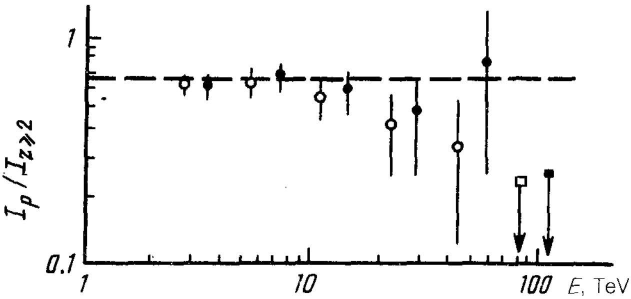

FIG. 3. Ratio of the proton intensity to the intensity of nuclei with $z \leqslant 2$ in the primary cosmic rays. O—Integral ratio; ●—differential ratio; dashed line—40% protons.

10). The error in the determination of the exponent for the energy spectrum, $\Delta\gamma = 0.05$, due to the error of the energy measurements, could cause an error ~25% in the intensity of the particles at ~1 TeV. The methodological uncertainty in our data also leads to an uncertainty ~20% in the intensity.

A distinctive feature of the approximation of the spectrum of all particles on the basis of the data from the Proton satellites (Fig. 2) is a step in the spectrum at 1–10 TeV, which the authors inferred from the steep primary-proton spectrum found in the measurements.[10] Figure 3 shows differential and integral (in the energy) ratios of the intensity of protons to the intensity of all nuclei with $z \geqslant 2$ according to the data from the Sokol instruments. It can be seen from this figure that over the energy range for which there is a reliable statistical base, up to 20–30 TeV, the relative number of protons in the primary cosmic rays remains ~40%. For the integral (again, in the energy) ratio there is an accumulation effect, so the low values of the ratio are associated with events with energies greater than ~100 TeV, where the statistical base is still shaky. Tabulated data on the charge composition of the primary cosmic rays found in the Sokol experiment were reported in Ref. 11.

1. J. Linsley in: 18 ICRC, Bangalore, 1983, Vol. 12, p. 135.
2. T. A. Danilova *et al.*, in: *Questions of Atomic Science and Engineering.* Series on Instrumentation for Experimental Physics, No. 3 (20), 1984, p. 20.
3. S. N. Vernov *et al.*, Izv. Akad. Nauk SSSR. Ser. Fiz. **49**, 1399 (1985).
4. N. L. Grigorov, Vestn. Mosk. Univ. Fiz. **29**, 44 (1988).
5. N. L. Grigorov *et al.*, Preprint 88-43/63, Scientific-Research Institute of Nuclear Physics, M. V. Lomonosov Moscow State University.
6. S. I. Vernov *et al.*, in: 17 ICRC, Paris, 1981, Vol. 8, p. 45.
7. N. L. Grigorov *et al.*, Space Research XI, Berlin, 1971, p. 1391.
8. N. L. Grigorov *et al.*, Space Research XII, 1972, p. 1617.
9. N. L. Grigorov *et al.*, in: 16 ICRC, Hobart, 1971, Vol. 5, p. 1746.
10. N. L. Grigorov *et al.*, Yad. Fiz. **11**, 1058 (1970) [Sov. J. Nucl. Phys. **11**, 588 (1970)].
11. I. P. Ivanenko *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 468 (1988) [JETP Lett. **48**, 510 (1988)].
12. G. B. Khristiansen, in: 20 ICRC, Moscow, 1987, Vol. 18, p. 54.

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