INVESTIGATION OF THE NATURE AND SPECTRA OF PARTICLES PRODUCED BY HIGH-ENERGY NUCLEONS

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The nature and the momentum spectrum of secondary particles produced in lead by high-energy cosmic ray particles were investigated at an altitude of 3250 m above sea level, using a magnetic mass spectrometer and a multi-layer proportional counter.

In the present article we report the results of an investigation of the nature and the spectra of particles produced by fast nucleons of cosmic radiation at the altitude of 3200 m above sea level (Aragats, Armenia).

The cross section of the apparatus in two perpendicular views is shown in Fig. 1. The instrument consists of a mass spectrometer (with a magnetic field of 6850 Oe), an additional hodoscopic arrangement placed above the spectrometer,[1] and a five-layer, thin-wall proportional counter.[2] The construction of the instrument makes it possible to observe nuclear disintegrations produced by fast nucleons in the lead generating layers placed in the gaps A, B, C, D, F of the hodoscope arrangement, and also to determine the momenta, the specific ionization, and the character of passage of the secondary products of the stars through the lead and copper absorbers placed below the spectrometer. The mean standard deviation of the determination of momentum amounted to 3, 13, and 65% for 0.2 Bev/c, 1 Bev/c and 5 Bev/c, respectively. The specific ionization of separate particles was determined with the average accuracy of ±14%.

RESULTS OF MEASUREMENTS

Two main series of measurements were carried out: with generators 10 cm and 25 cm, and a check experiment "without generators."* The results of measurements are divided into groups: (A) particles clearly produced in the generators by neutral radiation, and (B) products of stars produced by charged particles, and single charged particles passing through the generators;† μ mesons were excluded by the momentum-range method.

*The total thickness of matter in different series of the control check "without generators" amounted to 0.3 – 2 cm lead.

†Group B also included products of stars produced by neutrons, containing fast particles moving backwards.

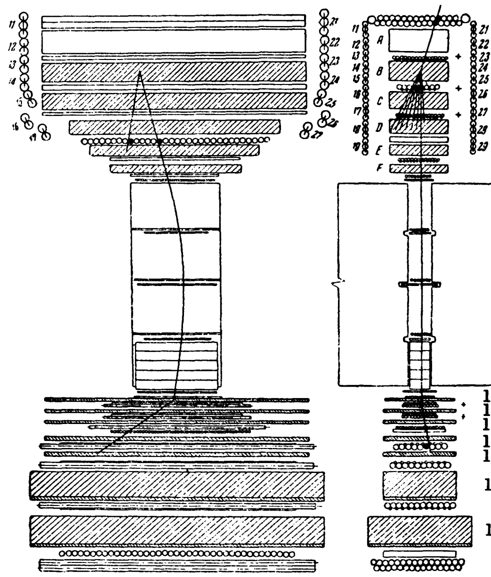

FIG. 1. Schematic diagram of the mass spectrometer in two perpendicular cross sections. A trajectory of a K^+ meson is shown in the diagram (Table I, case 133–122.).

The results of measurements of momenta and of specific ionization of secondary particles produced by neutral radiation in a lead generator 25 cm thick are given in Fig. 2a. The results of analogous measurements of the particles of the group B are given in Fig. 2b.

The accuracy of the measurements of the momentum and ionization of particles makes it possible to separate $\pi^{\pm}$ and $K^{\pm}$ mesons and heavy particles in the momentum range up to 700 Mev/c. In the range of larger momenta, the determination of the nature of separate particles is not always possible.

Protons and Deuterons. From the experimental material given in Fig. 2, one can obtain sufficiently complete data on secondary protons and, partially, on deuterons. We shall not discuss the data in detail, since that is not the aim of the present article.

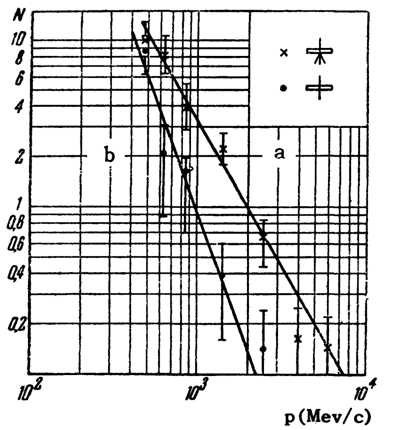

FIG. 3. Differential momentum spectrum of π^- mesons produced by neutrons: a – cascade particles, b – single particles.

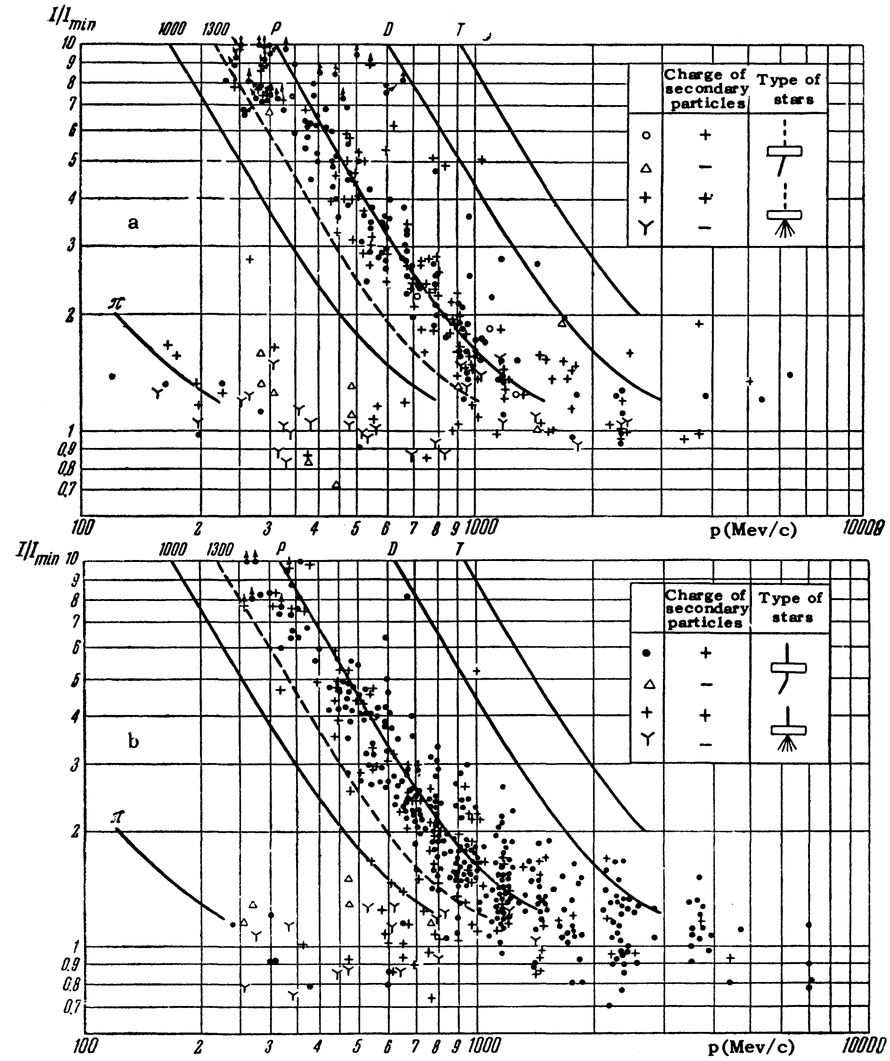

FIG. 2. Results of the measurements of the momentum and ionization of secondary particles observed under 25 cm Pb. a – particles produced by neutrons, b – particles produced by protons. Events in which the specific ionization of the particle was greater than the maximum measurement threshold are denoted by arrows (there is no difference in meaning between light and full circles).

We shall note only that, in two series of measurements in the momentum range 400 – 900 Mev/c, 35 deuterons were observed, 10 of which were produced by protons. According to this data, in the flux of cosmic rays at the altitude of 3250 m in the momentum range 400 — 900 Mev/c there are 3.5 times more neutrons than protons.*

The momentum spectrum of deuterons in the experiment "without generators" in the momentum range > 800 Mev/c (a total of 108 deuterons) can be represented by the expression $N(p) \sim p^{-\gamma}$, where $\gamma \approx 2$.

π mesons. The spectra of π^- mesons with momentum between 400 and 7000 Mev/c produced by neutrons are given in Fig. 3. Spectrum a corresponds to cases where the particle is clearly produced in a multi-prong star $(N > 2)$.† Spectrum b contains particles observed without an accompanying cascade $(N = 1)$. The spectra can be represented by a power function $N(p) \sim p^{-\gamma}$. For spectrum a, $\gamma = 1.7$; for the spectrum of single π^- mesons, $\gamma = 2.4$ (i.e., π^- mesons of large momentum are mainly observed in multi-prong stars. This fact has been mentioned in our ealier paper.[1]

Using the same apparatus, Khrimyan and Asatiani[4] obtained $\gamma = 1.5$ for the spectrum of π^- mesons in multi-prong stars produced by protons. Consequently, the spectrum of π^- mesons produced by fast neutrons is practically identical to the spectrum of π^- mesons produced by fast protons.

We have determined the ratio of the numbers of π^- and π^+ mesons produced by fast neutrons and protons in the momentum interval 125 — 720 Mev/c. Among the secondary particles produced by neutrons, the ratio $N_{\pi^-}/N_{\pi^+} = 89/49$,* i.e., we observed an excess of π^- mesons. In stars produced by protons, the ratio $N_{\pi^-}/N_{\pi^+} = 45/54$.

*The cross sections for the production of deuterons by protons and neutrons used in the estimates were taken from reference 3.

†N – number of observed components of the stars.

*Here we used also our data from reference 1.

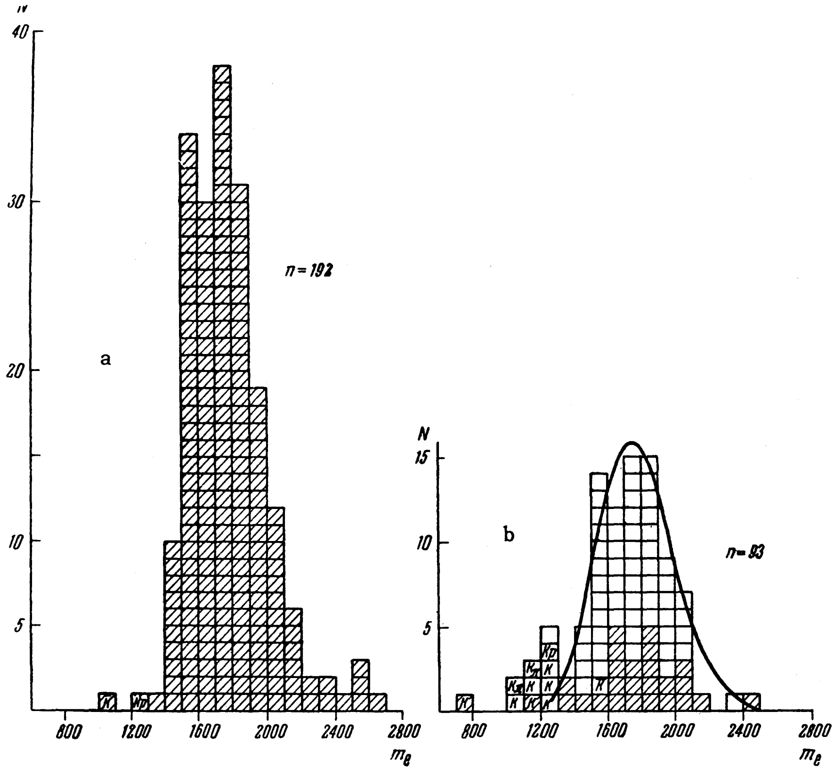

FIG. 4. Mass distribution with particles with momentum in the range 125–720 Mev/c and with ionization in the range 1.3–7 I_{min}, a – single particles produced by neutrons, b – products of multi-prong stars (dashed particles are produced by neutrons).

K mesons. The mass distribution of particles in the momentum range 125 — 720 Mev/c and with ionization 1.3 — 7 I_{min}* is given in Fig. 4. Single particles produced by neutrons are shown in the histogram a. The majority of these particles are protons. Secondary products of multi-prong stars produced by fast neutrons are represented in the histogram b. Particles produced by neutrons are shown crosshatched. This spectrum displays, apart from protons, a group of particles in the mass range 700 — 1300 m_e, the number of which amounts to about 10% of the number of protons. The appearance of these groups of particles cannot be explained by experimental errors since, firstly, a and b are obtained simultaneously using the same apparatus and, secondly, in the series of measurements "without generators" out of 1112 protons traversing the instrument, less than 1% of the particles (7 protons) were recorded by the instrument as particles with mass < 1300 m_e. The distribution of protons observed in the experiment "without generators" is represented by the solid curve in Fig. 4. The distribution is normalized to the total number of particles (n = 93).

In the momentum range $p \leq 720$ Mev/c and ionization range $I \geq 1.3\ I_{min}$, we determined for each particle the probability of that particle being a proton (W_p), K meson (W_K), or π meson (W_π) from the obtained values of momentum, ionization, and range, taking into account the frequency of observation of $\pi^\pm$ and $K^\pm$ mesons and protons. Particles for which $W_K > 5(W_\pi + W_p)$, were assumed to be K mesons. These particles are indicated by a subscript (K, p) or (k, π) in the spectra. Particles for which $K > 10(W_\pi + W_p)$ are denoted by the letter K (negative — by the letter $\overline{K}$).

Detailed data on all $K^\pm$ particles are given in Table I. $K^\pm$ particles observed in weak nuclear disintegrations or without an accompanying cascade which were not given in Fig. 4 are also included in the table.

According to data given in Table I, only 3 $K^\pm$ particles out of 19 observed were negative. The ratio $N_{K^+}/N_{K^-} = 16/3$.

Four K^+ and one K^- particles were produced by neutrons. The remaining (twelve K^+ and two K^-) particles were most probably produced by protons with the ratio $N_{K^\pm}(p)/N_{K^\pm} = 14/5$.

We note that the observed number of large stars produced by neutrons is also smaller (the ratio is 54/108) than the number of stars produced by charged particles. Such an asymmetry can be partly due to the fact that, when working with hodoscopes (and also with cloud chambers), it is impossible to distinguish stars produced by protons from stars produced by neutrons and having fast products moving backwards. The number of such neutron stars in our case, according to the estimate by Khrimyan,[5] amounts to about 30% of all observed neutron stars.

*For $I > 7\ I_{min}$ the electronic equipment was overloaded.

TABLE I

No of event	Sign of charge	p, Mev/c	I/I_{min}	Mass, m_e	Nature of the primary particle and the type of interaction
123—260	+	280	$2.8\ ^{+0.5}_{-0.4}$	735^{+60}_{-105}	Neutral*
81—88	+	315	$4.0\ ^{+1.0}_{-0.4}$	1060^{+140}_{-245}	Charged*
133—122	+	325	$4.65^{+0.8}_{-0.8}$	1210^{+130}_{-130}	Charged*
20—178	+	330	$5.0\ ^{+1.4}_{-0.35}$	1280^{+200}_{-60}	Charged*
21—41	+	450	$2.35^{+0.55}_{-0.25}$	1100^{+150}_{-90}	Charged*
83—34	+	455	$2.95^{+0.55}_{-0.40}$	1290^{+140}_{-110}	Neutral*
199—108	—	480	$1.45^{+0.25}_{-0.20}$	775^{+130}_{-115}	Charged
16—336	—	480	$3.45^{+0.95}_{-0.50}$	1500^{+230}_{-150}	Charged*
37—67	+	495	$26\ ^{+0.5}_{-0.4}$	1290^{+125}_{-125}	Charged*
192—29	+	555	$1.65^{+0.25}_{-0.25}$	1025^{+135}_{-135}	Charged*
179—18(?)	+	620	$1.5\ ^{+0.2}_{-0.2}$	1000^{+160}_{-160}	Charged*
14д—3(?)	+	666	$1.75^{+0.50}_{-0.15}$	1295^{+275}_{-115}	Charged*
72—91	—	680	$1.45^{+0.30}_{-0.15}$	1050^{+240}_{-145}	Neutral
12—272(?)	+	686	$1.65^{+0.25}_{-0.15}$	1230^{+180}_{-120}	Neutral
93—123	+	705	$1.47^{+0.3}_{-0.2}$	1140^{+250}_{-220}	Neutral*
119—34(?)	+	720	$1.5\ ^{+0.2}_{-0.2}$	1200^{+160}_{-240}	Charged*
139—172	+	720	$1.65^{+0.25}_{-0.25}$	1295^{+170}_{-230}	Charged
16a—5(?)	+	720	$1.6\ ^{+0.35}_{-0.20}$	1250^{+260}_{-180}	Charged
35—84(?)	+	720	$1.55^{+0.30}_{-0.15}$	1210^{+240}_{-130}	Charged

(?) Type (K, π?) (K, p?)
*Star

Accounting for this, the ratio of the number of stars produced by protons to the number of stars produced by neutrons equals $N_p/N_n = 1.5$.

π and K mesons in the momentum range 720 to 900 Mev/c. In the momentum range 720 — 900 Mev/c, the separation of K mesons and π mesons is difficult, while the separation of both kinds of particles from protons is still possible, since in that momentum range the ionization of protons, K mesons and π mesons is in the intervals 1.9 — 2.4 I_{min}, 1.2 — 1.4 I_{min}, and 1.03 I_{min}.

In this momentum range we separated a group of 38 particles consisting of a mixture of K and π mesons, out of which 10 were produced by neutrons and were mainly π mesons, while 28 were produced by charged primaries. Out of these 28 particles, 15 stopped in the absorber, which corresponds to a range > 16 cm Pb. Out of these 15 particles, 13 were positive, and these must be considered as different from protons also from range considerations, since protons with momentum 900 Mev/c have a range < 12 cm of Pb. A qualitative division of this group of 28 particles into K and π mesons is possible from the following considerations: Firstly, constructing the spectrum of π mesons produced by protons which, in general, is in good agreement with the law $N \sim p^{-1.6}$ in the range of 720 — 900 Mev/c, one observes an anomalously large number of particles. Such an anomaly in the spectrum of π mesons at sea level was observed by us previously.[2,6] If we assume that this is due to the presence of K mesons, then the group of 28 particles should be divided into (14 ± 5) K mesons and (14 ± 5) π mesons. Secondly, in this group of particles, a large positive excess is observed (22 positive and 6 negative particles), while in the spectrum of π mesons of lower momentum the positive excess is due to K^+ mesons, then this corresponds to a division of the group into (14 ± 5) K mesons and (14 ± 5) π mesons. Thirdly, the specific ionization of positive particles of this group is equal to (1.19 ± 0.03) I_{min}. The specific ionization of negative particles is equal to (1.03 ± 0.07) I_{min}. Hence, assuming a mean specific ionization of K mesons in the momentum range 720 — 900 Mev/c as equal to 1.32 I_{min}, and for π me-

TABLE II

Δp, Mev/c	π±		K±		p	
	N	%	N	%	N	%
240—480	60	56	8	8	38	36
480—720	58	50	11	10	46	40
720—900	24	~30	14	~15	45	~55

sons as equal to 1.03 I_{min}, we obtain (15 ± 4) K mesons and (13 ± 4) π mesons.

Therefore, in the momentum range 720 — 900 Mev/c, out of 38 π^- and K particles, 14 are most probably K mesons.

The numbers of observed $\pi^\pm$ and $K^\pm$ mesons and cascade protons in identical momentum ranges are given in Table II. According to these data, in the range of large momenta, the observed number of K mesons increases with increasing momentum. The ratio of the number of observed K mesons to the number of π mesons in the momentum range < 900 Mev/c amounts to about 0.2.

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