MEASUREMENT OF COSMIC-RAY INTENSITY IN THE STRATOSPHERE AT VARIOUS ALTITUDES AND LATITUDES

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We present the results of measurement of the altitude dependence of particles of various ranges contained in the soft component of cosmic rays at latitudes 51° and 31°. The altitude dependence of electrons of a given energy is computed from the energy spectrum of the μ-meson production in the atmosphere. The results of the calculations are in good agreement with the results of measurements made at a latitude of 31°. This indicates that the overwhelming majority of the soft-component particles are electrons generated by μ mesons at the indicated latitude. An analysis of the experimental and calculated data for 51° indicates the existence of an excess of electrons with ranges less than two or three g/cm^2. This phenomenon, which is most pronounced at 51°, is most probably due to gamma quanta emitted in the atmosphere in inelastic neutron-evaporation reactions. The energy flux carried away by these surplus short-range electrons is approximately 10% of the total energy flux of the electron component at this latitude.

The cosmic-ray energy flux has been evaluated at latitudes of 2°, 31°, and 51°. Based on these data, and also on data concerning the cosmic-ray particle intensity at the top of the atmosphere at 51° and 31°, an expression has been derived for the energy spectrum of the primary particles. A new value of 0.48 ± 0.04 particles/min-cm^2-sterad has been obtained for the primary cosmic-ray particle flux $(N_p + N_\alpha)$ at the equator (2°).

In spite of the sufficiently numerous measurements made in the upper layers of the atmosphere, no exact data have been obtained as yet on the absolute intensity of the cosmic radiation in the stratosphere. There is poor agreement between the measured values for the total and penetrating radiation in the vertical direction obtained by various authors using Geiger-counter telescopes.

Our own observations show that the discrepancies in the data on the total intensity are due essentially to failure to account for the absorption of particles in the counter and telescope walls. Depending on the type of counter employed, and also depending on the number of counters in the telescopes, the effective wall thickness fluctuates from 0.4 g/cm^2 (reference 1) to 6.0 g/cm^2 (reference 2). The measurements of Pomerantz[3] and Schein,[2] pertaining to latitudes from 52 to 55°, have been made with telescopes with walls 4.2 and 60 g/cm^2 thick, respectively. The values obtained by Pomerantz and Schein are 30 and ~ 40% lower than ours, obtained at 51° with a telescope having an effective counter wall thickness of 0.4 g/cm^2. Such a difference, obtained at the indicated wall thickness, is readily explained from the point of view of the data on the particle-range spectrum in the stratosphere, cited in reference 1.

In the upper layers of the atmosphere, the intensity of the proton component of cosmic radiation becomes commensurate with that of the μ-meson component. Under these conditions it becomes difficult to obtain with the aid of a telescope exact data on the flux of penetrating particles. Upon passing through the telescope absorber (usually 8 to 15 cm of lead), protons with energies less than 2 or 3 Bev form "stars" essentially without penetrating particles. Such protons do not pass through the absorber and do not produce the required coincidence in the telescope. This reduces the measured value of the penetrating-particle flux. On the other hand, the intensity of the penetrating particles may appear to be too high, owing to the presence of high energy protons. The latter is connected with the fact that the aperture ratio of the telescope is higher for protons, and these generate a noticeable number of penetrating particles in the telescope absorber. Because of the indicated apparatus effects, which depend on the energy spectrum of the protons, high-altitude measurements made at different latitudes cannot be compared with each other correctly. A. N. Charakhch'ian[4] overcame these difficulties by separating the single penetrating particles, which pass through the telescope absorber without interaction, from the particles that generate electron-nuclear showers in the telescope absorber. The absolute number of the electron-nuclear showers generated in the telescope absorber (10 cm of lead) was determined from the measured altitude dependence of the showers and from the geometric cross section of the nuclear interaction between the primary cosmic particles in lead. The total intensity of the penetrating components at various altitudes was obtained by adding the measured number of single particles to the number of showers. This led to data that are closer to the exact values of the absolute flux of penetrating particles in the upper layers of the atmosphere at various latitudes.

An important role is played in measurements in the atmosphere by the so-called "side" showers. The measured number of these showers depends on the multiplicity of the selected coincidences, and also on the amount of substance surrounding the telescope in the instrument. To exclude the influence of such showers, additional counters were placed on both sides of the telescope to measure the coincidences produced by the single particles passing through the telescope as well as the coincidences produced by the particles of the side showers.

CALCULATION OF THE INTENSITY OF THE ELECTRON COMPONENT

The calculations are based on the generally accepted premise that the electron-photon component of cosmic radiation in the stratosphere is produced by charged and neutral π mesons, which decay in accordance with the following schemes:

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu, \ \mu^{\pm} \rightarrow e^{\pm} + 2\nu \text{ and } \pi^0 \rightarrow 2\gamma.$$

The $\pi^{\pm}$ and π^0 mesons are produced in the atmosphere by nuclear interactions between high-energy nuclei (in excess of 1.5 Bev).

We used in the calculations the corresponding data from the theory of electromagnetic cascade processes, data on the energy spectrum of the generation of μ mesons in the atmosphere at 51° and 31°, and data on the altitude of the nuclear component that generates the electron-nuclear showers.

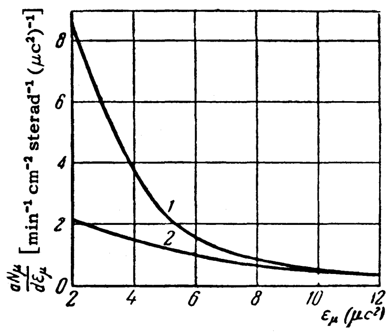

FIG. 1. Energy spectra for the generation of μ mesons in the atmosphere: 1) for 51° latitude; 2) for 31° latitude.

1. A substantial role is played in the calculations by cascades produced by the primary electrons or photons of low energies, on the order of the critical energy for air. We used for this energy range the cascade curves calculated by Ivanenko.[5] For electrons and photons with energies greater than 3×10^8 ev, the calculations were made with Belen'kii's formulas.[6]

In comparing the calculated data with experiment, it was necessary to estimate the role of the Coulomb scattering of the shower electrons in the atmosphere. We used for this purpose the values of the mean shower-electron deviation angles from reference 7. The angular distribution was assumed to be Gaussian.

The energy spectra for the generation of μ mesons in the stratosphere at 51° and 31° were investigated in references 8 and 9. The resultant spectra of the generated μ mesons are shown in Fig. 1, where the abscissa is the μ-meson energy in μc^2 units, and the ordinate represents the number of μ mesons. For μ-meson energies greater than $10\,\mu c^2$, the spectrum dependence is given by $200/\epsilon$ (references 2 and 6).

3. The variation of the generating component at 31° with altitude was taken to obey the absorption law for nucleons with energies greater than 1.5 Bev, which follows from Grigorov's calculations[10] of the altitude dependence of the nucleon component for 31°. The absorption law selected is quite close to actual one, since Grigorov's results are in good agreement with the experimental data on the absorption of protons with energies greater than 3 Bev in the atmosphere.[11] For primary particles that are sensitive to the earth's magnetic field between latitudes of 51 and 31°, the law of absorption of the generating component was taken in the form $\exp\{-x/b\beta_0\}$, where x is the amount of matter from the top of the atmosphere and $\beta_0 = 120$ g/cm^2.

The spectra of the photons generated by π^0 mesons were calculated under the assumption that they are the same as the spectra for the $\pi^{\pm}$ mesons. The primary energy spectrum of electrons at dif-

TABLE I. Calculated values of M_{π^0} and M_μ (min^{-1} cm^{-2} $sterad^{-1}$) for 31° latitude

Electron energy, E′, Mev	E′ > 0		E′ > 6		E′ > 26		$M_{\pi^0}(>0) - M_{\pi^0}(>6)$	$M_{\pi^0}(>0) - M_{\pi^0}(>26)$	$M_\mu(>0) - M_\mu(>6)$	$M_\mu(>0) - M_\mu(>26)$
Amount of matter from the top of the atmosphere, t units	M_{π^0}	M_μ	M_{π^0}	M_μ	M_{π^0}	M_μ				
1.4	3.3	2.89	2.52	2.24	1.86	1.67	0.54		0.53	
3.0	7.76	3.89	5.56	2.85	3.74	1.91	0.53		0.53	
4.6	9.7	3.67	6.92	2.61	4.42	1.65	0.53		0.52	
6.2	9.6	3.17	6.68	2.22	4.18	1.36	0.54		0.53	
7.8	8.64	2.54	5.68	1.75	3.44	1.08	0.57		0.54	
9.8	6.37	1.85	4.27	1.28	2.53	0.79	0.54		0.54	
12.2	4.22	1.25	2.78	0.86	1.63	0.52	0.55		0.53	
14.6	2.58	0.88	1.64	0.58	0.99	0.35	0.59		0.57	

TABLE II. Calculated values of M_{π^0} and M_μ (min^{-1} cm^{-2} $sterad^{-1}$) for the latitude difference (51°−31°)

Electron energy, E′, Mev	E′ > 0		E′ > 6		E′ > 26		$M_{\pi^0}(>0) - M_{\pi^0}(>6)$	$M_{\pi^0}(>0) - M_{\pi^0}(>26)$	$M_\mu(>0) - M_\mu(>6)$	$M_\mu(>0) - M_\mu(>26)$
Amount of matter from the top of the atmosphere, t units	M_{π^0}	M_μ	M_{π^0}	M_μ	M_{π^0}	M_μ				
1.4	3.10	3.06	2.36	2.42	1.66	1.74	0.51		0.49	
3.0	4.86	3.17	3.57	2.33	2.34	1.46	0.51		0.49	
4.6	4.49	2.77	3.18	2.01	1.90	1.24	0.51		0.50	
6.2	3.33	1.88	2.28	1.26	1.30	0.74	0.52		0.51	
7.8	2.34	1.09	1.48	0.74	0.85	0.43	0.57		0.53	
9.8	1.29	0.55	0.62	0.28	0.50	0.21	0.57		0.51	
12.2	0.68	0.25	0.45	0.17	0.26	0.10	0.55		0.53	
14.6	0.38	0.13	0.26	0.08	0.14	0.05	0.57		0.56	

TABLE III

Al, g/cm²	E, Mev	Al, g/cm²	E, Mev
0.4	1.2	2.0	5.8
0.9	2.6	6.6	25.0
1.2	3.3	11.4	45.0

ferent altitudes was calculated from the spectrum of the decay electrons of a μ meson at rest, with allowance for the energy distribution of the decaying μ mesons over the altitude.[8]

Experimental data on the intensity of the soft component at 31° are best reconciled with the calculated data if the ratio of the energy carried by the π^0 mesons to that carried by the $\pi^\pm$ mesons is taken as $k = 0.4$.

Tables I and II list some of the results of the calculations. Here M_{π^0} and M_μ are the intensities of the electrons obtained by decay of π^0 and μ mesons, respectively. The data in the last columns of the tables characterize the variation with pressure of the energy spectra of the electrons with energies less than 26 Mev.

We thus draw the following conclusions from the calculations: (1) The number of electrons formed by decay of π^0 mesons exceeds the number of electrons due to decay of μ mesons at practically all altitudes. (2) The energy spectra of low-energy electrons (< 26 Mev) are practically the same for both latitudes and depend little on the pressure.

It follows from a calculation of the Coulomb scattering of the electrons in the atmosphere that as the altitude increases the energy spectrum of the electrons becomes richer in low-energy electrons. This circumstance offers the most probable explanation for the fact, noted in reference 1, that the soft-component particle-range spectrum softens with increasing observation altitude.

The calculated energy spectrum of the electrons in the atmosphere differs from the Tamm-Belen'kii equilibrium electron spectrum lies essentially in the low-energy region. The relative number of electrons with energies less than 20 Mev near the maximum intensity in the atmosphere is approximately 25% less than the relative number of electrons of the same energy as given by the Tamm-Belen'kii equilibrium spectrum.

Table III gives the dependence of the effective electron range on the electron energy, obtained on the basis of experiments on the absorption of electrons in aluminum.[12]

APPARATUS

The number of charged particles with ranges from 1.2 to 2.0, from 2.0 to 6.6, and from 6.6 to 11.4 g/cm^2 in a vertical direction at latitudes 51° and 31° were measured simultaneously with three telescopes in an instrument with suitable absorbers. The right corner of Fig. 2 shows the placement of the counters in the first telescope, which measures the number of particles in the range interval from 1.2 to 2.0 g/cm^2 of glass. The telescope comprised counters 1 and 2, the coincidence of which produced the control pulse. Three counters in group 3, connected in parallel, were so arranged that single particles passing through telescopes 1 and 2 traversed the effective regions of counters 3. To measure the side showers, the particles of which produce double coincidences, telescopes 1 and 2 were surrounded on both sides by the parallel-connected counters of group 4.

The electronic circuitry described in reference 4 was used to transmit, for each of the telescopes in the instrument, radio signals of the following coincidences: (a) $1 + 2 - (3, 4)$ — coincidences of discharges in telescope counters 1 and 2, when no discharges occur in the remaining counters, including those in group 3. These coincidences are evidence that the particle has passed through less than five counter walls but more than three walls. (b) $1 + 2 + 3 - (4)$ — coincidences of discharges in counters 1, 2, 3 without discharges in counters 4 (these coincidences correspond to the registration of single particles). (c) $1 + 2 + 4 - 3$ and $1 + 2 + 3 + 4$ — coincidences in which counters 4 operated, and which were due essentially to side showers.

The thickness of one wall in counters 1, 2, or 3 is 1.2 mm of glass in the radial direction. Assuming the particles travel along the chords, the effective counter of thickness is increased by approximately 20%. Thus, three counter walls correspond to 1.2 g/cm^2, and five walls correspond to 2 g/cm^2. In the second telescope, where a 3-mm aluminum plate was placed between counters 1 and 2 and a 14 mm aluminum plate was placed between counters 2 and 3, the coincidences $1 + 2 - (3, 4)$ corresponded to the number of particles with ranges in the interval from 2.0 to 6.6 g/cm^2 of aluminum. In the third telescope, 20 mm of aluminum was placed between counters 1 and 2 and 14 mm of aluminum between counters 2 and 3. The coincidences $1 + 2 - (3, 4)$ corresponded there to the number of particles with ranges in the interval from 6.6 to 10.4 g/cm^2 of aluminum. The effective length of counters 1, 2 and 4 was 190 mm and that of the counters of group 3 was 300 mm. The inside diameter was 20 mm in all counters. The distance between centers of counters 1 and 2 was 150 mm. The telescopes were calibrated, with an accuracy of approximately 1.5%, against the measured intensity of the hard component on the surface of the earth at 51°. This intensity is 0.46 particles/min-cm^2-sterad with a 10-cm lead absorber. In the processing of the measurement results, allowance was made for the increased aperture of the telescopes with altitude. At an altitude corresponding to a pressure of 40 g/cm^2, this increase (above sea level) amounts to 10%. Measurements at 51° were taken on April 1, 1952, and on May 29 and September 4, 1954. The measurements at 31° were made on August 6, 12, and 30, 1955.

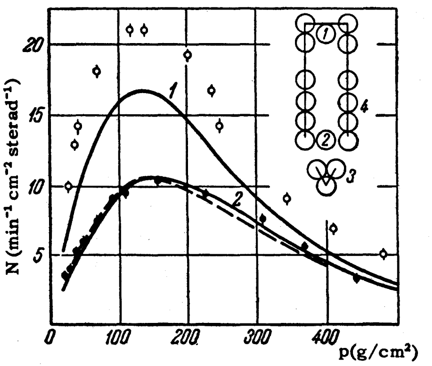

FIG. 2. Altitude dependence of the number of particles of the soft component with ranges more than 1.2 g/cm² of glass: o) experimental data at 51°, •) experimental data at 31°. Solid curves — calculated electron component: 1) for 51°; 2) for 31°. Dotted curve — results of calculation with allowance for the Coulomb scattering of electrons in the atmosphere at 31°.

MEASUREMENT RESULTS

The results of the measurement of the total intensity of the particles are best presented in the form of two plots, one of the intensity of the penetrating particles, and one of the intensity of the

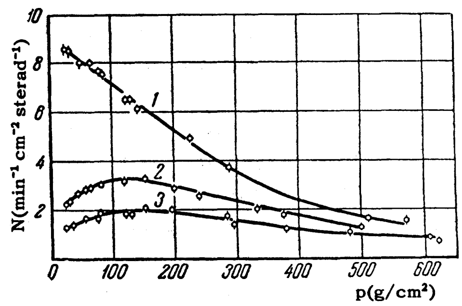

FIG. 3. Altitude dependence of the intensity of penetrating particles (with a 10 cm lead absorber) at the following geomagnetic latitudes: 1) 51°, 2) 31°, 3) 2°.

so-called soft component, obtained by subtracting the number of penetrating particles from the total number of particles. This makes it possible to separate, as a first approximation, the electronic from the non-electronic components. The altitude dependence of the intensity of the penetrating particles (for a 10-cm lead absorber), taken from reference 4 for altitudes 51°, 31° and 2°, is shown in Fig. 3. The corresponding variation of the intensity of the soft-component particles (with ranges greater than 1.2 g/cm^2 of aluminum) with altitude is represented by the dots of Fig. 2 for 51° and 31°. The smooth curves represent the calculated values (the abscissa indicates the atmospheric pressure in g/cm^2, and the ordinate the number of particles). As can be seen from Fig. 2, the measurement results obtained at 31° are in good agreement with the calculated data. At 51°, the measured intensity of the soft-component particles exceeds the calculated value. However, with only these measurements of the total intensity of the soft-component particles it is difficult to explain the discrepancy between the calculated data for electrons and the measured intensities of the soft-component particles.

Figure 4 shows, for the 31° latitude, the altitude dependence of the number of particles with ranges from 1.2 to 2.0, from 2.0 to 6.6, and from 6.6 to 11.4 g/cm^2 of aluminum and of particles with ranges greater than 11.4 g/cm^2 of aluminum and less than 114 g/cm^2 of lead. The dots indicate the measured results and the smooth curve the calculated values. Disregarding certain discrepancies between the experimental and calculated data for particles with ranges from 1.2 to 2.0 g/cm^2 of aluminum (the meaning of which will be explained below), a comparison of the measures and calculated results, shown in Fig. 4, leads to the conclusion that the theory explains the generation of the electron component in the atmosphere rather well not only qualitatively, but also quantitatively, and that at 31° the soft-component particles in cosmic radiation consist for the most part of electrons.

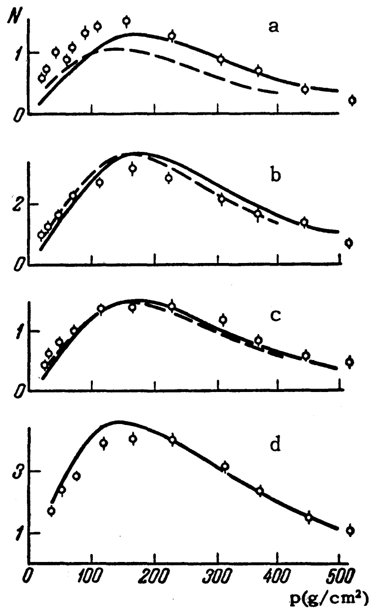

FIG. 4. Altitude dependence of the number of particles (min^{-1} cm^{-2} sterad^{-1}) of the soft-component at 31° for particles with the following ranges: a) from 1.2 to 2.0, b) from 2.0 to 6.6, c) from 6.6 to 11.4 g/cm^2 of aluminum, d) from 11.4 g/cm^2 of aluminum to 114 g/cm^2 of lead; •) experimental data. Solid curves – calculated results, dotted curves – calculated results with allowance for the Coulomb scattering of electrons in the atmosphere.

Since the measured intensity of the soft-component particles at 31° agrees with the expected intensity for the electrons generated by the π mesons, the excess soft-component particles observed at 51° must be attributed essentially to phenomena caused by primary particles with energies less than 7 Bev (for protons). It is therefore advisable to subtract the 31° data from the measured data obtained at 51°. As a result we obtain the variation with altitude of the difference of the soft-component particle intensity, $N_s^p = N_s^{51°} - N_s^{31°}$. The dots on Fig. 5 show these relations for the same range intervals as for the 31° latitude, while the smooth curves show the results of the calculations. We see that the excess noted above in the total number of soft-component particles at 51° is due essentially to short-range particles (see curve 5a) and to particles with relatively large ranges $R > 11.4$ g/cm^2.

The discrepancey between the measured and

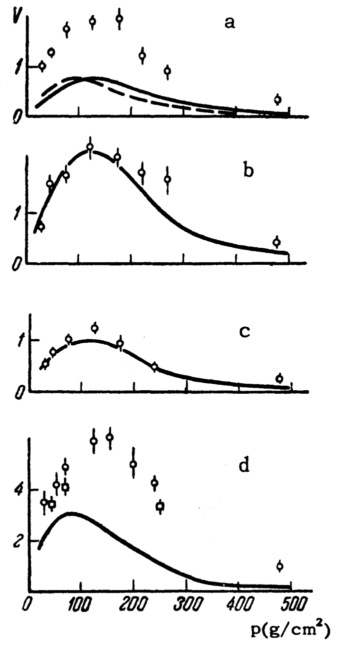

FIG. 5. Variation with altitude of the number of particles $N_s^p = N_s^{51°} - N_s^{31°}$ (min^{-1} cm^{-2} sterad^{-1}) of the soft component, generated by the primary particles with a critical energy less than 7 Bev (for protons), for particles having the following ranges: a) from 1.2 to 2.0, b) from 2.0 to 6.6, c) from 6.6 to 11.4 g/cm^{-2} of aluminum and d) from 11.4 g/cm^2 of aluminum to 114 g/cm^2 of lead. o) experimental data. Dotted curves – calculation with allowance for the Coulomb scattering of electrons in the atmosphere; solid curves – results of calculations.

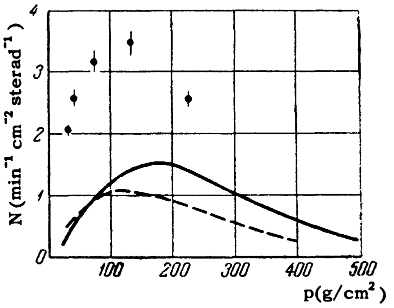

FIG. 6. Variation with altitude of the number of the soft-component particles with ranges in the interval from 0.4 to 0.9 g/cm² of glass at a latitude of 51°. ●) experimental data. Solid curve – results of calculation; dotted curve – result of calculations with allowance for the Coulomb scattering of electrons in the atmosphere.

computed values for ranges above 11.4 g/cm² of aluminum is attributed to the noticeable number of slow protons, with ranges from 11.4 g/cm² of aluminum to 114 g/cm² of lead, contained among the particles in this interval. These protons produce an increased ionization (by a factor from 1.5 to 3 times). Rapoport,[13] who measured the ionization spectrum of particles in the stratosphere at 51° latitude with the aid of a pulse ionization chamber, determined the intensity of particles that have this increased ionization. The small squares in Fig. 5d represent the sum of our calculated electron intensity and the intensity obtained by Rapoport for the protons. Consequently, taking into account the intensities of the protons of the corresponding ranges, the measured and calculated results for electrons with ranges more than 11.4 g/cm² of aluminum are in satisfactory agreement at 51°, too.

At short ranges, a discrepancy between the calculated and experimental data is found not only for 1.2 to 2.0 g/cm² of aluminum, but to an even greater extent for 0.4 to 0.9 g/cm² of aluminum. Figure 6 shows the experimental points corresponding to the intensity of particles with ranges from 0.4 to 0.9 g/cm² of aluminum at the latitude of 51° (reference 1), and the calculated curve of electron intensity for the same range interval. The assumed existence of a noticeable number of protons among the short-range particles in the above two range intervals contradicts the known data on the excess ionization produced in the stratosphere by the slow protons.[13] In addition, on the basis of the work cited above, Rapoport has concluded that more than 80% of the particles with ranges close to those considered here are light particles (electrons).

A striking fact is that the latitude effect of short-range electrons is large at great depths. At a depth of 500 g/cm² this latitude effect, between 51° and 31°, is close to 2. Not a single component of cosmic radiation, with the exception of the star-producing component, has a latitude effect of such order of magnitude at great depths. This suggests that a noticeable portion of the short-range electrons is due to the star-producing component or most readily to its principal portion, the neutrons.

No electrons or photons of low energy are produced in stars generated directly by fast neutrons. However, evaporation neutrons produced in stars are capable of producing hard gamma quanta during nuclear reactions in the atmosphere. At the present time there are no exhaustive data on the hard quanta emitted in reactions between neutrons and nitrogen or oxygen for the entire energy spectrum of the neutrons. Data are available for 14.1-Mev neutrons, for which the cross section of the inelastic reaction with nitrogen amounts to approximately 30% of the total cross section.[14] Since neutrons lose a small fraction of their energy (~ 15%) in elastic reactions, and since hard gamma quanta carry away about half the kinetic energy of the incident neutron in inelastic reactions,[15,16] neutrons with energies from 5 to 15 Mev give up a substantial portion of their energy to gamma quanta as they pass through the atmosphere.

It appears therefore that the excess intensity of short-range electrons obtained by us at 51°, particularly in the region of medium altitudes, is essentially due to the above mechanism of radiation of hard gamma quanta. At the present time it is impossible to give a quantitative estimate of the role of the above phenomenon in the generation of short-range electrons in the atmosphere. Nevertheless, we can attempt to answer the following question: does the intensity of the neutrons generated in the atmosphere seem reasonable if it is assumed that all the energy carried by the excess short-range electrons is due to gamma quanta from neutron reactions in the atmosphere?

From the area under the excess-intensity curve of the short-range electrons, the energy carried away by these electrons is ~ 1.5 Bev min^{-1} cm^{-2} sterad^{-1} (amounting to approximately 10% of the total energy of the electron component). It is reasonable to assume that the average energy of the gamma quanta radiated during neutron reactions in the atmosphere amounts to approximately 5 Mev. To obtain the above 1.5 Bev min^{-1} cm^{-2} sterad^{-1}, we must assume that 300 evaporation neutrons are generated on the average in one min-cm²-sterad in the entire atmosphere at a latitude of 51°. We can start with the assumption that in the entire atmosphere an intensity equilibrium is established between the evaporation neutrons and the thermal neutrons. Assuming that approximately 30% of the neutrons are absorbed after inelastic nuclear reactions (for example, in reactions $N^{14}(n\alpha)B^{11}$ etc.[16]), the expected number of thermal neutrons in the atmosphere is 200 neutrons (cm^{-2} min^{-1} $sterad^{-1}$).

According to measurement data,[17] the intensity of thermal neutrons in the entire atmosphere at a 51° is 135 neutrons (cm^{-2} min^{-1} $sterad^{-1}$), which is close enough to the value obtained above. This is another argument in favor of the neutron origin of the considerable portion of the excess short-range electrons observed by us.

SPECTRUM OF PRIMARY COSMIC RADIATION

The expressions found in the literature for the spectrum of primary particles are contradictory in that respect, that the spectra obtained in investigations based on the measurement of the intensity of primary particles at different latitudes give for the primary cosmic-ray energy flux a value that is two or three times greater than that obtained experimentally. On the other hand, the spectrum obtained in reference 8 gives for the primary-particle flux values that are 1.5 or 2 times less than would follow from references 19 and 20.

It seems to us that these contradictions are due to the inaccuracy of experimental data used to obtain the primary-particle spectrum. When measuring the particle intensities with the aid of rockets, the backward flux of low energy particles and the showers produced in the rocket housing increase artificially the value of the flux of the primary particles. The lower the latitude at which the measurements are performed, the more do these secondary effects manifest themselves in the experimental results. It is therefore necessary to assume that the authors who made the rocket measurements used exaggerated values of the particle flux to obtain the spectrum of the primary particles, particularly at the equatorial latitude. The data used in reference 18 on the cosmic-ray energy flux at various latitudes are not sufficiently accurate. In particular, owing to the lack of data on the intensity of the electron and μ-meson component, the value of the energy carried away by the neutrino in the decay of μ mesons at various latitudes remains undetermined.

The investigations reported below on the energy spectrum of primary cosmic particles are based on data of the altitude dependence of the electrons studied in this investigation, and also on data on the altitude dependence of the μ-meson and nucleon components, reported in references 8 and 10 for 51°, 31° and 2°. In addition, we used in this work the values of the cosmic-ray intensity on the top of the atmosphere, obtained for 51° and 31°.

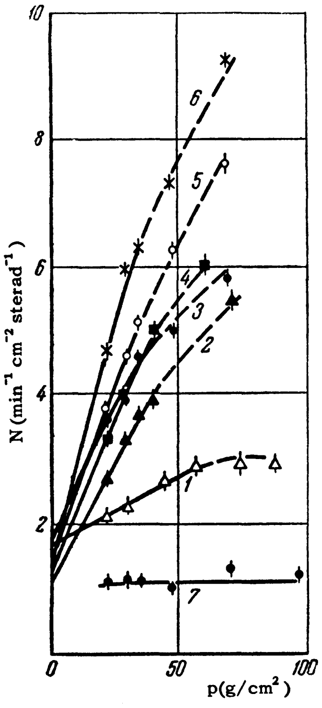

FIG. 7. Variation with altitude at 31°: 1) number of penetrating particles; 2 and 3) number of identical particles with ranges greater than 3 and 10 mm lead; 4, 5, and 6) number of single particles with ranges greater than 11.4, 6.6, and 2.0 g/cm^2 of aluminum, respectively; 7) number of side showers, obtained when measuring (with a telescope) single particles with ranges greater than 2.0 g/cm^2 glass.

PRIMARY FLUX OF COSMIC RADIATION AT 31°

In the measurements described above we also obtained data on the intensity of single particles with ranges greater than 2.0, 6.6, and 11.4 g/cm^2 of glass and aluminum, and also with ranges greater than 3 and 10 mm of lead. The results of these measurements, made at low pressures, are shown in Fig. 7, where the ordinates are the measured intensities of single particles and the abscissas the pressure in g/cm^2.

Let us examine the particle intensities obtained by extrapolation of these variations with altitude to the top of the atmosphere. As can be seen from Fig. 7, the straight lines (each of which passes through three measured points on curves 2, 3, 4, 5, and 6) intersect the ordinate axis within an intensity range from 1.2 to 1.9 particles (min^{-1} cm^{-2} $sterad^{-1}$).* Curve 1 of Fig. 7, representing the intensity of the penetrating particles, is based on the data of reference 4. The average value of the flux of primary particles is 1.5 ± 0.1 particles. It is somewhat smaller than the values obtained in reference 21 (1.8 particles) and in reference 22 (2.0 particles). The above error for the particle intensity corresponds to the mean squared deviation from these extrapolations.

*Henceforth we shall omit the dimensions min^{-1} cm^{-2} $sterad^{-1}$.

In the measurements we also obtained data on the intensity of the side showers registered with the telescope. The results of one of the measurements are given in Fig. 7 (curve 7). This curve represents the altitude dependence of the intensity of the side showers, obtained when measuring single particles with ranges greater than 2.0 g/cm^2. As can be seen from the diagram, to us the intensity of the showers is almost constant in the pressure range of interest. It is therefore quite likely that the number of showers remains constant to the top of the atmosphere. Under the conditions of our experiments, this gives 1.1 particles, leading to an increase of approximately 60% in the flux of the primary particles.

ENERGY OF PRIMARY COSMIC RADIATION

The energy carried away by the primary cosmic radiation has been determined in the following manner. Knowing the altitude dependence of the intensity of the electron and μ-meson components, we determined the energy carried away by the $\pi^{\pm}$ and π^0 mesons in the atmosphere. The energy liberated in the atmosphere by slow nucleons[10] is then added to the found π-meson energy.

The initial data for the determination of the energy flux carried away by the π mesons in the atmosphere are the data on the electron component. By calculating the area under the curve of the intensity of the soft component in the altitude interval from the top of the atmosphere to sea level, and multiplying this area by the ionization losses of the electrons in air (2.15×10^6 ev-g^{-1}-cm^{-2}), we find that the energy carried by the electrons with ranges more than 1.2 g/cm^2 of glass amounts to 8.2 ± 0.16 Bev at 31°. On the basis of the calculations performed, this energy must be increased by 25% because of the electrons with ranges greater than 1.2 g/cm^2. Thus, the energy liberated by the electrons in the atmosphere at 31° amounts to 10.2 ± 0.2 Bev.

For the 2° latitude, there are no direct data on the composition of the soft-component particles. Nevertheless, it is quite likely that at this latitude, as at 31°, the predominant portion of the soft component is made up of electrons. When evaluating the electron energy at 2° from the data of reference 23, the area under the soft-component intensity curve is reduced by 8% (because the side showers have not been excluded in the measurements made at 2°) and is increased by 25% (on account of the electrons with ranges less than 1.2 g/cm^2). After introducing these corrections, the electron energy liberated in the atmosphere at 2° latitude becomes 6.10 ± 0.2 Bev.

It was shown above that at 51° the soft component contains a noticeable number of slow protons. In addition, a considerable portion of the electrons with ranges less than 2 or 3 g/cm^2 is generated not by π mesons, but by gamma quanta emitted upon interaction of the evaporation neutrons in the atmosphere.* The energy of the electron-photon component, due to π mesons at 51°, is therefore best determined from the calculations. These yield a value of 13.5 Bev.

Starting with the known π-meson decay schemes ($\pi^{\pm} \rightarrow \mu^{\pm} + \nu$, $\mu^{\pm} \rightarrow e^{\pm} + 2\nu$, and $\pi^0 \rightarrow 2\nu$) it is possible to obtain a relation between the energy of the electron component and the energy carried by the π mesons in the atmosphere. The energy transferred to the electron component in the process of decay of charged π-mesons is

$$\frac{1}{3}\left(\frac{m_\mu}{m_\pi} E_{\pi\pm} - E_{\mu\,\text{ion}}\right),$$

where $E_{\pi^\pm}$ is the energy carried by the $\pi^{\pm}$ mesons; $E_{\mu\,\text{ion}}$ is the energy lost by the μ mesons to ionization in the atmosphere and in the soil; m_μ and m_π are the rest masses of the μ and π mesons. Adding to this energy the energy E_{π^0} of the neutral π mesons, we obtain for the energy of the electron component in the atmosphere

$$E_e = \frac{1}{3}\left(\frac{m_\mu}{m_\pi} E_\pi - E_{\mu\,\text{ion}}\right) + E_{\pi^0}.$$

After suitable transformations, we obtain for the total energy of the $\pi^{\pm}$ and π^0 mesons, at $m_\mu/m_\pi = 0.78$:

$$E_{\pi\pm} + E_{\pi^0} = \frac{1+k}{0.26+k}\left(E_e + \frac{1}{3} E_{\mu\,\text{ion}}\right), \tag{1}$$

where k is the ratio $E_{\pi^0}/E_{\pi^\pm}$.

The energy lost by the μ mesons to ionization in the atmosphere at 51°, 31°, and 2° was determined from the areas under the corresponding penetrating-particle intensity curves (Fig. 3), with correction for the intensity of the protons, the variation with altitude of which was determined from the variation with altitude of the electron-nuclear showers.[21] The energy carried by the mesons at sea level was taken to be 2.0 Bev.

The value of the ratio $k = E_{\pi^0}/E_{\pi^\pm}$ in formula (1) has not been established experimentally with sufficient accuracy. According to the data of the

*These two sources of soft-component particles are naturally also present at 31° latitude. But the contribution of such particles to the soft component, compared with the number of electrons due to generation of π mesons in the atmosphere, is much less at 31° than at 51°.

TABLE IV

Geomagnetic latitude	2°	31°	51°
Energy flux *carried by π mesons, $E_{\pi^\pm} + E_{\pi^0}$	15.5±0.5	24.8±0.5	32.5±0.5
Energy consumed in nuclear disintegration, E_{nuc}	3.2±0.3	5.6±0.4	22.5±1.2
Energy lost to ionization by primary cosmic particles, E_p	0.4±0.04	0.5±0.05	1.7±0.2
Total flux of energy of cosmic radiation $E_\pi + E_{\pi^0} + E_{nuc} + E_p$	19.1±0.6	30.9±0.6	56.7±1.3
Flux of primary particles $N_p + N_\alpha$, $min^{-1}\,cm^{-2}\,sterad^{-1}$	9.0	1.5±0.1	0.48±0.04

*The energy is given in $Bev\text{-}min^{-1}\text{-}cm^{-2}\text{-}sterad^{-1}$.

present work, this ratio in the stratosphere at 31° is 0.4, and at any rate not greater than 0.5. We assume $k = 0.4$ regardless of the latitude. The inaccuracy admitted in the value of k cannot influence the results substantially. Thus, for example, the total energy $E_{\pi^\pm} + E_{\pi^0}$ will be only 7% greater at $k = 0.4$ than at $k = 0.5$, and 8% less when $k = 0.3$.

Inserting into expression (1) the values of E_e and $E_{\mu\, ion}$ for the corresponding latitudes, we obtain the total energy carried by the charged and neutral π mesons at geomagnetic latitudes of 51°, 31°, and 2°. These data are given in the first line of Table IV.

In the generation of the electron component in the atmosphere, a certain role is played by the π and μ mesons, which come from the decay of K mesons. In this case the fraction of the energy that goes to the neutrino will be greater compared with the fraction of the neutrino energy accounted for by formula (1), the latter being obtained under the assumption that all the charged mesons are formed directly in nuclear interactions. However this hardly affects our results, as can be seen from the following example. We can assume, for example, for a latitude of 2°, that the energy carried away by the charged K mesons amounts to 0.25 of the total energy of the charged π and K mesons, and that the neutral to charged π meson energy ratio is 0.5. Then, in the decay of a K meson into a π meson and two neutrinos, when the energy carried away by the neutrino is maximum, the energy flux of the cosmic radiation at 2° increases by only 5%.

The second line of the table gives the energies E_{nuc} going into nuclear disintegration, as given in reference 10. The value of E_{nuc} cited for 51° is increased by 30%, owing to the need for considering that approximately 20% of the global flux of charged particles at this latitude is due to nuclear disintegration. The third line of the table gives the energy lost to ionization by primary particles. The values of the total energy liberated in the atmosphere by cosmic radiation are given in the fourth line. The fifth line gives data on the flux of primary particles (for 51°, in accordance with reference 21). The errors in the table are statistical. The value for 2°, which will be discussed below, was obtained in the present work.

EMPIRICAL EXPRESSION FOR THE ENERGY SPECTRUM OF THE PRIMARY PARTICLES

With data on hand on the flux of energy of cosmic radiation at 51°, 31°, and 2°, and with a definite assumption made regarding the α particle to proton intensity ratio in the primary radiation, it is possible to find the energy spectrum of the primary particles. At the present time there is no agreement on primary-proton to α-particle intensity ratio. However, the available experimental data do not contradict the opinion that the fraction of the particles in the total flux is independent of the latitude.

For primary particles with energies that are not too low, it is advisable to use first a power-type spectrum of the type $\epsilon^{-\bar{\gamma}}$, where $\bar{\gamma}$ is a constant. In this case the relation between the energy flux U_p and the intensity $N_p(>\epsilon_p)$ of the primary protons has the simple form

$$U_p = N_p(>\varepsilon_p)\,\frac{\bar{\gamma}-1}{\bar{\gamma}-2}\,\varepsilon_p, \qquad (2)$$

where ϵ_p is the kinetic energy of the protons.

It follows from Eq. (2) that if the values of U_p and ϵ_p are specified, the value of the flux $N_p(>\epsilon_p)$ will increase with increasing $\bar{\gamma}$. The experimental data lead to the assumption that $\bar{\gamma} \leq 3.0$. Taking $\bar{\gamma} = 3.0$ we find an upper limit for the intensity $N_p\ (>\epsilon_p)$.

For the 2° latitude, the flux of the cosmic-ray energy is 19.1 ± 0.6 Bev. The energy flux carried by the protons is accordingly 13.3 Bev. Inserting this value for U_p and a value of 14 Bev for ϵ_p into Eq. (2), we find that $N_p^{2°}$ (> 14) ≤ 0.48 protons. Performing analogous operations for the 31° latitude, we find that $N_p^{31°}$ (> 7) ≤ 1.6 protons. Measurements of the intensity of primary particles at these latitudes should give results that are in agreement with the preceding inequalities. From this point of view, our value of the total intensity of the primary particles at 31° appears sensible.

We obtain the flux of the primary protons at 2° with the aid of relation (2), which we apply to the 2° and 31° latitudes:

$$N_p^{2°}(>\varepsilon_p^{2°}) = (U_p^{2°}/U_p^{31°})(\varepsilon_p^{31°}/\varepsilon_p^{2°})N_p^{31°}(>\varepsilon_p^{31°}), \qquad (3)$$

where $\epsilon_p^{2°}$ = 14.0 Bev and $\epsilon_p^{31°}$ = 7.0 Bev.

We assume that $U_p^{2°}/U_p^{31°}$ equals the corresponding ratio of the fluxes of the total energy of the cosmic radiation, and that $N_p^{31°}$ amount to 85% of the total flux of primary particles. Inserting these values into (3) we find that $N_p^{2°}$ (14) = 0.41 ± 0.03 protons. Accordingly, the total flux of the primary particles $N_p + N_\alpha$ will be 0.48 ± 0.04 particles at 2°.

With the aid of a power-law energy spectrum it is possible to obtain the ratio

$$(\varepsilon_p^{31°}/\varepsilon_p^{2°})^{\bar{\gamma}-2} = U_p^{31°}/U_p^{2°},$$

from which we get $\bar{\gamma} - 2$ = 0.7 ± 0.05.

It is preferable to represent the general empirical expression for a primary-particle integral energy spectrum that satisfies the experimental data at the three latitudes, 51°, 31°, and 2°, in the following form

$$N_p(>\varepsilon_p) = \frac{A_p}{(\varepsilon_p+2)^{\gamma-1}} - \frac{A_p'}{(\varepsilon_p+2)^{2\gamma-1}};$$
$$N_\alpha(>\varepsilon_\alpha) = \frac{A_\alpha}{(\varepsilon_\alpha+5)^{\gamma'-1}} - \frac{A_\alpha'}{(\varepsilon_\alpha+5)^{2\gamma'-1}}. \qquad (4)$$

Here the first expression is for protons and the second for α particles, while ϵ_p and ϵ_α are the kinetic energies of the primary protons and the primary α particles, in Bev. The other quantities in the right halves of the equations are constant, including γ and γ'. The terms 2 and 5 in Eq. (4) are so chosen as to make the ratio $(\epsilon_\alpha + 5)/(\epsilon_p + 2)$ independent of ϵ_α and ϵ_p. This ratio is equal to 2, accurate to within 3 or 4%, for ϵ_p > 1.5 and accordingly ϵ_α > 2.2 Bev (values of the critical energies at 51°). If $\gamma = \gamma'$, the integral spectra of the protons and α particles will be similar, and the fraction of the α particles will be independent of the latitude. The constants A_p, A_p' for N_p (> ϵ_p) and A_α, A_α' for N_α (> ϵ_α) in Eq. (4) are chosen such as to make the value of the primary-particle flux at 51°, for definite values of the index γ, equal to none particles,[21] with 85% of this value pertaining to protons and 15% to α particles. This value of the flux of primary particles at 51° is quite accurate and has been well confirmed in supplementary experiments performed by us at this latitude.

TABLE V

Geomatic latitude	Exponent	Flux of primary cosmic-radition energy (Bev-min⁻¹ cm⁻²-sterad⁻¹)	Intensity of primary cosmic particles (min⁻¹ cm⁻² sterad⁻¹)
2°	2.8	28.7	0.70
	3.0	18.6	0.50
	3.2	12.4	0.38
	Experiment	19.1±0.6	0.48±0.04
31°	2.8	43.2	1.96
	3.0	31.0	1.60
	3.2	23.2	1.30
	Experiment	30.8±0.6	1.5±0.1
51°	2.8	69.5	9.0
	3.0	58.3	9.0
	3.2	51.0	9.0
	Experiment	56.7±1.3	9.0

With the aid of the spectra (4), we calculated the energy fluxes at 51°, 31°, and 2° and the intensities of the primary cosmic particles at 31° and 2° for values of γ of 2.8, 3.0, and 3.2. These data are given in Table V. The third column of the table gives the values of the total energy carried by the primary protons, α particles, and particles with charge Z ≥ 3 (the energy flux carried by the particles with charge Z ≥ 3 has been estimated to be approximately 20% of the energy flux carried by the α particles). The fourth column gives the values of the flux of primary particles $N_p + N_\alpha$. The table gives also experimental data for the corresponding latitudes, taken from Table IV. As can be seen from Table V, a good description of the experimental data is obtained when the index is γ = 3.0. For γ = 3.0, the spectra (4), written with the numerical values of the constants, become

$$N_p(>\varepsilon_p) = 110/(\varepsilon_p+2)^{\gamma-1} - 700/(\varepsilon_p+2)^{2\gamma-1},$$
$$50 > \varepsilon_p \geqslant 1.5;$$
$$N_\alpha(>\varepsilon_\alpha) = 80/(\varepsilon_\alpha+5)^{\gamma-1} - 4\cdot 10^3/(\varepsilon_\alpha+5)^{2\gamma-1}, \qquad (5)$$
$$100 > \varepsilon_\alpha \geqslant 2.2,$$

where $\gamma = 3.0^{-0.05}_{+0.07}$. The second terms in (5) decrease rapidly with increasing proton and α-particle energies. For ϵ_p = 1.5 Bev and ϵ_α = 2.2 Bev,

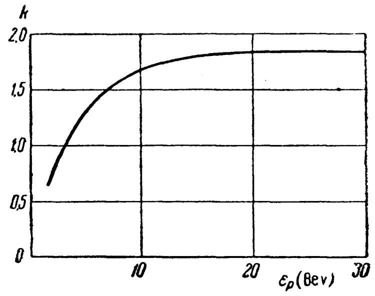

FIG. 8. Dependence of the exponent k on the energy ε for an integral spectrum of primary particles of the type const/ε^k.

the second terms amount to 15% of the first terms. When $\epsilon_p = 4$ Bev and $\epsilon_\alpha = 6.6$ Bev, the second terms diminish by a factor of 6.

Naturally, high-energy primary particles are not effective in our experiments. Only one-third of the flux of cosmic-ray energy at 2° is due to primary particles with energies greater than 50 Bev (for protons). The foregoing energy spectrum (5) cited above is therefore apparently effective up to primary-proton energies of 30 to 50 Bev. We remark that the spectra (5) are equivalent to a power relation of the type const/ϵ^k, where the exponent k is a function of the energy ϵ. The dependence of k on ϵ is illustrated in Fig. 8. It is seen from this diagram that k(ϵ) varies rapidly at first and, at energies of 10 to 20 Bev, reaches values of 1.7 to 1.8, usually obtained in extensive atmospheric showers.

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[1] Ageshin, Charkhch'ian, and Charakhch'ian, Izv. Akad. Nauk SSSR, Ser. Fiz. **19**, 533 (1955), [Columbia Techn. Transl. **19**, 478 (1955)].

[2] M. Vidale and M. Schein, Phys. Rev. **81**, 1065 (1951).

[3] M. A. Pomerantz, Phys. Rev. **75**, 69 (1949).

[4] A. N. Charakhch'ian, Dissertation, Phys. Inst. Acad. Sci. U.S.S.R., 1952.

[5] I. P. Ivanenko, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 135 (1957), Soviet Phys. JETP **6**, 105 (1958).

[6] S. Z. Belen'kii, Лавинные процессы в космических лучах (Cascade Processes in Cosmic Rays), Gostekhizdat, 1948, p. 101.

[7] S. Z. Belen'kii, ibid. p. 150.

[8] P. N. Ageshin and T. N. Charakhch'ian, Вестник МГУ (Bull. Moscow State Univ.) **2**, 77 (1956).

[9] V. F. Tulinov, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1163 (1957), Soviet Phys. JETP **6**, 894 (1958).

[10] N. L. Grigorov, Usp. Fiz. Nauk **58**, 599 (1956).

[11] Vernov, Kulikov, and Charakhch'ian, Izv. Akad. Nauk SSSR, Ser. Fiz. **17**, 13 (1953).

[12] Johns, Cunningham, and Katz, Phys. Rev. **83**, 952 (1951). F. L. Hereford and C. P. Swann, Phys. Rev. **78**, 727 (1950).

[13] I. D. Rapoport, Izv. Akad. Nauk SSSR, Ser. Fiz. **19**, 519 (1955) [Columbia Techn. Transl. **19**, 466 (1955)].

[14] J. R. Smith, Phys. Rev. **95**, 730 (1954).

[15] Scherrer, Thens, and Faust, Phys. Rev. **91**, 1476 (1953).

[16] F. Ajzenberg and L. Lauritsen, Revs. Modern Phys. **27**, 132 (1955).

[17] C. L. Yuan, Phys. Rev. **81**, 175 (1951).

[18] G. Nier, Physics of Cosmic Rays, (Russ. Transl) IIL, 1954, p 251.

[19] Winckler, Stok, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[20] I. A. Van Allen and S. F. Singer, Phys. Rev. **78**, 819 (1950); **80**, 116 (1950).

[21] S. N. Vernov and A. N. Charakhch'ian, Dokl. Akad. Nauk SSSR **91**, 487 (1953).

[22] K. I. Alekseeva and N. L. Grigorov, Dokl. Akad. Nauk SSSR **115**, 259 (1957), Soviet Phys. "Doklady" **2**, 317 (1957).

[23] Vernov, Kulikov, and Charakhch'ian, Dokl. Akad. Nauk SSSR, **85**, 525 (1952).

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