INVESTIGATION OF NUCLEAR DISINTEGRATIONS PRODUCED BY THE CHARGED COMPONENT OF COSMIC RADIATION

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Results are presented of a mass-spectrometer study of the products of disintegrations produced by the charged component of cosmic radiation. Methods of distinguishing nuclear disintegrations from showers originating in electromagnetic interactions of μ mesons are indicated. The differential momentum spectrum of secondary particles in stars with $n > 2$ has been measured. It has been found that the ratio $N(\pi^+)/N(\pi^-)$ for the produced π mesons is equal to 1.18 ± 0.23 in the momentum range 0.12 to 0.9 Bev/c, and that the π mesons constitute $53 \pm 5\%$ of the secondary particles with momentum ≥ 1 Bev/c. The ratio of charged to neutral star producing particles of ~ 30 Bev is equal to 1.2 ± 0.16.

In a hodoscope study of the secondaries of stars produced by charged particles a difficulty is encountered due to the considerable background of showers originating in electromagnetic interactions of μ mesons. The majority of investigators limit therefore their experiments either to the stars produced by neutral particles[1-4] or to the large stars $(m \geq 2, n \geq 5)$* produced by charged particles.[5] In the latter case, smaller stars, which constitute $\sim 50\%$ of all events produced by charged particles, are disregarded.

In the present work, data are given on secondaries observed in large $(m \geq 2, n \geq 5)$ and small $(m \geq 2, n < 5; n = 1, n > 2)$ stars produced by the charged component of cosmic radiation.

The measurements were carried out using the Alikhanian-Alikhanov magnetic mass-spectrometer at 3250 m above sea level (Aragats). The hodoscope, placed above the magnet, detected nuclear disintegrations in the targets A, B, C, D, E, F placed between the counter trays. The nature of secondaries was studied by means of the mass spectrometer. The instrument and the method of selection of particles by the magnetic field have been described in reference 5. The thickness of the targets and absorbers, and their position in the instrument, are given in Table I.

In this article we discuss only the stars in which the angle between the primary trajectory and the vertical was not greater than 35°. According to Camerini et al.,[6] the fraction of such stars amounts to $\sim 75\%$ of all stars produced by charged particles. The distribution of the secondaries of large stars $(m \geq 2, n \geq 5)$ with respect to the direction of motion (the angle with the primary trajectory) in the plane perpendicular to the magnetic deviation is shown in Fig. 1. Data obtained by Camerini[6] by means of emulsions are included in the figure. It follows that our apparatus located with a large efficiency particles emitted at an angle $\leq 35°$ which, according to reference 6, amount to $\sim 90\%$ of all secondaries.

*Stars observed by means of a hodoscope are characterized by the numbers m and n, where m is the number of trays (separated by targets) traversed by at least two particles of the star, and n is the observed number of secondary star particles (multiplicity).

SEPARATION OF NUCLEAR DISINTEGRATIONS AND SHOWERS INITIATED BY μ MESONS

All observed stars were divided into groups according to the number of secondaries and their range in the targets (Table II). To determine the groups that did not contain showers initiated by μ mesons, we studied the passage of the secondaries of a given group through the absorbers (Table II).* For this purpose we used the results of the third series of measurements, in which the total thickness of absorbers is 2.5 times larger than the nuclear-interaction mean free path.

It follows from the data that the stars with five and more secondaries, at least two of which pass through the next target [i.e., stars of the type $(m \geq 2, n \geq 5)$], represent nuclear disintegra-

*For comparison, data on the passage of secondary nuclear-active particles produced by neutrons are given at the end of the table.

TABLE I

Series	Lead target, cm						Absorber, cm					
	A	B	C	D	E	F	1	2	3	4	5	6
							Graphite					
1	0	7	6	5	4	3	4	9	4	3.6	3.9	1Pb + 9Cu
2	0	7	6	0	0	0	4	9	4	2	2	1Pb + 9Cu
7	7	6	5	0	0	0	4	8	4	2	2	11Cu
11	7	6	5	0	0	0	4	8	4	2	3Pb+0.6Cu	11Cu
							Copper					
3	8	7	6	5	4	3	3.6	8.26	4.26	3.1	4 or 2.6 + 1 Pb	12 or 9.25 + 1 Pb

tions produced by charged particles. All stars of this type, observed in all series of measurements, were regarded therefore as such.

The remaining groups ($m \geq 2$, $n < 5$ and $m = 1$, $n > 2$) contain both electronic showers initiated by μ mesons and nuclear disintegrations. In these, only the stars in which the secondaries underwent nuclear interactions in the absorbers were accepted as nuclear events. In order to exclude completely the μ mesons that produce showers both in the targets and in the absorbers of the instrument, we studied the passage of μ mesons through the lead and graphite absorbers.

Showers initiated by μ mesons. All single particles with momentum $p \geq 1$ Bev/c which passed through all the targets (25 cm Pb) without an interaction were assumed to be μ mesons, since the fraction of nuclear-active particles among such particles amounts to $\sim 2\%$ only.* Data on the passage of μ mesons through the absorbers of the apparatus as well as on the passage of secondary particles of large and small stars through the absorbers, are given in Table III.

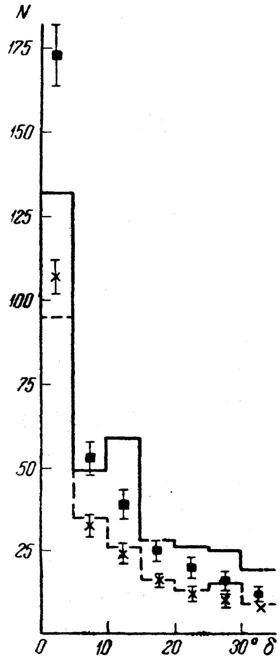

FIG. 1. Direction distribution of secondary particles (with respect to the primary). Solid curve represents all particles produced in large stars, dashed – positive particles with $p \geq 10^9$ ev/c and all negative particles (i.e. shower particles); ×) ■ data of Camerini et.al., renormalized to the area.

It follows from the table that: (1) interactions of the type b, c, d, e, and f originate in the majority of cases in electromagnetic interactions of charged particles, and it is therefore impossible to distinguish nuclear-active particles from μ mesons; (2) stars of the type g ($m \geq 2$, $n \geq 2$), large-angle scattering events (h), and stopping of particles not due to ionization losses (i) involve nuclear-active particles only. The stars, in which the secondaries underwent interactions of the type g, h, and i in the absorbers were considered therefore as nuclear disintegration.†

NATURE AND MOMENTUM SPECTRUM OF SECONDARY PARTICLES

We observed 135 particles with mass $M \leq 1300\ m_e$ in nuclear disintegrations with $n > 2$ in the momentum range from 0.12 to 0.9 Bev/c. The upper mass limit of the particles was estimated from their momentum and minimum range. The minimum range was defined as the absorber thickness traversed by the particle without a visible interaction. The mass distribution of the particles is given in Table IV. Of the 135 particles, 73 were positive and 62 negative, i.e., the ratio of positive to negative mesons produced in lead by charged particles equals 1.18 ± 0.23. The result

*According to references 7 and 8, the fraction of nuclear-active particles amounts to ~10% of the total flux at 3200 m altitude. Of these, not more than 20% can traverse 25 cm Pb without an interaction.

†Interactions of the type g, h, and i involving μ mesons (~1%) are explained by the presence of ~2% protons among the "μ mesons," half of which should, according to data of Table III, undergo interactions of the type g, h, and i.

TABLE II*

Type of star	Passage of secondaries through absorbers: No interaction	Weak interaction**	Nuclear interactions: scattering $>2\langle\vartheta\rangle$	stopping (not due to ionization)	star $m\geqslant 2,\ n>2$	Total
$m=1,\ n>2$: $\delta<5°$	184	16	5	6	—	211
$5\leqslant\delta<9°$	3	2	1	—	—	6
$\delta\geqslant 9°$	4	—	—	1	—	5
$m\geqslant 2,\ n<5$	21	3	7	10	1	42
$m\geqslant 2,\ n\geqslant 5$	7	2	8	19	16	52
Neutron-produced stars	4	—	18			22

*δ) angle of emission of secondary particles with respect to the direction of the primary, $\langle\vartheta\rangle$) mean angle of multiple scattering.

**Discharges in two adjacent counters in two consecutive trays or three discharges in one tray, and stars m = 1, n > 2; m ≥ 2, n, = 2.

obtained refers to π^+ and π^- mesons since of the 135 particles selected by the momentum-minimum range method, the masses of 83 particles are clearly less than that of the K•meson, and K mesons cannot constitute more than 20% of the remaining 52 particles.[9,10]

The differential momentum spectrum of secondary particles produced in large stars ($m \geq 2$, $n \geq 5$) is shown in Fig. 2. The spectra may be represented by a function $N(p) \sim p^{-\gamma}$, where $\gamma = 1.48 \pm 0.14$ for negative particles in the momentum range ≥ 0.4 Bev/c, and $\gamma = 2.04 \pm 0.19$ for positive particles of ≥ 1 Bev/c.*

TABLE III

Passage through the absorbers**	μ-mesons: N	N, %	Secondaries in small stars: N	N, %	Secondaries in large stars: N	N, %
a	316	72	513	85	18	36
b	45	10.3			1	
c	31	7.1			3	
d_1	10	2.3			2	
$d_2\ (m=1,\ n=2)$	11	2.5			3	
$e\ (m=1,\ n>2)$	6	1.4	17	2.8	2	5.3
$f\ (m=2,\ n=2)$	13	3	12	2	2	
$g\ (m\geqslant 2,\ n>2)$	3	0.7	14	2.3	13	17.3
h	2	0.5	16	2.7	7	9.3
i	—	—	32	5.3	24	32
Total	437	100	604	100	75	100

*Data of the first series or measurements. N) number of particles.

**a) no interaction; b) two adjacent discharges in a tray; c) two non-adjacent discharges in a tray; d) two adjacent discharges in two non-consecutive trays; d_2, e, f, g) stars of various types; h) scattering at an angle greater than twice the mean multiple scattering angle; i) stopping.

TABLE IV

Upper mass limit		$M\leqslant 1300m_e$	$M\leqslant 900m_e$	$M\leqslant 500m_e$
Number of particles	N^+	73	44	12
	N^-	62	39	12

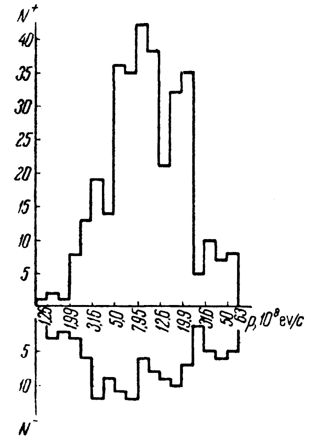

FIG. 2. Differential momentum spectrum of secondaries in large stars (m ≥ 2, n ≥ 5).

442 particles, among them 115 negative, were observed in the momentum range from 0.12 to 6.3 Bev/c. In the range ≥1 Bev/c the ratio of positive to negative particles is 156 : 51, i.e. $N_\pi/N_S = 0.5$ to 0.6 (N_π is the number of π mesons and N_S is the number of particles with momentum ≥ 1 Bev/c.).

The differential momentum spectrum of 407 secondary particles in the momentum range from 0.12 to 6.3 Bev/c produced in small stars ($m \geq 2$,

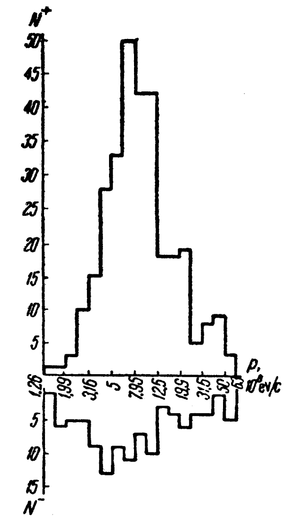

FIG. 3. Differential momentum spectrum of secondaries in small stars (m = 1, n > 2; m ≥ 2, n < 5).

*The exponent γ was determined by the method of least squares, taking into account the statistical weight of the experimental points. In determining the spectrum of positive particles, ionization losses in the target were neglected.

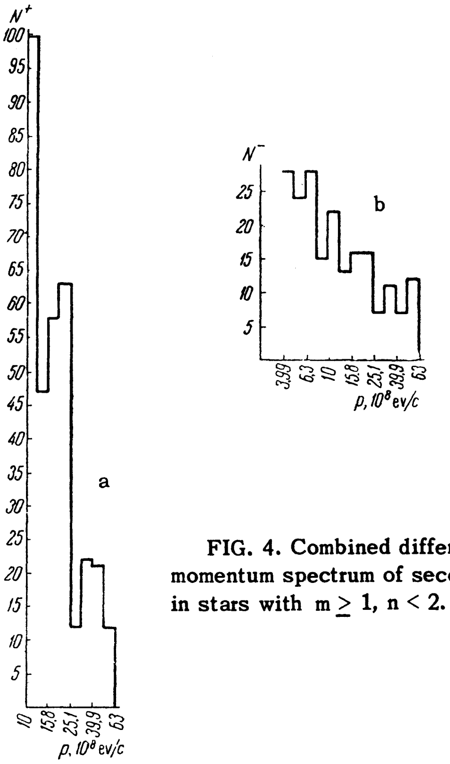

FIG. 4. Combined differential momentum spectrum of secondaries in stars with $m \geq 1$, $n < 2$.

$n < 5$; $m = 1$, $n > 2$) is shown in Fig. 3. The spectrum of negative particles in the momentum range from 0.4 to 6.3 Bev/c may be described by a function $N(p) \sim p^{-1.61 \pm 0.16}$, while the spectrum of positive particles with $p \geq 1$ Bec/c is of the form $N \sim p^{-2.2 \pm 0.2}$. The ratio of positive to negative particles in the range ≥ 1 Bev/c is 122:37, i.e., $N_\pi / N_s \sim 0.5$.

The combined differential momentum spectrum of secondary particles produced in all observed nuclear disintegrations with $n > 2$ (the spectrum of positive particles in the momentum range ≥ 1 Bev/c and of negative particles in the range ≥ 0.4 Bev/c) is shown in Fig. 4a and 4b. The spectra were corrected for secondaries in small stars, which did not interact in the absorbers and were excluded according to the selection rules for small stars. The correction was determined from a study of the passage of secondary particles of large stars ($m \geq 2$, $n \geq 5$) produced by charged particles, and of particles produced by the neutral component.

RATIO OF CHARGED TO NEUTRAL STAR-PRODUCING PARTICLES AND THEIR ENERGY

The energy of primary particles producing large stars ($m \geq 2$, $n \geq 5$) amounts to ~ 30 Bev.[5] This value was estimated from the angular distribution of penetrating particles.

The interactions of secondary particles of a known momentum in the lead absorbers of the array (series 3, Table I) were used for an estimate of the minimum energy of primary particles producing small stars, ($m \geq 2$, $n < 5$; $m = 1$, $n > 2$). Nineteen such stars were observed. It was found that the minimum momentum of the particles which produced them was ≥ 3 Bev/c.

For the determination of the ratio of neutral to charged star-producing particles of ~ 30 Bev, in the seventh and eleventh series of measurements we studied large stars ($m \geq 2$, $n \geq 5$) produced both by the charged and the neutral component. Out of 238 stars, 83 were produced by neutral particles (N_n^0).* Among the remaining 155 stars, there were stars of the type $N_n^1 + N_n^2$, which cannot be distinguished from proton-produced stars N_p because of fast secondaries (with range $R >$ 8 cm Pb). If we consider the stars produced by primary particles arriving within the angle of 35° then the number of stars N_p^1† with one secondary emitted at an angle $\leq 35°$ with respect to the primary amounts to $\sim 12\%$ of $N_p^0 + N_n^1$. If the direction of the primaries is arbitrary, then

$$N_p^1 \sim 0.3\,(N_p^0 + N_n^1).$$

If we consider therefore the stars having not more than one fast secondary ($N_p^0 + N_p^1$; $N_n^0 + N_n^1$), the ratio of star producing protons N_p to star-producing neutrons N_n of ~ 30 Bev in cosmic radiation at 3250 m altitude is equal to 1.2 ± 0.16.

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*N_n^k – number of neutron-produced stars with multiplicity k.

†We determined the number of stars with two fast particles ($R > 8$ cm Pb) in the upper hemisphere $N_p^1 + N_n^2$. It was assumed that all these stars were produced by charged particles, i.e. $N_p^1 \gg N_n^2$ and that $N_p^1/N_n^1 = N_p^0/N_n^0$.

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