Space Research XII — Akademie-Verlag, Berlin 1972

STUDY OF ENERGY SPECTRA OF PRIMARY COSMIC RAYS AT VERY HIGH ENERGIES ON THE PROTON SERIES OF SATELLITES

N. L. GRIGOROV, V.E. NESTEROV, I. D. RAPOPORT and I. A. SAVENKO

Academy of Sciences, Moscow, USSR

The results of the Proton 4 measurements of the energy spectrum of all particles in primary cosmic rays in the 10^{11}–4×10^{15} eV energy range are presented. In the 10^{13}–10^{15} eV range the measured spectrum is of power-law form ($\gamma = 1.60 \pm 0.01$) and at energies higher than 2×10^{15} eV the spectrum becomes steeper. The Proton 1, 2, 3 and 4 measurements have shown that the all-particle spectrum has a discontinuity in the 10^{12} eV range where the Proton 1, 2 and 3 measurements have a steeper proton spectrum. The results of the Proton 3 measurements of the primary cosmic ray α-particle energy spectrum in the 10^{10}–10^{12} eV/nucleon energy range are presented.

1. Introduction

Heavy satellite investigations of high and ultrahigh energy cosmic rays beyond the atmosphere began as early as the launches of the Proton 1, 2 and 3 satellites, using the SEZ-14 spectrometer [1] and were continued on the Proton 4 satellite using the IK-15 ionization calorimeter [2]. The results of the Proton 1, 2 and 3 measurements of the energy spectra of protons and all particles in primary cosmic rays are presented in [3]. The present report examines the results of further analysis of the experimental data obtained from Proton 1, 2 and 3 and the preliminary results of Proton 4 measurements of the primary cosmic-ray spectrum.

2. Primary Cosmic Ray α-Particle Energy Spectrum according to Proton 3 Data

The Proton 3 satellite measured the primary cosmic ray α-particle energy spectrum with SEZ-14 directional Cerenkov counters [4]. The detectors record α-particles entering the instrument through its inlet window, the influence of shower particles leaving the calorimeter or the surrounding matter being small. To select α-particles from the flux of primary cosmic-ray particles of different charges each half of the instrument included double proportional counters. To identify α-particles the amplitude of the pulse recorded in each proportional counter must be within 2.7 V_{prob} and 8.0 V_{prob}, where V_{prob} is the most probable pulse amplitude produced by a single-charge relativistic particle in the proportional counter. Knowing the width of the pulse amplitude distribution in the proportional counters from ground muon measurements and considering that for α-particles the distribution width should decrease by a factor of 2, one finds that the probability that the pulses are produced by an α-particle within the above limits is 0.7.

The α-particle energy was measured with an ionization calorimeter.

Electronic circuits selected six-fold coincidence of the signals from the directional detector, from two differential discriminators for the proportional counters as discussed above, from the integral discriminators of energy release

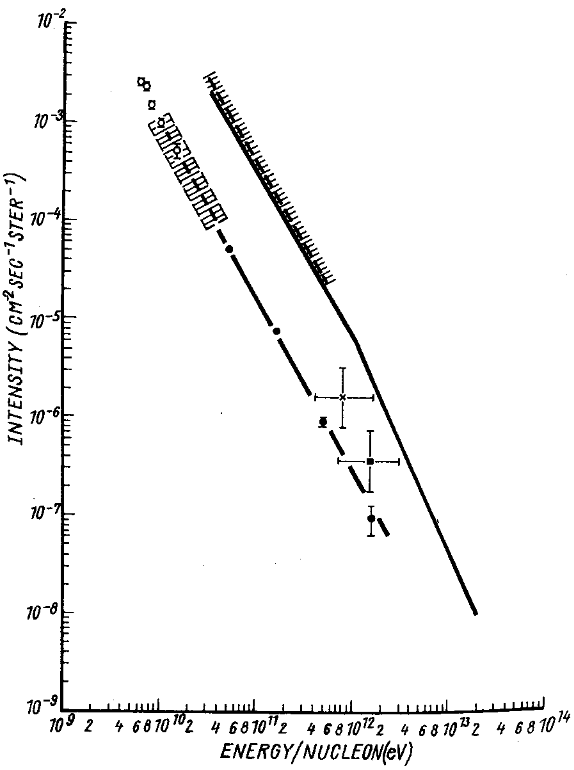

Fig. 1. Primary cosmic ray α-particle energy spectrum as measured on Proton 3 and other satellites, and by other methods.

●, Proton 3 data; |||| data from [6]; ○, data from [5]; ×, data from [7]; ■, data from [8]. upper curve, proton spectrum as measured on Proton 1, 2, 3 satellites [3].

in the ionization calorimeter, and from the scintillation counters arranged above and under the calorimeter. The complex signal (the result of these six-fold coincidences) was supplied to scalers which were interrogated each 8.5 sec by a memory device. The results for each measurement period of half a day were summed.

The intercomparison of the counting rates from these signals for periods when the predominant direction of the instrument axis was pointing to the zenith and to the earth has shown that the intensity ratio for these directions is 3.5:1.

The α-particle to proton flux ratio may be determined by measuring the counting rates from α-particles and protons at the same energy thresholds on the same half of the instrument. For such a determination it is not necessary to know the absolute values of the α-particle and proton fluxes. The measured value of I_α/I_p has to be corrected for the detection efficiency for α-particles (0.7) and protons (0.8) and the fact that the energy release in the calorimeter from α-particles is about 10% in excess of that of protons. With these corrections $I_\alpha/I_p = 0.56 \pm 0.01$.

Fig. 1 presents the α-particle energy spectrum as measured on Proton 3 and the proton spectrum according to Proton 1, 2 and 3 measurements [3]. The particle energy per nucleon is plotted as abscissa, and as ordinate the particle flux in absolute units ($cm^{-2}\ s^{-1}\ sr^{-1}$) obtained by dividing the measured counting rates by 57 cm^2 sr (the geometrical factor of the instrument), by 0.65 (the coefficient including the shielding of the inlet window by the earth) and by 0.7 (the efficiency of α-particle detection with the proportional counter). Fig. 1 presents also the values of α-particle fluxes from [5–8], which are in good agreement with those measured on Proton 3.

The comparison of the α-particle and proton energy spectra in Fig. 1 shows that the spectra are similar up to an energy of 5×10^{11} eV/nucleon, which corresponds to 10^3 GV magnetic rigidity. Because of insufficient statistical accuracy in the α-particle measurements at energies higher than 10^{12} eV/nucleon, it is still impossible to establish whether or not the α-particle spectrum becomes steeper at energies higher than 10^{12} eV/nucleon, as does the proton spectrum.

3. Primary Cosmic Ray Energy Spectrum according to the Proton 4 Data

The Proton 4 satellite was used to extend the measurements of the primary cosmic-ray energy spectrum to much higher energies. The measurements with the IK-15 ionization calorimeter [2] were carried out in two ways: (i) using integral amplitude discriminators dividing the energy range 2×10^{11}–4×10^{15} eV into nine approximately equal intervals (on a logarithmic scale); (ii) using a 64-channel analyser in the 3×10^{13}–10^{16} eV energy range.

In the first case no requirements are imposed as to the kind of particles, the direction of their motion and the point of entry into the calorimeter. The + crosses in Fig. 2 show the results of such spectral measurements for 50 days of the flight. The integral discriminator thresholds were fitted to the detected particle energy by normalizing the intensity to the spectrum as measured from Proton 1, 2 and 3. The × crosses in Fig. 2 show the results using the pulse height analyser for about 80 days of the flight.

It can be seen from Fig. 2 that the spectrum in the 2×10^{11}–2×10^{15} eV energy range is of a quasi-power form, and agrees fairly well with the spectrum measured on Proton 1, 2 and 3 up to energies of 10^{14} eV. At energies higher than 2×10^{15} eV an abrupt steepening of the measured spectrum of all particles is observed. This cannot be explained as a systematic effect since limiting in the electronic circuits should result in a steepening of the measured spectrum only at energies higher than 10^{16} eV. It can be also seen from Fig. 2 that in the 10^{12}–10^{13} eV energy range the spectrum has a somewhat steeper slope than at energies higher than 10^{13} eV. This discontinuity is studied below.

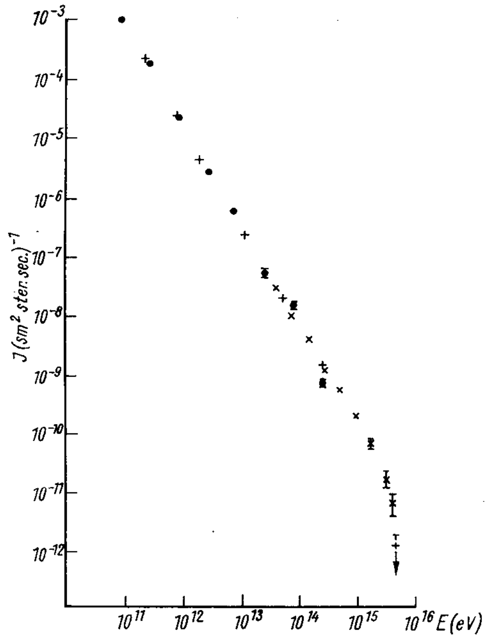

Fig. 2. Primary cosmic-ray (all nuclei) energy spectrum as measured on Proton 4 satellite: +, integral amplitude discriminators; ×, differential amplitude analyser; ●, Proton 1, 2, 3 data.

4. The Discontinuity in the Primary Cosmic Ray Energy Spectrum in the 10^{12} eV Energy Range

The information available from the Proton 1, 2 and 3 satellites was analysed to study the discontinuity in the energy spectrum of all primary cosmic-ray particles. About 50% of the information from these satellites (186 measurement periods broken into 6 series) was used earlier [3] to plot the spectrum. After considering an additional 151 measurement periods (6 series) of Proton 2 and 3 data, the information on the all-particle spectrum was nearly doubled. To find possible deviations of the spectrum from a power law, the measured spectrum was analysed by plotting log $[I(\geq E) \cdot E^{\gamma}]$ against $\log(E/10^{11})$ where E is the energy, and I is the particle intensity expressed in arbitrary units. Averaging was carried out for intervals of $\log(E/10^{11}) = 0.3$. For each of these intervals the mean value of log $[I(\geq E) \cdot E^{\gamma}]$ and the rms error was determined for some values of γ. It can be seen from Fig. 3, which gives the results for $\gamma = 1.60$, that discontinuity in the spectrum is observed in the 10^{12} eV energy range.

To study quantitatively this discontinuity two approximations were considered and the degree of their agreement with the experimental data was established using the χ^2 test. The value of γ was determined as the weighted mean value of the Proton 1, 2 and 3 data presented in Fig. 3. The values of χ^2 calculated for various values of the integral all-particle spectrum power exponent

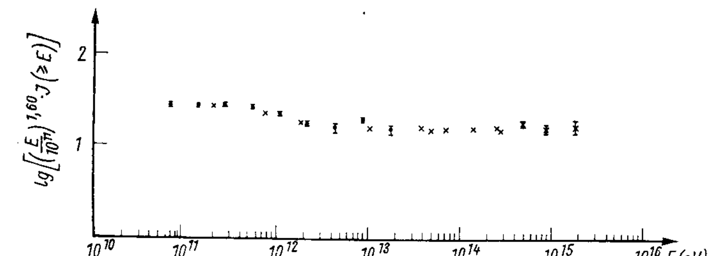

Fig. 3. Energy dependence of $\log [I(\geqq E) \cdot E^{\gamma}]$ (at $\gamma = 1.60$) for the average (over all measurement series) values obtained on Proton 1, 2, 3 satellites (●) and for a single series of Proton 4 measurements (×).

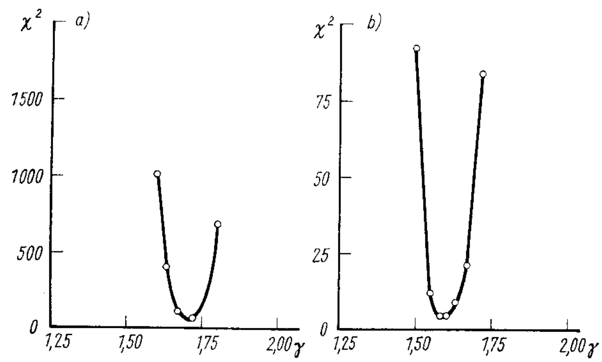

Fig. 4. The values of χ^2 at various values of the integral spectral power exponent γ for the energy dependence of $\log [I(\geqq E) \cdot E^{\gamma}]$ shown in Fig. 3 according to Proton 1, 2, 3 data: (a) approximating function, a single constant and a single range; (b) approximating function, two energy ranges with a single value of the exponent γ.

are presented in Fig. 4(a). It can be seen from this figure that with a power law the best agreement with the experimental data is at $\gamma = 1.72$, in agreement with the value $\gamma = 1.73 \pm 0.05$ as given in [3]. The approximation of the spectrum by a power function with a single exponent over the whole energy range is not satisfactory since the minimum value of χ^2 is 68 at 8 degrees of freedom. Approximation of the dependence shown in Fig. 3 over two ranges $0.3 < \log E/10^{11} < 0.9$ and $1.2 < \log E/10^{11} < 2.4$, proved to be more satisfactory. The values of χ^2 for various γ are shown in Fig. 4(b). It can be seen from this figure that the best agreement is observed at $\gamma = 1.60$. At this value of the power exponent χ^2 is 4.5 at 6 degrees of freedom which indicates a fairly good agreement of the proposed approximation with the experimental data. Thus, the primary cosmic-ray energy spectrum can be described best by a function with a discontinuity in the 10^{12} eV range, but with the same $\gamma = 1.60$ at energies below and above this discontinuity.

The irregularity found in the primary cosmic-ray energy spectrum using both sets of measurements favours the actual existence of a discontinuity since the Proton 4 equipment [2] differs drastically from the Proton 1, 2 and 3 equipment [1]. It should be noted that the irregularity is observed in the energy range where the Proton 2 and 3 measurements showed an increase in the steepness of the primary cosmic-ray proton spectrum where the integral spectrum exponent is increased from $\gamma = 1.60$ to $\gamma = 2.3$–2.5 [3].

5. Conclusions

1. The α-particle energy spectrum up to an energy of 10^{12} eV/nucleon has been measured on the Proton 3 satellite using direct methods. The α-particle fluxes detected in the 10^{10}–5×10^{10} eV/nucleon range agree well with the data available elsewhere.

2. The energy spectrum of all particles (protons and heavier nuclei in the 2×10^{11}–4×10^{15} eV energy range) has been measured on the Proton 4 satellite. It has been established using direct methods that, at energies higher than 2×10^{15} eV, the primary cosmic-ray energy spectrum becomes steeper in accordance with the data obtained earlier using indirect methods.

3. A discontinuity found in the spectrum in the 12^{12} eV energy range probably indicates a change in the chemical composition of primary cosmic rays in the 10^{12} eV range. The discontinuity is observed in the energy range where a steeper proton energy spectrum is observed.

Acknowledgment

The authors are indebted to V. V. Akimov, Yu. V. Gubin, N. A. Mamontova and V. L. Prokhin for their help when treating and analysing the experimental data.

References

[1] N. L. GRIGOROV et al., Kosm. Issled. **5**, 383 (1967).
[2] V. V. BUGAKOV et al., Izv. Akad. Nauk SSSR, ser. fiz. **34**, 1818 (1970).
[3] N. L. GRIGOROV et al., Nuclear Physics (USSR) **11**, 1058 (1970).
[4] N. L. GRIGOROV et al., Nuclear Physics (USSR) **11**, 4, 814 (1970).
[5] K. C. ANAND et al., Proc. 9th Int. Conf. Cosmic Rays, London 1965, **1**, 312 (1966).
[6] R. PINKAU et al., Proc. 11th Int. Conf. Cosmic Rays, Budapest 1969.
[7] P. FOWLER and C. WADDINGTON, Phil. Mag. **1**, 637 (1956).
[8] P. JAIN, C. LOHRMANN and M. TEUCHER, Phys. Rev. **115**, 654 (1959).