HEAVY NUCLEI FLUX IN THE PRIMARY COSMIC RADIATION AT A GEOMAGNETIC LATITUDE OF 31°N

K. I. ALEKSEEVA and N. L. GRIGOROV

Moscow State University

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The flux of primary heavy particles in the stratosphere was measured with apparatus consisting of a telescope surrounded by hodoscope counters and of two pulse ionization chambers placed between the trays of the telescope counters. The ionization produced in each of the chambers by single particles with a charge $Z \geq 1$ traversing the telescope was measured. The flux of primary α particles at the top of the atmosphere at a geomagnetic latitude of 31° N was found to be equal to 0.335 ± 0.035 particles $cm^{-2}min^{-1}sterad^{-1}$, which is $(16 \pm 2)\%$ of the total particle flux. The flux of primary particles with $Z > 2$ under similar conditions was found to be equal to 0.019 ± 0.006 particles $cm^{-2}min^{-1}sterad^{-1}$, which is $\sim 6\%$ of the number of α particles and about 1% of the total particle flux at the top of the atmosphere at a geomagnetic latitude of 31° N.

INTRODUCTION

THE discovery of atomic nuclei of heavy elements in primary cosmic radiation in addition to protons[1,2] has aroused great interest in the study of the composition of primary cosmic rays. As has been determined since, in spite of the small fraction of heavy nuclei in the total flux of primary particles, these heavy nuclei amount to 30 — 35% of all nucleons reaching the top of the atmosphere and carry about 30% of the total energy of the cosmic radiation, and produce about 50% of the ionization in the upper layers of the atmosphere. An accurate knowledge of the composition of the multi-charged primary component is necessary also for a solution of the problem of the origin of the cosmic radiation and the distribution of its sources. A wide range of problems connected with the composition of the heavy primary component of cosmic rays has led to a number of experimental investigations. In addition to the fundamental experiments on the determination of the spectrum of heavy nuclei, as carried out by Bradt and Peters et al. with nuclear photo-emulsions,[3-5] a series of experiments with low-pressure Geiger counters,[1,2] proportional counters,[6] and scintillation counters[7] have been carried out.

A study of the charge spectrum of cosmic-ray primaries in the stratosphere was carried out in our laboratory using pulse ionization chambers and a hodoscope. By means of a telescope and hodoscope, the vertical beam of single particles traversing the apparatus was selected. By measuring the ionization produced by these particles in two pulse ionization chambers placed inside the telescope, we were able to determine the charge spectrum and, consequently, the mass spectrum of the heavy nuclei of the primary cosmic radiation. On September 18, 1954, the apparatus constructed for this purpose was lifted by probing balloons to the stratosphere at 31° N geomagnetic latitude, and, for a period of several hours, stayed at an altitude of 25 — 27 km (an average atmospheric depth of 24 g/cm^2). The measurements of the ionization chambers and of the hodoscope were transmitted to the earth by radio.

APPARATUS

A schematic diagram of the position of the counters and ionization chambers in the apparatus, and a block diagram of the electronic circuitry, using miniature directly-heated tubes, are shown in Fig. 1.

The telescope, which selected a vertical beam of single particles, consisted of three trays A, B, C, of self-quenched Geiger-Müller counters, three counters in each tray,* connected to a triple-coincidence circuit (see Fig. 1). Two identical cylin-

*The dimensions of the counters were: internal diameter, 2 cm; geometrical length, 30; thickness of the glass walls, 1-1.5 mm. The counters were filled with a mixture of argon and ethylene. A thin graphite layer spread on the internal surface of the glass wall served as the cathode.

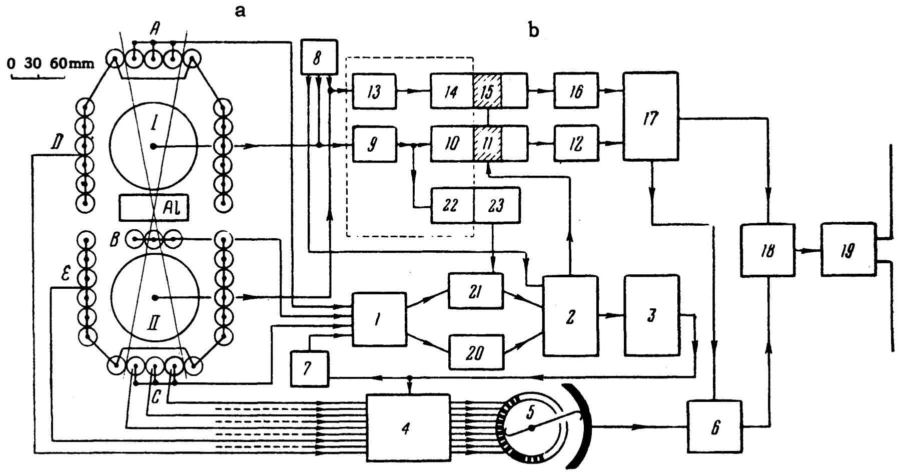

FIG. 1. a — diagram of the position of the counters and ionization chambers in the apparatus; b — block diagram of the electronic circuits of the apparatus: 1 — triple coincidence circuit; 2 — gating univibrator; 3 — hodoscope master pulse shaping circuit; 4 — hodoscope; 5 — rotary switch; 6 — hodoscope pulse tube; 7 — triple coincidence gating circuit; 8 — generator of calibration pulses; 9 to 10, 13 to 14, and 9 to 22 — channels of linear amplification; 11 and 15 — gating circuits; 12 and 16 — pulse stretching circuits; 17 — circuit for simultaneous transmission of pulses of both chambers; 18 — modulator of the transmitter; 19 — transmitter; 20 — scaling circuit 1:4; 21 — "four-fold" coincidence circuit; 23 — univibrator with trigger level set for the pulse produced in the ionization chamber by two to three relativistic particles.

drical pulse ionization chambers,* I and II, were placed inside the telescope for the measurement of the specific ionization of particles traversing the telescope. The chambers were connected to linear amplifiers 9 — 10, 13, 14, and 9 — 22. The ionization chambers and the telescope were surrounded by two groups of counters D and E. The counters D and E, and also each of the telescope counters, were connected to a hodoscope. The passage of several particles (nonlocal showers) through the instrument, and also the production of electron-nuclear showers in the material of the telescope by the particles traversing it were, as a rule, accompanied by a discharge of the counter groups D, E, or the discharge of more than one counter in the telescope trays. Such showers were excluded from consideration since, in the majority of cases, they were nonlocal. Only these cases where one counter was discharged in each of the telescope trays A, B, and C, owing to single particles traversing the telescope without interaction, were subject to further analysis. In order to minimize the loss in the number of single particles due to the production of δ-showers and electron-nuclear showers in the material inside the telescope, it was necessary to reduce the amount of matter in the telescope to a minimum. Nevertheless, an aluminum absorber of 3.0 cm thickness was placed between the trays A and B of the telescope counters under the upper ionization chamber I. This was done in order to exclude the secondary low-energy protons, with an initial ionization greater than three times the minimum ionization, from the flux of single particles, and thus to lower the background in the ionization range of α particles. In the following, in the calculation of the flux of multiply-charged particles, a correction was applied for the exclusion of single particles from the beam due to the production of showers in the matter inside the telescope.

The instrument was triggered by a triple coincidence ($\tau = 5 \times 10^{-6}$ sec) of discharges in the counter trays A, B, C of the telescope (block 1). To increase the statistical accuracy of the measured flux of multi-charged particles, we constructed an instrument with a rather large geometrical factor $S\Omega = 22.7$. To avoid overloading of the electronic circuits by a large number of pulses from single particles, all pulses from the triple coincidence circuit (block 1) were fed through 20 with a scaling factor of 1:4. However, to prevent a decrease in the number of the recorded multiply-charged particles, "four-fold coincidences" between the total number of triple coincidences without scaling and the pulses due to particles which, in chamber I, produced two to three times the ionization of a singly-charged relativistic particle, were analyzed by circuit 21.

*The dimensions of the cylindrical pulse ionization chambers were: diameter, 10 cm; length, 30 cm; wall thickness, 0.5 mm brass. The diameter of the internal electrode consisting of a steel rod placed along the cylinder axis was equal to 3 mm. The chambers were filled with spectrally pure argon at a pressure of 5 atmos. The working voltage was 1000 v.

The ionization pulses were fed to a "four-fold" coincidence circuit through a parallel amplification channel 9 — 22 and a univibrator 23 with a triggering level corresponding to a pulse produced in the ionization chamber by two to three singly-charged particles. The "four-fold" coincidences were analyzed by circuit 21. A marker circuit containing a neon lamp MTKh-90 was connected to the common anode of the tubes of this circuit. Whenever a "four-fold" coincidence occurred, the neon lamp was ignited and a voltage pulse appeared on the switch blade connected to its cathode. The marker circuit was also connected to the output of scaler 20. Pulses from circuit 21 ("four-fold" coincidences) as well as the pulses from circuit 20 (triple coincidences scaled down in the ratio 1:4) were fed to a univibrator 2 generating square pulses of 2×10^{-4} sec duration. The pulses from the gate univibrator were used to trigger the amplifying channel of the chambers and to start a short powerful pulse for triggering the hodoscope, which was produced by a short-duration ($\tau = 5 \times 10^{-6}$ sec) univibrator with consecutive power amplification by means of a cathode follower (block 3). The shaped master pulse from block 3 was fed to the screen grids (connected in parallel) of the tubes of the hodoscope 4. The hodoscope was similar to the one used in the experiments of Vernov and Charakhch'yan.[8] Pulses from the hodoscope were fed to a mechanical rotary switch 5,[8] the blades of which were connected to the cathodes of the neon lamps MTKh-90 placed in the anode circuit of the hodoscope tubes, and which were used as the indicators of discharge of the given hodoscope counters. The central connection of the switch contacted, in turn, all the blades and passed the voltage pulses from the neon lamps to a cut-off tube of the hodoscope 6, which was gated a short time after the passage of the stretched pulses from the two chambers. The resolving time of the hodoscope was 2×10^{-5} sec. To avoid the superposition of hodoscope pulses corresponding to various master pulses, a special circuit 7 blocked the coincidence circuit during the recording of the pulses of the chambers and of the hodoscope.

Electron pulses produced in chambers I and II during the passage of charged particles were fed to low-noise linear amplifiers 9, 10, 13, and 14.* Since we were not interested in the continuous recording of all pulses from the chambers, but only of those pulses produced in the chamber during the passage of a particle through the telescope, it was necessary to trigger the amplification channel of the chamber, i.e., to gate the channel in points 11 and 15 for a passage of a particle through the telescope. The opening of the closed gates 11 and 15 was done by a square pulse produced by the gate univibrator 2. The time during which the amplification channel was open was equal to 2×10^{-4} sec, the width of the transmitted pulse being $\sim 1 \times 10^{-4}$ sec.

For radio transmission of the chamber pulses, the amplitude of the pulse V was, after the amplification of the pulses and their passage through the gating lamps, transformed into the pulse length T by means of stretching circuits 12 and 16. The linearity between V and T was insured in a sufficiently wide range.

In the construction of the instrument, we were faced with the problem of a simultaneous radio transmission of the pulses from the two chambers and the pulses from the hodoscope. For a simultaneous recording of the pulses from the two chambers, a special three-tube multivibrator was designed (block 17). This multivibrator, upon a simultaneous arrival of the stretched pulses from both chambers, produced pulses with a frequency of the order of 300 kcs. After the pulse in one of the chambers had ended, the multivibrator frequency was changed to ~ 1000 kcs. A special marking circuit made it possible to determine whether the larger of the pulses belonged to the upper or to the lower chamber, according to the discharge (or the lack of it) of the neon lamp incorporated in this circuit. The pulses modulated in such a way were fed to modulator 18 of the transmitter and then to the transmitter 19. A short time after the pulses from the chambers were transmitted, the pulses from the hodoscopes also arrived through the tube 6. After the hodoscope pulses had been automatically recorded a few times by means of a relay, the voltage was taken off the neon lamps of the hodoscope and of the neon tube of circuit 7 which blocked the coincidence circuit and, after that, the instrument was ready for recording the next pulse.

The signals received on earth were recorded by photographing, on moving film, the electron beam of an oscillograph connected to the output of the receiver. An example of such a film record of the pulses from the two chambers and from the hodoscope made during the flight is given in Fig. 2.

To convert the length of the stretched pulse into multiplicity of ionization (in terms of the probable ionization due to a single-charged relativistic particle) the instrument was calibrated

*The circuit diagram of the low-noise linear amplifier was taken from reference 9.

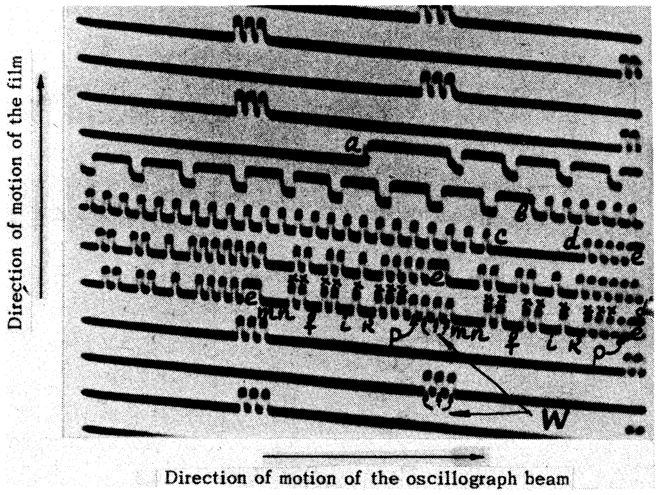

FIG. 2. A picture of the recorded pulses from the chambers and the hodoscope on film during flight: ab – pulse from an α particle in the top chamber; multiplicity of ionization equal to 4.0-4.25; ab + bc – pulse from the same α particle in the lower chamber; multiplicity of ionization equal to 4.75-5.0; dd′ – pulses from the hodoscope; e – marker of the master pulse; f, i, k – discharge counters; pulses on the blades of the switch for nondischarging counters are denoted by x; m – marker of the pulse amplitude from chambers; n – marker of triple coincidences with scaling factor; p – marker of "four-fold" coincidences; w – barograph signals.

by measuring (before the flight) the dependence of the length of the signal at the amplifier output on the amplitude of the signal at the input. For use in the stratosphere, the calibration curves obtained were corrected using the singly-ionizing particles which give a well defined maximum in the particle-ionization spectrum in the atmosphere, and using the fixed calibration signals in the region of 15-fold ionization produced by a special internal generator 8 built for this purpose. Signals from the generator during the time of flight were fed, a few times per minute, to the amplifier input and, correspondingly, to the gating univibrator 2. The range of linearly amplified pulses from the chambers was 10 to $\sim 400\ \mu v$ at the amplifier input. This permitted a good measurement of the ionization produced by singly-charged relativistic particles (the probable ionization due to a singly-charged relativistic particle produces a pulse equal to 18 μv at the amplifier input) and by multiply-charged particles with $Z = 2$, 3, and 4. Heavy nuclei with $Z \gtrsim 4$, causing saturation of the last tubes of the linear amplifier, could not be distinguished one from another.

As an illustration of the resolving power of the instrument in the ionization range $J/J_0 = 1 - 4$ (J_0 is the probable ionization produced in the chamber by a relativistic singly-charged particle; J is the ionization produced in the chamber by the given particle), the spectrum of ionization pulses from single particles obtained in measurements at the surface of the earth ($H = 1$ km) is shown in Fig. 3. The half-width of the distribution obtained is determined by: a) fluctuations in the ionization produced by relativistic particles in the gas of the chamber, and b) by the superposition of noise. (The rms value of the noise at the amplifier input was equal to $\sim 10 \times 10^{-6}$ v for the probable pulse from a singly-charged particle equal to 1.8×10^{-5} v.)

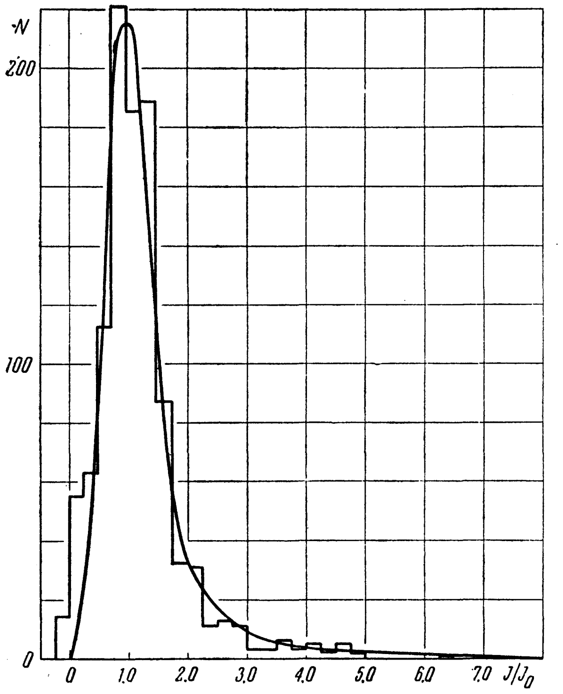

FIG. 3. Spectrum of ionization pulses from single cosmic ray particles at an altitude $H = 1$ km. N – number of particles; J/J_0 – ionization in relative units.

REDUCTION OF EXPERIMENTAL DATA

In view of the presence of a large background from slow singly-charged particles in the stratosphere in the ionization range $J/J_0 = 1 - 4$, and also because of the presence within that range of a certain number of singly-charged relativistic particles (see Fig. 3), it was not possible to find, for α particles, a sharp maximum at the point $J/J_0 = 4.0$ in the ionization spectrum of particles in the stratosphere. The experimental material obtained was reduced therefore in the following manner:

Distributions were plotted in the (x, y) plane (see, e.g., Fig. 4) of simultaneous pulses produced by single particles in the upper and lower chambers. Each particle had a definite place in such a diagram, depending on the ionization produced in chamber I (x axis) and chamber II (y axis).

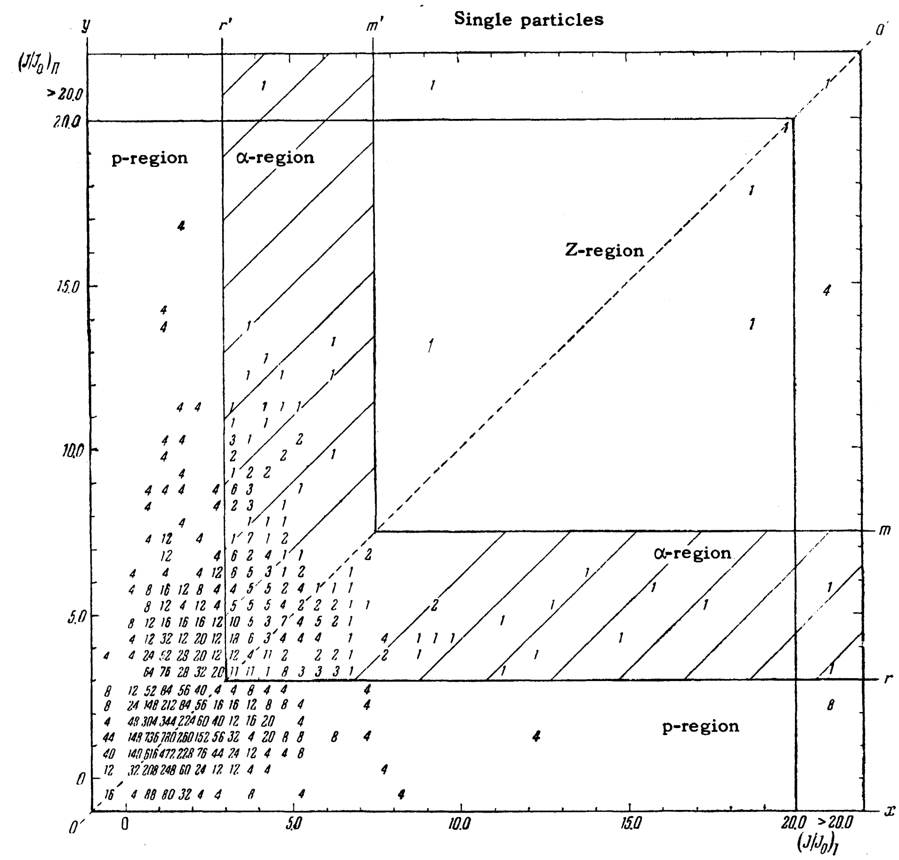

FIG. 4. Distribution of single particles traversing the instrument at an altitude H = 25-27 km with respect to the ionization produced by them in the two chambers. The value of the pulse in the top chamber $(J/J_0)_I$ is given on the x axis, and the value of the simultaneous pulse in the lower chamber $(J/J_0)_{II}$ on the y axis.

(The value of ionization is expressed in units equal to the probable ionization due to a relativistic singly-charged particle.) In the absence of fluctuations in the ionization, the nuclei of H, He, Li, etc., on this plane would be grouped along the straight line OO′ running from the origin of coordinates O at an angle of 45°, around points with coordinates 1:1, 4:4, 9:9, etc. In the presence of fluctuations, the particles with a given value of Z will fall into a certain ionization range, with the most probable value at the above points. For the determination of the flux of α particles, it was necessary to determine the actual limits of the ionization range of α particles and the value of the background from singly-charged particles in that range. In practice, we followed the following procedure: Ionization diagrams of single particles were constructed for three altitudes, H = 1 — 11 km, H = 11 — 15 km, and H = 25 — 27 (plateau of the flight, Fig. 4). It could be assumed with certainty that, at altitudes below 15 km, there was no considerable amount of primary α particles in the composition of cosmic rays. This means that all particles detected in the range of ionization due to α particles at altitudes below 15 km are background pulses of singly-charged particles. The upper limit of the α particle region accepted by us which roughly coincided with the lower limit of the region of particles with Z > 2 (Z region), is denoted in the diagram by two perpendicular lines m and m′ (see Fig. 4) parallel to the coordinate axes x and y, with the point of intersection on the straight line OO′ going through the origin of coordinates at an angle of 45° with the coordinate axes. The lower limit of the α region is denoted on the diagram by the lines r and r′. This limit, and also the background of singly-charged particles in the α region (in the region between the lines r — r′, and m — m′, dashed on the drawing) were determined by us experimentally.

To evaluate the background magnitude in the α region, we moved the point of intersection of the lines r and r′ in the ionization diagrams along the straight line OO′, giving it a sequence of values $(J/J_0)_I = (J/J_0)_{II} = 4.0,\ 3.5,\ 3.0,\ 2.5,$ and 2.0. For all these positions of the limit, we counted the number of pulses in the α-particle region and in the p region (the region of singly-charged particles) for altitudes H = 1 — 11 km and H = 11 — 15 km, using the total geometrical factor of the apparatus. The ratio of the number of particles in the α region to the number of particles in the p region gives the background due to singly-charged particles in the α region. The value of the background in the α region, ex-

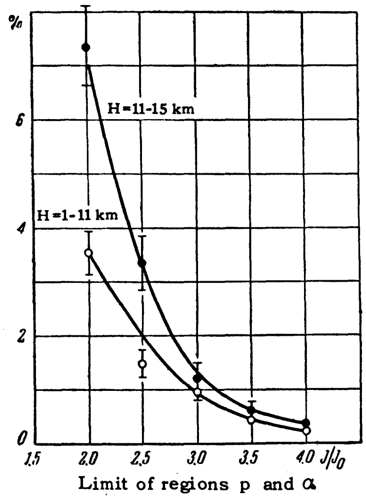

FIG. 5. Value of the background from singly-charged particles in the α region at the altitudes H = 1-11 km, and H = 11-15 km as a function of the choice of the lower limit of this region (top limit of α region $J/J_0 = 7.5$). Value of the background is given in percent of the number of singly-charged particles in the p region.

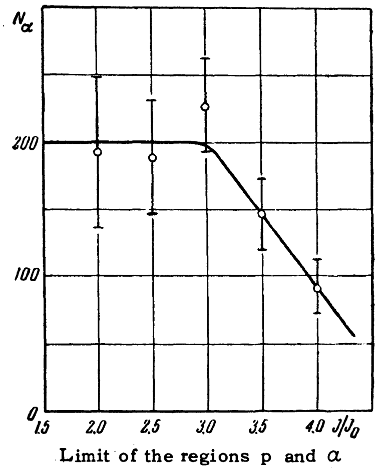

FIG. 6. Number of single α particles N_α recorded on the plateau (H = 25-27 km, t = 78 min) as a function of the choice of the lower limit of the α particle region. Correction for the background of singly-charged particles has been introduced.

pressed as a fraction (in %) of the number of singly-charged particles in the p region, as a function of the chosen limits of the regions p and α for altitudes H = 1 — 11 km and H = 11 — 15 km, is given in Fig. 5.

The number of α particles recorded at the plateau (H = 25 — 27 km, t = 78 min) is given in Fig. 6 as a function of the position of the limit $r - r'$ between the proton and the α-particle region obtained from the data of Fig. 4.* The background due to singly-charged particles, according to the data of Fig. 5, for the altitude H = 11 — 15 km has been subtracted from each point of the curve in Fig. 6. The curve in Fig. 6 shows that when the point of intersection of the straight lines r and r′ moves from the value $(J/J_0)_{\mathrm{I}} = (J/J_0)_{\mathrm{II}} = 4.0$ towards smaller values, the number of α particles first increases and then, beginning with the value $(J/J_0)_{\mathrm{I}} = (J/J_0)_{\mathrm{II}} = 3.0$, remains constant. Thus, by passing the lower limit of the α region through the point $(J/J_0)_{\mathrm{I}} = (J/J_0)_{\mathrm{II}} = 3.0$, as shown in Fig. 4, we practically take all α particles into account.

EXPERIMENTAL RESULTS

The results of the measurement of the flux of primary α particles and heavy primary nuclei with $Z > 2$ in the stratosphere at 31° N geomagnetic latitude are given in the table. The first row of the table lists the number of single particles in the α region ($Z = 2$) and in the Z region ($Z > 2$) which did not produce nuclear interactions recorded at the depth of 24 g/cm^2. To the recorded number of particles in the region $Z = 2$, we applied a correction for the background from single-charged particles and for α particles producing δ stars in the matter of the telescope, and which, therefore, were excluded from the category of singly-charged particles.* After introducing the corrections, we obtained the number of primary α particles at the depth of 24 g/cm^2 which did not produce nuclear interactions in the matter of the telescope (4th and 5th rows of the table). Also presented here is the number of primary heavy nuclei with $Z > 2$, in the calculation of which we introduced no correction for δ showers, in view of the arbitrariness of its introduction, and no correction for the background, in view of the small statistical accuracy of its determination at low altitudes.

For the determination of the flux of α particles and heavy nuclei with $Z > 2$ at the top of the atmosphere, it is necessary to take into account the absorption of the flux due to nuclear in-

*The numbers in Fig. 4 denote the number of particles in the given ionization range recorded during the stay of the instrument at the altitude of 25-27 km. In the proton region these numbers were obtained as a result of multiplication by four of the recorded number of triple coincidences with a scaling factor 1:4, accompanied or not accompanied by a "four-fold" coincidence. In the α-particle region and in the region of particles with $Z > 2$ these numbers were obtained as the result of adding the scaled-down number of triple coincidences multiplied by four, not accompanied by "four-fold" coincidences to the total number of "four-fold" coincidences (accompanied and not accompanied by a scaled-down triple coincidence).

*The correction for δ showers was introduced on the basis of measurements carried out in the laboratory with other instruments without absorbers consisting of a small-sized telescope surrounded by hodoscoped counters. These instruments, in view of their small dimensions, practically did not record nonlocal showers. Therefore, all showers recorded by these instruments at sea level could have been regarded as δ showers. From data obtained by means of this instrument, δ showers are produced by singly-charged particles which amount to ~5% of the number of single particles traversing the instrument. Since the ionization is proportional to the square of the charge of the ionizing particle, we assumed the percentage of δ showers produced by α particles to be equal to 20% of the number of single α particles.

Results of the measurement* of the flux of heavy primary particles in the stratosphere at 31° N geomagnetic latitude

Charge of the heavy primary nucleus	$Z = 2$	$Z > 2$
Number of single particles recorded at the depth of 24 g/cm² in the ionization regions	317±18	10±3.2
Correction for the background due to singly charged particles	−90±22	not introduced
Correction for the number of nuclei producing δ showers	+45±6	not introduced
Number of primary heavy nuclei at the depth of 24 g/cm² not producing nuclear interactions	272±29	10±3.2
The same in $cm^{-2}min^{-1}sterad^{-1}$	0.154±0.016	0.0056±0.0018
Absorption coefficient of heavy nuclei due to nuclear interactions in the matter of the apparatus, exp (−x/L)	0.815	0.740
The same in the layer of air above the instrument	0.565	0.400
The flux of heavy nuclei I_Z^0 at the limit of the atmosphere at 31° N geomagnetic latitude in $cm^{-2}min^{-1}sterad^{-1}$	0.335±0.035	0.019 ±0.006
I_Z^0/I_0, %	16±2	~1

*Duration of measurements t = 78.0 min; geometrical factor of the instrument $S_\Omega = 22.7$; the number of single particles in the Z = 1 ionization range recorded at the depth of 24 g/cm² equals 7512 ± 87; amount of matter in the telescope of the setup – 8.1 g/cm²Al + 1.7 g/cm²Cu + 2.0 g/cm²glass.

teractions in the matter of the instrument and in the layer above it. The values of the absorption coefficient exp (−x/L) in the matter of the absorber and in the layer of air above it are given in the table for α particles and heavy nuclei with Z > 2 (x denotes the thickness of the absorber, and L the mean free path for inelastic interactions). In the calculation of these coefficients, we used the geometrical cross section of the inelastic interaction of α particles and nuclei* with Z = 7 with Al, Cu, and N nuclei of the medium. After taking the nuclear interactions into account, the flux of α particles at the limit of the atmosphere at 31° N geomagnetic latitude was found to be equal to 0.335 ± 0.035 particles $cm^{-2}min^{-1}sterad^{-1}$, which amounts to (16 ± 2) % of the total flux I_0 of primary particles.[10,11] For the flux of heavy nuclei with Z > 2, the value obtained was 0.019 ± 0.006 particle $cm^{-2}min^{-1}sterad^{-1}$, i.e., ~ 6% of the number of primary α particles and ~ 1% of the total particle flux..

V. F. Grushin took part in the experiment.

*The average value of the atomic number for the flux of heavy nuclei with Z > 2 was assumed to be equal to 7.

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