no anomalous behavior above the Curie point, similar to that observed in the other antiferromagnetic materials, was found in this case. The line width for CuF_2 was constant in the temperature region investigated and equal to 400 oersted. The strength of the resonance absorption at the maximum was reduced by a factor of one and one-half as the temperature was increased. Eq. (2) is in good agreement with the results found in CuF_2 over the entire temperature region from 90° to 294°K. Thus the behavior of CuF_2 above the Curie point is that of a typical paramagetic material.

In conclusion we may note that the effective g-values for all materials investigated were close to 2 and temperature independent within the limits of the experimental accuracy. The experimental resonance absorption curves are a better fit to a Lorentzian line-shape than a Gaussian shape.[11]

This work was carried out under the guidance of B. M. Kozyrev.

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CLOUD CHAMBER INVESTIGATION OF THE NUCLEAR-ACTIVE COMPONENT OF AIR SHOWERS

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Nuclear processes induced by particles of extensive air showers were studied by means of a cloud chamber containing seven lead plates. The lateral distribution of nuclear-active particles in extensive showers as well as the nature and the energy spectrum of the particles were found.

THE nuclear-active component of extensive air showers was studied by means of the previously described experimental arrangement[1] consisting of a cloud chamber[2] and a counter telescope. Seven lead plates, 0.5, 1.5, 2, 2, 2.5, 2, and 2.5 cm in thickness (top to bottom respectively) were placed in the cloud chamber $60 \times 60 \times 30$ cm. The effective chamber area for detection of nuclear-active particles, accounting for their angular distribution, was equal to 0.15 m^2. A shower-detecting counter system was used to trigger the hodoscope and the cloud chamber. The hodoscope made it possible to determine the distance of the shower axis from the cloud chamber and the total number of particles in the shower.

A particle was considered nuclear-active if it produced a shower in a lead plate, satisfying at least one of the following requirements:

(1) At least two penetrating particles could be found among the secondaries when the primary was charged, and at least one when the primary particle was neutral. A particle was considered as penetrating if it traversed at least one lead plate without multiplication.

(2) At least one heavily ionizing particle was present among the secondaries.

2175 extensive air showers were recorded during 1189 hours of operation. In these, 30 nuclear-active particles were detected. The number of chance coincidences between a single nuclear-active particle and an extensive shower was calculated and found to be less than 1 during the whole period of operation.

1. LATERAL DISTRIBUTION OF NUCLEAR-ACTIVE PARTICLES

We found first the flux density $\rho_n(r)$ of nuclear-active particles in extensive air showers at various distances from the axis using the well-known formula

$$\rho_n(r) = \frac{N_n(r)}{C(r)\,\sigma\,[1 - \exp(-x/\lambda)]},$$

where $C(r)$ is the total number of extensive air showers with axes falling at the distance r from the cloud chamber, $N_n(r)$ is the number of nuclear-active particles at the distance r, σ is the effective area of the chamber, λ is the interaction mean free path of nuclear-active particles (in lead $\lambda = 160\ g/cm^2$), and x is the total thickness of lead plates in the chamber ($x = 140\ g/cm^2$).

The results for extensive air showers with the mean number of particles $\bar{N} = 2 \times 10^5$ are shown in Fig. 1. The large statistical errors make it impossible to conclude about the exact shape of the lateral distribution function of nuclear-active particles. The results, however, do not contradict a function of the type r^{-n} with n close to 1, which is in agreement with the results of Ref. 3, in which a hodoscope covered with lead was used for the detection of nuclear-active particles.

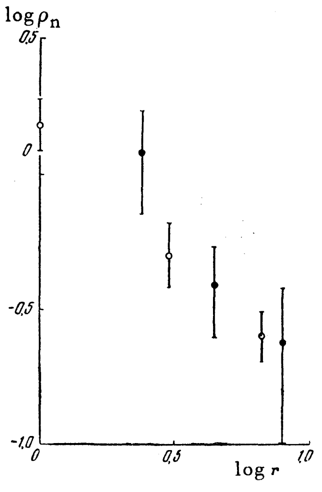

FIG. 1. Lateral distribution of nuclear-active particles.

It should be noted that our data obtained by means of a cloud chamber are in agreement, with respect to the absolute value of the flux of nuclear-active particles, with the results obtained at sea level by means of a hodoscope array.[3] The light circles in Fig. 1 denote the experimental points referring to showers with $\bar{N} = 3 \times 10^5$, given in Ref. 3. Since the identification of nuclear-active particles by means of a cloud chamber is more positive, the agreement in the values for the absolute density of the particle flux proves the correctness of the criterion for the selection of nuclear-active particles assumed in the counter work.

2. ANALYSIS OF NUCLEAR INTERACTIONS OBSERVED IN THE CLOUD CHAMBER

A careful study of the electron-nuclear showers generated by nuclear-active particles showed the existence of two separate groups:

The first group comprised electron-nuclear showers containing dense electronic cascades. Thirteen such showers were detected. In ten of these, penetrating or heavily ionizing particles were present in addition to electrons. An example of such a shower is shown in Fig. 2. In the remaining three events no particles other than electrons could be observed due to high particle density. These three cases were produced by neutral primaries with path length in lead longer than 2 cm. The primaries could not have been identified as photons since the probability that a photon traverses without multiplication more than 4 radiation units is equal to 0.05. Moreover, only 8 photons of a similar energy were detected at all. In the first group of showers penetrating particles, if visible, were going at relatively small angles to the direction of the electronic cascade.

The second group consisted of electron-nuclear showers in which high-energy electron cascades were absent. A rather large number (about 10) of penetrating particles going at widely distributed angles, heavily ionizing particles, and low-energy electrons absorbed in next lead plate, were present in these showers. Eight such cases were recorded. An example of a shower of that type is shown in Fig. 3.

A narrow angular distribution of particles and large energy of π^0 mesons generating the electron-photon cascades are, therefore, the characteristic features of the first group of showers. The showers of the second group are, on the other hand, characterized by a wide lateral distribution of particles and a relatively low energy of π^0 mesons.

It follows from the well-known formula of relativistic angle transformation that as the velocity of the center of mass of colliding particles increases, the spread of produced particles in the laboratory system becomes narrower. It can be assumed therefore that the showers of the second group were induced by collisions with a small velocity of the center-of-mass system. Since, however, these showers consist of large numbers of particles, the primary energy should be large.

On the strength of the above, we assumed that the showers of the first type originated when the primary particle collided with a small number of nucleons in the nucleus, in the main with one only, and the showers of the second group were produced in collisions between the primary and several nucleons of the lead nucleus. In that case, the velocity of the center of mass may be small even for a relatively large energy of the primary because of the large mass of all nucleons involved in the collision.

Two smaller groups of electron-nuclear cascades were observed besides the two main types. The third group consisted of four cases only. The showers were of low energy and the secondaries consisted of a few heavily ionizing particles, a few electrons, and 1 — 2 penetrating particles. The latter might have been also absent. An example of a shower belonging to this group is shown in Fig. 4. Finally, the fourth group of showers, consisting of five events, contained showers originating in the last, 7th, plate. In that case it was impossible to differentiate between penetrating particles and electrons and it was therefore impossible to find any characteristic features which would enable the classification of the event within one of the three groups. Additional criteria (neutral primary, presence of heavily ionizing secondaries) made it possible to ascertain that the showers belonged to the electron-nuclear type. An example of such a shower is shown in Fig. 5. Data on all recorded showers are given in Table I.

3. DETERMINATION OF THE ENERGY OF NUCLEAR-ACTIVE PARTICLES

The energy of nuclear-active particles was determined for the different groups of showers by a method most suitable for the type of event.

We used the method of Ref. 4 for determination of the energy of nuclear-active particles generating the showers of the second group. This method is based on the application of the statistical theory of Fermi[5] to collisions of the primary with several nucleons of the target nucleus and consists in finding the energy of the primary particle and the number of nucleons involved in the collision from the number of penetrating secondaries and the velocity of the center of mass of colliding particles. The first is observed directly, and the second can be found from the angular distribution of secondary particles if we assume that (1) the distribution is isotropic in the center-of-mass system and (2) the velocities of particles in that system are close to c.

Under these assumptions one can obtain easily the relation between the velocity of the center of mass, or the value $\gamma_c = (1 - v^2/c^2)^{-1/2}$ and the

TABLE I. Data on nuclear interactions*

Charged primary				Neutral primary				Charge of primary undetermined			
Case no.	r, m	N	E_k (ev)	Case no.	r, m	N	E_k (ev)	Case no.	r, m	N	E_k (ev)
22.22	0.5	$4\cdot10^4$	$7\cdot10^9$	3.30	3	$1,3\cdot10^4$	$1.5\cdot10^{10}$	18,29	7	$6\cdot10^4$	$1.5\cdot10^{10}$
28.32	2,6	$5,3\cdot10^5$	$3.7\cdot10^{10}$	28,4**	8	$1,5\cdot10^6$	$2,5\cdot10^{10}$	40.16	9	$1,5\cdot10^5$	$6\cdot10^9$
73,39	3,2	$4\cdot10^4$	$2,3\cdot10^{10}$	36,12	3,5	$8\cdot10^4$	$3\cdot10^{10}$	15,49**	0,5	$7,4\cdot10^3$	$2\cdot10^{10}$
57,10	1,4	$1,1\cdot10^4$	10^9	45,10	0.5	$7,4\cdot10^4$	$3\cdot10^{10}$	22,72**	0,5	$2.5\cdot10^5$	$1,5\cdot10^{10}$
60,14	2,7	$3,1\cdot10^4$	$2\cdot10^9$	46,1	3.1	$2\cdot10^5$	$6\cdot10^9$	44.14	4	$1,1\cdot10^5$	$1.2\cdot10^{10}$
78,20	2,8	$1,5\cdot10^5$	$3\cdot10^{10}$	63,7		—	$4\ 3\cdot10^9$	55,1	6,7	$3\cdot10^6$	—
76,51	2,5	$2,4\cdot10^5$	$1,5\cdot10^{10}$	75,4	4,6	$1,9\cdot10^5$	10^9	70,37	5	$2.3\cdot10^5$	$1,5\cdot10^{10}$
82,21**	2,5	$6,7\cdot10^5$	$3\cdot10^{10}$	80,17	5.5	$8,4\cdot10^5$	$2\cdot10^{10}$	85,19	0,6	$1.5\cdot10^5$	$1,5\cdot10^{10}$
				80,33	3,8	$2,3\cdot10^5$	$1.5\cdot10^{10}$	72,13	4,7	$1,4\cdot10^5$	$1,5\cdot10^{10}$
				86,40	3,2	$1,5\cdot10^4$	$2.5\cdot10^9$	63.48**	0,5	$4.6\cdot10^4$	$<10^{10}$
				87,2	8,3	$5,5\cdot10^5$	$3,3\cdot10^{10}$	87.28	9,5	$2\cdot10^5$	$2,3\cdot10^{10}$

*r – distance between shower axis and the cloud chamber (in meters), N – number of particles in the extensive air shower, E_k – kinetic energy of the particle generating the shower in the cloud chamber.

**Event originating in the last plate.

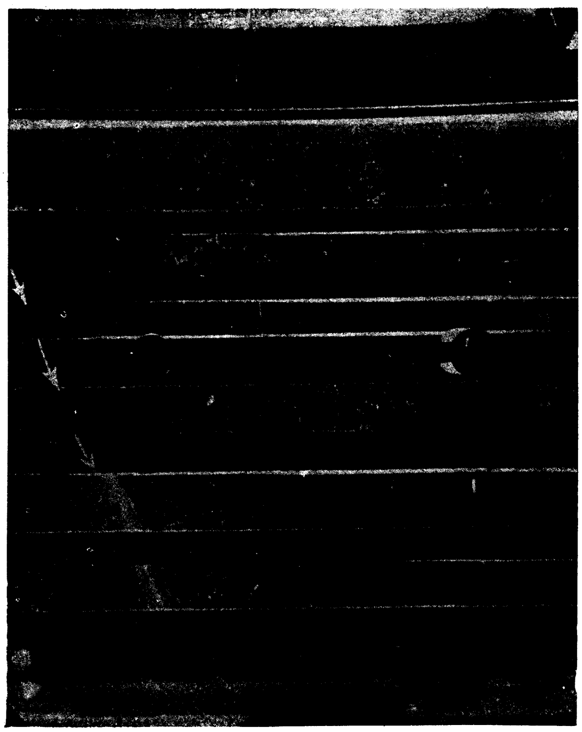

FIG. 2. Electron-nuclear shower generated by a charged particle in the fifth plate of the cloud chamber (case 78, 20). Track of the primary particle indicated by arrows.

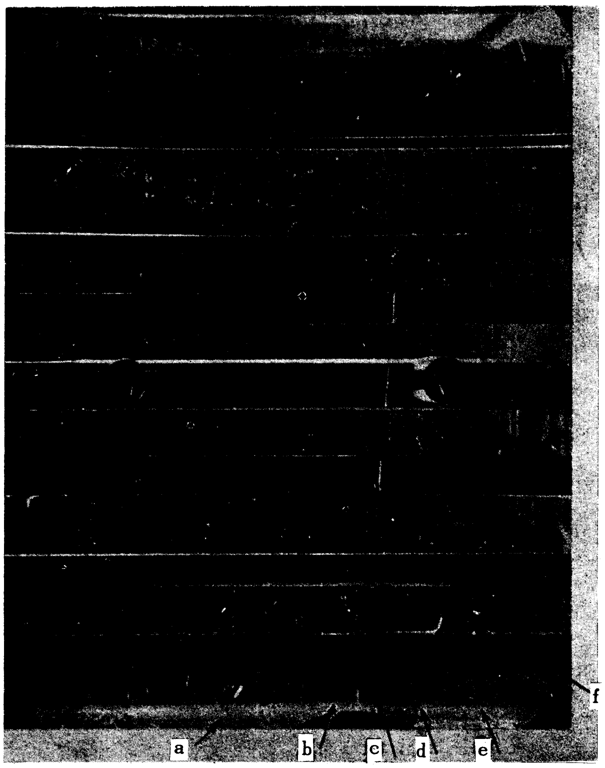

FIG. 3. Electron-nuclear shower consisting of a large number of penetrating particles (a, b, c, d, e, f) (case 22,22). Track of the primary particle indicated by arrows.

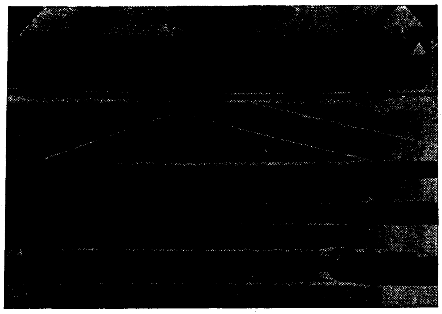

FIG. 4. Electron-nuclear shower produced in the gas by a low-energy particle (case 60, 14).

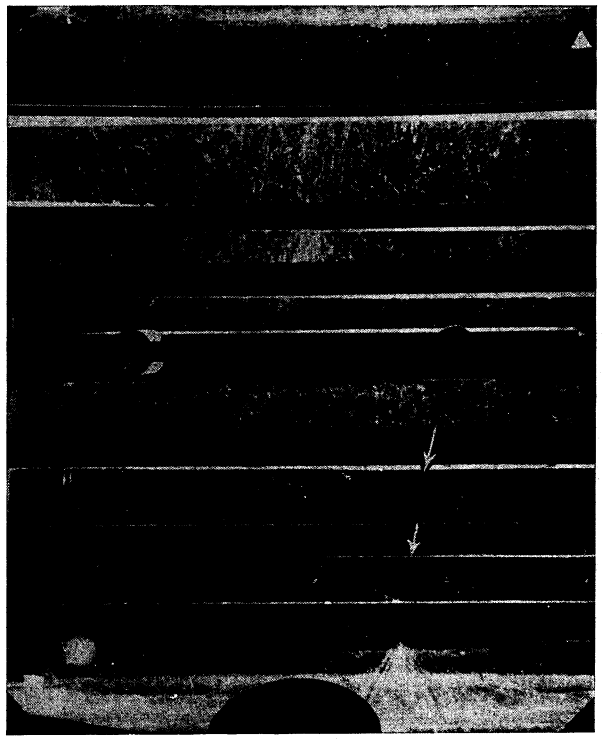

FIG. 5. Electron-nuclear shower generated by the primary particle in the seventh plate of the chamber (case 82,21). Track of the primary particle indicated by arrows.

angle $\theta_{1/2}$ which contains half of the particles in the laboratory system:

$$\sqrt{\gamma_c^2 - 1} = 1/\tan\theta_{1/2} \qquad (1)$$

We used Eq. (1) to calculate γ_c for all showers of the second group and, using the graph in Fig. 1 of Ref. 4, determined the values of kinetic energy E_k of primary particles initiating the showers as well as the possible number n of nucleons involved in the collision. The results are given in Table II. The error in the energy value, due to the error in γ_c, amounts to 30 – 50%.

The values of γ_c calculated according to Eq. (1) might possibly be overvalued because of the

TABLE II. Showers of the second group*

Case no.	N_p	N_{hi}	N_e	$\theta^{\circ}_{1/2}$	γ_c	n	m	E_k (ev)	$\bar{\varepsilon}_\pi$, (ev)
22,22	7	0	3—4	48	1,35	5	6	$7\cdot10^{9}$	$4{,}9\cdot10^{8}$
28,32	12	6	2—4	23	2,6	5	13	$3{,}7\cdot10^{10}$	$1{,}9\cdot10^{9}$
44,14	9	2	3	42	1,5	6	9	$1{,}2\cdot10^{10}$	$6{,}2\cdot10^{8}$
63,7	5	2	0	55	1,2	5	4	$4{,}3\cdot10^{9}$	$3{,}3\cdot10^{8}$
73,39	14	8	1	40	1,55	9	15	$2{,}3\cdot10^{10}$	$7{,}6\cdot10^{8}$
80,17	7	1	6—8	23	2,6	3	8	$2{,}0\cdot10^{10}$	$1{,}4\cdot10^{9}$
87,2	11	1	2	27	2,2	5	12	$3{,}3\cdot10^{10}$	$1.3\cdot10^{9}$
87,28	9	10	6	30	2 0	4	10	$2.3\cdot10^{10}$	$1{,}2\cdot10^{9}$

*N_p – number of penetrating particles in the shower, N_{hi} – number of heavily ionizing particles in the shower, N_e – number of electrons, n – number of nucleons involved in the collision, m – number of produced π mesons.

assumption that the velocity of all particles in the center-of-mass sytem is close to c. We therefore found γ_c for the showers of the second group in yet another way. The energy of the particles, all assumed to be π mesons, was determined from their range in the lead plates of the cloud chamber. In case of particles not stopping in the chamber, the minimum value of energy was found. A value γ_c for which the distribution in the center-of-mass system became isotropic was then found by means of curves giving, for various γ_c, the relation between the angle in the laboratory system and the angle in the center-of-mass system for particles with various momentum. Such a value represented the lower limit of γ_c since, for the case of many particles a minimum energy was assumed instead of the real value. The values for γ_c obtained using the above method were, within limits of accuracy, identical with those obtained from Eq. (1).

The absence of high-energy electron cascades in showers of the second group was explained calculating the mean energy of π mesons under the assumption that the kinetic energy is divided evenly between the particles at the moment of disintegration. The values of the mean energy of π mesons are given in the last column of Table II.

It can be seen from the table that the mean energy of π mesons is relatively small in the cases 22,22; 44,14; and 63,7. It should be remembered also that the energy of photons originating in π^0 decay is, in the mean, smaller by a factor of 2. All this could explain the absence of dense electronic cascades when a few electrons only are present directly under the plate in which the interaction occurred. The approximate number of such electrons is given in column 4 of the table. In the cases 80,17 and 87,28 the mean energy of the π mesons is quite large. The interactions, however, occurred near the border of the illuminated region of the chamber and the continuation of the electronic cascades could have well developed beyond the visible region; 6 — 8 electrons are observed below the plate in which the interaction took place. Finally, in the cases 28,32; 73,39; and 87,2 the absence of large electronic cascades can be explained either by fluctuations in the ratio of charged and neutral π mesons or by fluctuations in energy distribution, favoring the charged mesons. It can be seen from the table that in those cases the largest number of charged penetrating particles N_p is observed. If the primary energy is recalculated assuming that only one neutral π meson was produced, the energy of the nuclear-active particle decreases only by 20 — 30%.

It was impossible to determine the energy of the showers of the first group in the same way since a part of penetrating particles might have been hidden in dense electronic cascades. Consequently, it was impossible to determine the velocity of the center-of-mass system. The energy of the primary particles generating the showers of the first group was, therefore, found from the energy of the electronic cascades. As it was mentioned above, the relatively small number of penetrating particles in these showers and their narrow angular distribution made it possible to assume that the showers originated in nucleon-nucleon collisions. If we assume that the relation between the mean energies of the nucleons and π mesons obtained for the showers of the second group remains valid for the first group, i.e., that in the mean a nucleon carries away an amount of energy three times larger than a π meson, then the energy carried away by all π^0 mesons can be written as follows:

$$E_{\pi^0} = \frac{m}{3}\frac{E_L}{3n+m} = \frac{m}{3}\frac{\gamma_c E_0}{3n+m},$$

where E_0 is the total energy in the center-of-mass system, E_L is the total energy in the laboratory system ($E_L = E_k + nM_0$, where M_0 is the nucleonic mass), m is the number of π mesons, n is the number of nucleons (in the above case

TABLE III. Showers of the first group

Case no.	E_{π^0}, (ev)	N_p	N_{hi}	θ^*_{max},	n = 2			n = 3		
					E_K, (ev)	m	γ_c	E_K, (ev)	m	γ_c
3,30	$2,5\cdot10^9$				$1.5\cdot10^{10}$	5	3,0			
18,29	$3\cdot10^9$	2—3	2	62	$1.5\cdot10^{10}$	5	3,0	$1,6\cdot10^{10}$	7	2,2
36,12	$5\cdot10^9$		—	—	$3\cdot10^{10}$	7	4,0			
40,16	10^9	1	—	25	$6\cdot10^9$	3	2,0			
45,10	$5\cdot10^9$				$3\cdot10^{10}$	7	4,0			
56,1	10^9		2		$6\cdot10^9$	3	2,0			
70,37	$2,5\cdot10^9$	$\geqslant5$	1—2	47	$1,5\cdot10^{10}$	5	3,0	$1,6\cdot10^{10}$	7	2,2
72,13	$3,10^9$	$\geqslant3$	1	48	$1,5\cdot10^{10}$	5	3,0	$1,6\cdot10^{10}$	7	2,2
76,51	$3\cdot10^9$	>1	1	30	$1,5\cdot10^{10}$	5	3,0			
78,20	$5\cdot10^9$	$\geqslant4$	1	40	$3\cdot10^{10}$	7	4,0	$2,8\cdot10^{10}$	9	2,8
80,33	$3\cdot10^3$	$\geqslant2$			$1,5\cdot10^{10}$	5	3,0			
85,19	$3\cdot10^9$			38	$1,5\cdot10^{10}$	5	3,0			

*θ_{max} – maximum angle of emission of a penetrating particle with respect to the direction of the primary in the laboratory system.

n = 2).

Using the above formula and the curve for nucleon-nucleon collisions from Fig. 1 of Ref. 4, it is possible to find the energy of the shower generating primary from the energy of the electronic cascade. The energy of electronic cascades was determined from cascade curves[6] using the method described in Ref. 7. Energies of primary particles generating the showers of the first group are given, together with other data on the showers, in Table III.

It should be noted that among the showers of the first group some may be due to collisions with two or more nucleons of the target nucleus. Such may be, e.g., the cases 18,29; 70,37; 72,13; and 78,20 in which a relatively large number of penetrating particles is observed. It should be noted that only penetrating particles emitted at large angles to the direction of the primary are given in Table III, since particles going in the core are hidden by dense electron cascades. The energy of the primary particle can be found by a similar method assuming that three nucleons were involved in the collision. The values of γ_c and E'_k obtained in that way for the four events are given in Table III. It can be seen that the assumption that the collision involved two nucleons of the nucleus, instead of one only, hardly changes the value for the primary energy. Only the number of π mesons produced and the value of γ_c are affected.

Corresponding to the narrow angular distribution of particles in showers of the first group the values of γ_c are larger than is the case for showers of the second group.

Showers of the third group were generated, clearly, by particles with energy close to the electron-nuclear shower production threshold. The energy of the primaries was therefore determined approximately from the number of charged particles in the shower using the curves of Camerini et al.[8] which give the dependence of the number of relativistic, grey, and black tracks on the energy of the primary particle. The results are given in Table IV.

TABLE IV.

Showers of the third group

Case no.	N_p	N_{hi}	E_k
57,10	—	2	$\sim10^9$
60,14	1	3	$\sim2\cdot10^9$
75,4	1	4	$\sim10^9$
86,40	2	—	$2,5\cdot10^9$

Determination of the energy of primaries was especially difficult for showers of the fourth group since it was impossible to discern between penetrating particles and electrons. The energy was estimated as follows: it was assumed that all relativistic particles were electrons and that the interaction occurred in the middle of the plate. The energy carried away by π^0 mesons was found from cascade curves. The primary particle energy was then determined by a method similar to that used for the showers of the first group. Such an estimate is very crude since, firstly, penetrating particles may be present among relativistic particles and, secondly, the energy of electron cascade is not given very accurately by the number of electrons at a single — and at that uncertain — depth. The results, nevertheless, agree in the order of magnitude with the values obtained for the other shower groups and there are therefore reasons to believe that they do not differ more from the true values than by a factor of 2 or 3.

The energies of nuclear-active particles generating showers in the lead plates of the cloud chamber are given in Table I.

The integral energy spectrum of nuclear-active particles is given in Fig. 6. The spectrum refers to extensive air showers with number of particles in the range $10^4 - 10^6$ ($\overline{N} = 1.4 \times 10^5$) and distances < 10 m from shower axis ($\overline{r} = 3.7$ m).

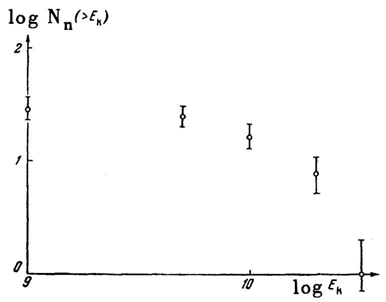

FIG. 6. Integral spectrum of nuclear-active particles in extensive air showers. $N_n(> E_k)$ is the number of nuclear-active particles with energy > E_k.

4. NATURE OF NUCLEAR-ACTIVE PARTICLES

In 19 cases out of the 30 recorded nuclear interactions it was possible to determine if the generating particles were charged or neutral. In 11 cases no conclusions could be drawn concerning the nature of primary because of unfavorable position of the shower in the cloud chamber (close to the glass or to the walls, in a dense electron cluster). The charge of the primary, for the cases when it could be ascertained, is given in Table I.

It can be seen that about half of the nuclear-active particles are charged and half neutral. This leads naturally to the assumption that at sea level the nuclear-active component of extensive air showers with energies of $10^9 - 10^{11}$ ev consists mainly of nucleons.

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