MEASUREMENTS OF THE PRIMARY COSMIC RAY SPECTRA
IN THE $10^{10} - 10^{14}$ eV ENERGY RANGE FROM PROTON-1, 2, 3
SATELLITES

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This paper presents the results of measurements of the spectrum of the primary
cosmic ray protons in the $10^{10} - 10^{13}$ eV energy range and the spectrum of all particles
of the primary cosmic rays in the $10^{14} - 10^{15}$ eV energy range carried out on Proton-1, 2, 3
satellites. The approximating function which describes the proton spectrum is presented.
It has been shown that the spectrum of all particles can be represented by superposing
the obtained proton spectrum and power spectrum of nuclei with $Z \geq 2$.

The measurements of the spectra were carried out on Proton-1, 2, 3 satellites
using the SEZ-14 instrument consisting of two identical halves each of which included
a charge detector (double proportional counter), scintillation detector of interactions,
ionization calorimeter (energy detector), and lower scintillation counter intended for
limiting the angular aperture of the instrument. Changeable graphite and polyethylene
targets were placed between the proportional counter and interaction detector. The
SEZ-14 instrument is described in detail in [1].

The instrument installed on Proton-3 was supplemented with two large Čerenko-
kov counters placed above the proportional counters. Čerenkov detectors selected
only those cases for detection when a primary particle entered the instrument from
the proportional counter end of the instrument, i.e. they were used as the detectors
which determine the direction of the entry of primary particles; thus we called them
"direction detectors" (DD). Detection of protons in the 1st half of the SEZ-14 took
place only when the direction detector was in operation whereas in the 2nd half the
measurements were carried out both with and without DD, i.e. the measurement
programme was similar to that on Proton-1, 2. The processed data showed that in
time intervals, when the total solid angle of SEZ-14 device was shaded by the Earth,
the counting rate of protons was zero. This suggests that the SEZ-14 device with
a direction detector records only those protons which enter the device from the pro-
portional counter end.

Measurement results

1. The spectrum of primary cosmic ray protons

Previously the spectrum of primary cosmic ray protons was considered to be
the spectrum of $Z_{1} N_{1} E_{C}$ type events, corresponding to the detection of one singly
charged particle in both proportional counters ($Z_{1}$) and interaction detector ($N_{1}$)
energy release in the calorimeter exceeding the $i$-th threshold ($E_{i}$), and the operation
of the lower scintillation counter limiting the solid angle of the instrument (index "C"). A change in the spectrum exponent from \( \gamma \approx 1.7 \) at \( E < 10^{12} \) eV to \( \gamma \approx 2.5 \) in the \( 2 \cdot 10^{12} - 10^{13} \) eV energy range was observed in the spectra of such events obtained from Proton-1, 2 satellites [2].

The Proton-3 measurements confirmed this character of the \( Z_1 N_1 E_C \) events. As we have shown before, according to our estimate [3] the observed changes in the spectrum exponent cannot be explained by the secondary particles entering the interaction detector from the ionization calorimeter.

To give an experimental confirmation of this we considered the dependence of the event sum intensity \( Z_1 N_1 E_C + Z_1 N_2 E_C \) (without the direction detector) and also \( Z_1 N_1 DDE_C + Z_1 N_2 DDE_C \) (with the direction detector) on energy \( E \). In this sum of events there are no limits to the number of particles in the interaction detector. (\( Z_1 N_2 E_C \) events differ from \( Z_1 N_1 E_C \) events only in the number of particles \( N \geq 2 \) in the interaction detector.) Therefore their intensity will not depend on the presence or absence of the inverse particle flow from the ionization calorimeter into the interaction detector.

To decrease the possibility of the secondary particles entering the proportional counters, measurements with targets have been considered for the event sum \( Z_1 N_1 E_C + Z_1 N_2 E_C \). In this case there was more than 30 g \cdot cm\(^{-2}\) of light material between the proportional counters and the ionization calorimeter.

The results of measurements are presented in Fig. 1. Along the abscissa axis the energy of the proton is given. Along the ordinate axis, to the right, the counting rate of event sum \( Z_1 N_1 E_C + Z_1 N_2 E_C \) is given from Proton-2 [1, 2] and Proton-3 satellite measurements. The counting rate of the event sum \( Z_1 N_1 DDE_C + Z_1 N_2 DDE_C \) measured by SEZ-14 with the direction detector on "Proton-3" [4] satellite was normalized to the counting rate \( Z_1 N_1 E_C + Z_1 N_2 E_C \) in one point at \( E = 10^{12} \) eV. The normalization factor 3 is connected with the additional counting effect (see [3, 4]).

From Fig. 1 we see that

1. The intensities of the event sum \( Z_1 N_1 E_C + Z_1 N_2 E_C \) according to three measurement series are in good agreement.

2. Measurements either without or with the direction detector give the same form of the proton spectrum and confirm the previous result concerning the slope spectrum change at \( E \approx 10^{12} \) eV.

The left ordinate axis scale presents the absolute proton flux intensity. It is obtained from counting rate measurements of events \( Z_1 N_1 DDE_C + Z_1 N_2 DDE_C \), as in measurements with the direction detector the additional counting is essentially smaller than that without it (for details see [4]).

The proton spectrum obtained can be approximated by the function

\[
I_p = 3 \cdot 10^{-4} \left( \frac{100}{E} \right)^{1.62} \cdot \left[ 1 + \left( \frac{E}{1500} \right)^{2.35} \right] \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}
\]

shown in Fig. 1 with a solid line. The energy was measured in GeV.
Fig. 1. Energy spectrum of the primary cosmic ray protons (for symbols see text)

Fig. 2. Energy spectrum of all particles of primary cosmic rays. Solid line represents the expected form of spectrum (see text)
2. The spectrum of all particles of primary cosmic rays

The integral spectrum of ionization bursts in the calorimeter caused by all cosmic ray particles irrespective of their nature and point of entering the calorimeter was considered as the spectrum of all particles.

The results of all measurement series carried out on Proton-1, 2, 3 are shown in Fig. 2.

The energy thresholds of all instruments were adjusted according to the latitude effect in the cosmic ray protons. This problem was considered in detail in [3, 4].

If one assumes that the spectrum of particles with charges $Z \geq 2$ is of the form:

$$I_Z(\geq E) = B \left( \frac{100}{E} \right)^{1.62}$$

the observed spectrum $I(\geq E)$ will be the sum of

$$I_p(\geq E) \quad \text{and} \quad I_Z(\geq E).$$

It can be seen from the ratio of the value of absolute fluxes of protons and all particles at energies of $10^{11}$ eV that $B = 3 \cdot 10^{-4}$. Thus, the summary spectrum of all particles is of the form:

$$I = I_p + I_Z = 3 \cdot 10^{-4} \left( \frac{100}{E(\text{GeV})} \right)^{1.62} \left[ 1 + \left( \frac{1}{E \cdot 1500} \right)^{2.30} \right] \text{cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}.$$ 

This function is shown in Fig. 2 by the solid curve. It can be seen that it agrees sufficiently well with experimental data.

References