[11] Bernardini, Booth and Lederman, Phys. Rev. 83, 1075 (1951). G. Bernardini and I. Levy, Phys. Rev. 84, 610 (1951).

[12] Grigoriev, Osipenkov, Petrov and Rusakov, J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 1097 (1956); Soviet Phys. JETP 4, 922 (1957).

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Interaction of 5–50 bev Cosmic Ray Particles with Be Nuclei. I

N. G. Birger, N. L. Grigorov, V. V. Guseva, G. B. Zhdanov,
S. A. Slavatinskii and G. M. Stashkov
P. N. Lebedev Physical Institute, Academy of Sciences, USSR

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Meson production by cosmic ray particles with energy 5–50 bev was investigated in a cloud chamber containing a 9.8 gm/cm^2 Be plate under conditions closely approximating nucleon-nucleon interaction. Eleven interactions involving formation of four or more secondary charged particles are analyzed in detail. The angular distribution of pions and nucleons in the center-of-mass system of the two colliding nucleons was obtained, as well as the energy distribution of the energy of the primary particle among the various secondary particles.

THE character of nucleon–nucleon interactions can be conveniently studied today up to energies ~ 5 bev[1] by means of artificially accelerated particles. For the study of the interaction at higher energies, we must make use of cosmic ray particles. Here, however, the situation is complicated by the low intensity of cosmic radiation and by indefiniteness in the energy determination. The low intensity does not permit us to obtain direct evidence on nucleon–nucleon interaction by irradiating hydrogen with cosmic ray particles. The analysis of large experimental material, obtained in the irradiation of nuclei of heavy atoms (photoplates) by cosmic rays, can give only indirect evidence on the nucleon–nucleon interactions of high energy.

1. APPARATUS

The purpose of our research was the investigation of meson generation by cosmic ray particles with energies in excess of 5 bev under conditions that are close to nucleon–nucleon collisions. We used a Wilson cloud chamber, which contained a plate of Be of thickness 9.8 gm/cm^2 (for 100 hours of the research, a graphite plate was used inside the chamber in place of the beryllium). The Wilson chamber, of diameter 30 cm and depth of irradiated region 8 cm, was placed in the magnetic field of an electromagnet of average magnetic field 8500 Oe. Control of the chamber was maintained by a system of counters located as shown in Fig. 1. Coincidence discharges were recorded in the counters of groups 1,2,3 (combined in parallel) and in any two counters of the groups 4 and 5 in the absence of discharges in the counters of group *A*. A lead filter was placed over the entire apparatus, to diminish the background of the electron component. The work was carried out at an altitude of 3860 m above sea level (Pamir Scientific Station). The total research time with the apparatus, after deduction of the dead time of the chamber (2 min) was equal to 950 hours. In this time about 5300 photographs were obtained.

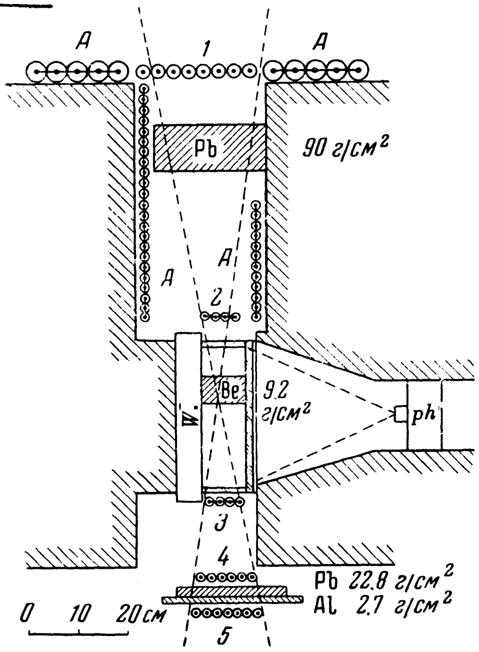

FIG. 1. Experimental scheme: *ph*–photographic apparatus; *W*–Wilson chamber.

In 31 photographs there were electron–nuclear showers of four and more particles, formed in Be or C inside the chamber. Showers with a smaller number of particles (2,3 secondary particles) were observed in about 10 cases. The discrimination of showers of a small number of particles was determined by a system of control counters. Comparison of the number of observed showers, formed in Be, with the number of expected showers which ought to be produced by nucleons with energies $\geq$ 5 bev (minimum value of the energy of nucleons which form the observed shower, see Table III, below), shows that the events which are separated by the apparatus amount to about 10% of all cases of interaction with atomic nuclei of nucleons having energies $\geq$ 5 bev. This points to the fact that showers of a small number of particles are formed in a large number of interactions at these energies.

Below we shall consider the characteristics of such interactions which lead to the emission of not less than four secondary particles. Here we selected only those showers for which it proved possible to measure the momenta of the majority of secondary particles. In such showers, we measured the spatial angles which are formed by secondary particles with the direction of motion of the primary particle, and the momenta of the secondary particles. The error in the measurement of the three-dimensional angles did not exceed 1.5°; the maximum measured momentum for tracks of particles with track length $\sim$ 8 cm was 3.7 bev/c.

2. SHOWERS FROM $n_s \geq 4$ SECONDARY PARTICLES

Data are given in Table I for showers with an equal number of secondary particles, formed in beryllium and graphite plates in the chamber during the entire time of operation of the apparatus.

The numbers in parentheses denote the number of showers for which quantitative measurements of momenta and angles of most of the secondary particles was impossible, either because of their position inside the chamber, or because of the poor quality of the photographs. Data on the angles of emission of the particles relative to the direction of motion of the generating particle, θ, momenta p and ionization I of the secondary particles in the case of "excellent" showers are given in Table II. As a footnote, we mark the presence in the volume of the chamber of other rapid charged particles, in addition to the shower particles. These arrive in the chamber simultaneously with the shower-forming particles. In Figs. 2 and 3 (inset), there are shown two showers as examples, Nos. 43.27 and 95.87.

3. THE ENERGY OF THE SHOWER GENERATING PARTICLES

The experimental characteristics of the observed showers permit us to make an estimate of the energy of the generating particles under the assumption that in the center-of-mass system of the colliding particles there takes place a symmetric scattering of the secondary particles that are formed. Such an assumption is natural if the shower arises in the interaction of two nucleons. However, in our case, the interaction cannot be a nucleon-nucleon interaction for two reasons:

1. The presence of the lead filter over the entire apparatus can lead to the fact that the showers inside the chamber will be produced by particles which are formed in the lead filter overhead. In such a case, the shower-generating particles can be nucleons as well as pions. Below we shall therefore consider only the case of the passage of the generating particle through the chamber without the accompaniment of other fast charged particles, not connected with the shower.

2. The formation of the shower on a compound nucleus, even as light as Be or C, can occur in the interaction of the primary nucleon with certain nucleons inside the nucleus. We can point out a criterion, non-fulfillment of which means that the observed shower is not the result of nucleon-nucleon interaction.

TABLE I

Plate in chamber	No. of hours of research	Total no. of frames	Generating particle	n_S											Total showers
				4	5	6	7	8	9	10	11	12	13	14	
Be	824	4650	Charged	2 (3)	2 (4)	1 (1)	3 (1)	1 (1)	2 (1)	— —	— —	— —	1 —	— —	12 (11)
Be			Neutral	1 —	— —	— —	— —	— —	— —	— —	— —	— —	1 —	— —	2 —
C	131	667	Charged	2 (1)	— —	— —	1 (1)	— —	— —	— —	— —	— —	— —	1 —	4 2)
C			Neutral	—	—	—	—	—	—	—	—	—	—	—	—

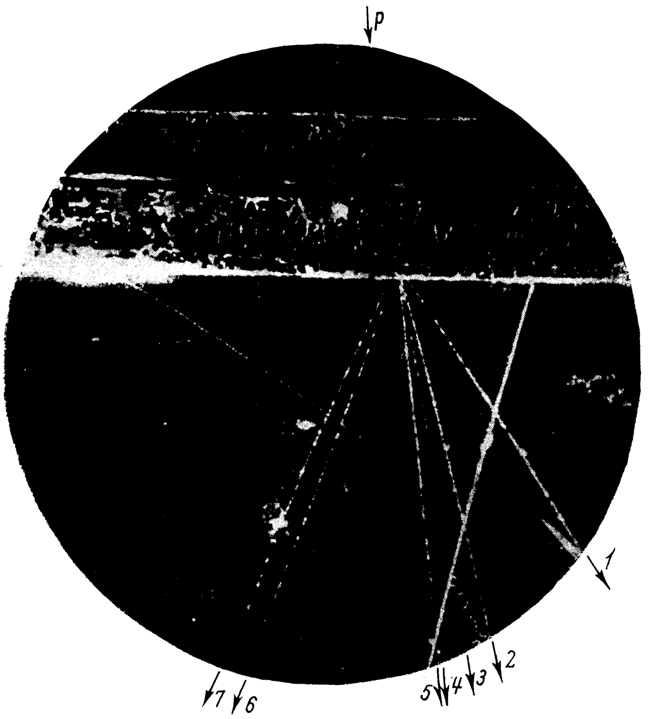

FIG. 2. Shower No. 43.27. Shower particle No. 1 (pion) creates a star in the gas of the chamber.

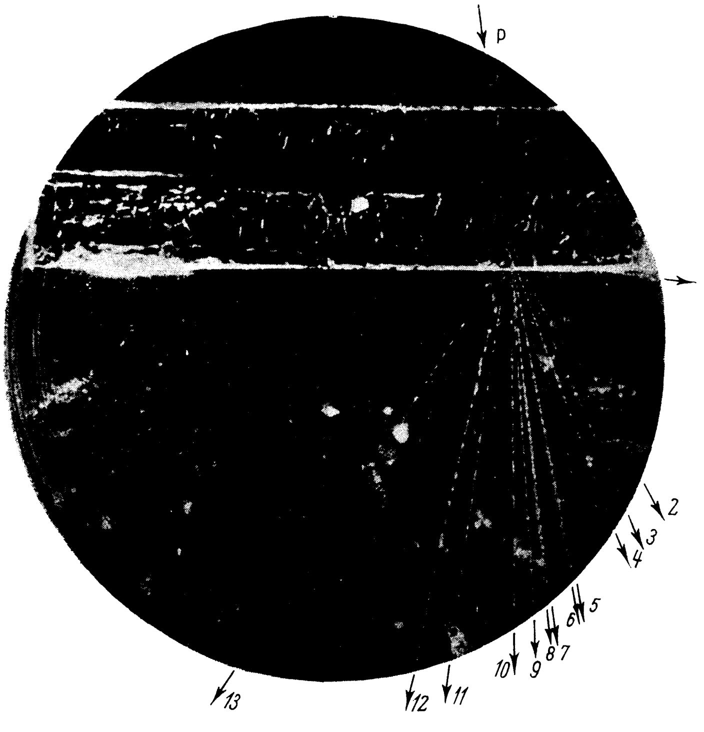

FIG. 3. Shower No. 95.87.

Let us consider the interaction of two nucleons with the formation of pions. Making use of the laws of conservation of energy and momentum, we can write

$$(E_0 - p_0c) + Mc^2 = \Sigma\,(E_i - p_ic\cos\theta_i) + E_\delta - p_\delta c\cos\theta_i, \qquad (1)$$

where E_p', p_0 are the total energy and momentum of the emergent nucleon in the laboratory system, E_i, p_i θ_i are the energy, momentum and angle of emergence of the shower particles; E_δ, p_δ and θ_δ are the corresponding quantities for the nucleon at a distance; M is the mass of the nucleon.

The energy of the generating nucleon for all the observed showers exceeds 5 bev; therefore, we can neglect the difference $E_0 - p_0 c$ in comparison with Mc^2. Then, for charged shower particles, assuming that all the particles are pions, the following condition must be satisfied:

$$Mc^2 > \Sigma\,(E_i - p_ic\cos\theta_i). \qquad (2)$$

If $Mc^2 < \Sigma(E_i - p_i c \cos\theta_i)$, then the generation of the shower occurs without nucleon–nucleon interaction. Applying the condition (2) to the showers of Table II, we can show that the shower from graphite No. 14.20 is formed in the interaction of the incident particle with several nucleons inside the nucleus. Actually, in this case, $\Sigma\,(E_i - p_i c\cos\theta_i) = 13 \times 10^8$ ev. For the remaining showers of Table II, which are formed by a single generating particle, condition (2) is satisfied (for shower No. 95.87, this condition is satisfied on the boundary). This does not mean, naturally, that interaction in all such cases takes place only between two nucleons. However, in what follows we shall depart from the assumption that for all showers of Table II, which are generated by a single particle and which satisfy condition (2), the scattering of the secondary particles in the center-of-mass system (c.o.m.) of two colliding nucleons takes place symmetrically with respect to the plane perpendicular to the direction of motion of the primary particle. Making use of such an assumption, we can obtain an estimate of the energy of the primary particle in the following way.

According to the equation

$$\operatorname{tg}\theta_{iC} = \sin\theta_i/\gamma_C\,[\cos\theta_i - (\beta_C/\beta_i)]$$

we find the angles θ_{ic} which are formed (in the c. o. m. system) by the shower particles with the direction of motion of the emergent nucleon for different values of the velocity of the c. o. m. system β_c in the laboratory system of coordinates (l.s.). (β_i is the velocity of the secondary particles in the laboratory system of coordinates). We consider that the real value of the velocity β_c corresponds to that value for which the angular scattering of charged particles in the c. o. m. system is very close to symmetric. Determination of

$$\gamma_C = 1/\sqrt{1-\beta_C^2}$$

in this fashion is the more accurate the greater the number of particles in the shower. For example, the angular distribution of the charged particles in shower No. 95.87 for $\gamma_C = 3$, $\gamma_C = 4$, $\gamma_C = 5$ is plotted in Fig. 4.* The value $\gamma_C = 4$ corresponds best to the symmetry condition.

By the method just described, we have determined γ_C for all showers. The results are shown in Table III (third column). The scatter of the angular distribution of the charged particles in the c.o.m. system and the number of neutral π^0–mesons do not permit us to calculate the errors in the values of γ_C in each individual case. However, analysis of diagrams similar to those in Fig. 4 allow us to think that the errors in γ_C do not exceed 50% in showers of 4–6 particles, and 30% in showers with the number of particles ≥ 7.

It should be noted that the determination of the energy by this method gives results which differ from those obtained by the method of finding γ_C with the aid of the angular distribution of secondary particles under the supposition that $\beta_C = \beta_{ic}$, where β_{ic} is the velocity of the secondary particles in the c.o.m. system. For primary energies $\sim 10^{10}$ ev, the latter assumption leads to a noticeable increase in the value of γ_C in certain cases. Thus, for example, for the shower 60.89, γ_C, determined under the assumption that $\beta_C = \beta_{ic}$, is equal to 5.3 instead of 3.5 (see Table III).

4. DISTRIBUTION OF THE ENERGY AMONG THE SECONDARY PARTICLES

For the characteristics of the interaction process of the nucleons, the energy distribution among the different secondary particles is essential. In particular, we need to know the distribution between nucleons and pions. Direct determination of the amount of energy retained by a fast nucleon is impossible, inasmuch as it is not possible in the showers that we have studied to intensify the fast particles which emerge (in the c.o.m. system) in the direction of motion of the primary nucleon. The situation is different with shower particles that emerge in the reverse direction in the c.o.m. system. For most of these particles, we can determine their nature by their momentum and by the ionization they produce in the gas of the chamber, and consequently separate the pions from the

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*Here and below, we shall denote, in the indices, the quantities which relate to the c.o.m. system by the letter C and those pertaining to the l.s. by the letter L.

TABLE II

Momenta and emission angle of slower particles, formed in Be by charged particles

No. of photograph	No. of particles	Sign	Momentum, $10^8\ \frac{\text{eV}}{c}$	Angle in l.s. θ_L degrees	Ionization	Nature of particle	Comment
1	2	3	4	5	6	7	8
43.27 Shower without accompaniment	1	+	7 ± 2	25	~ min.	π	Creates a star in the gas of the chamber
	2	+	$11^{+4.5}_{-2.5}$	13	„	?	
	3	?	—	22	„	?	
	4	+	24^{-9}_{+36}	2	„	?	
	5	?	>38	6	„	?	
	6	+	5.5 ± 1	28	„	π	
	7	—	2.9 ± 0.3	34	„	π	
47.14 Shower with accompaniment	1	—	$7^{+1.4}_{-1.0}$	27	~ min.	π	
	2	+	$8.5^{+2.5}_{-1.5}$	10	„	?	
	3	—	11^{+4}_{-2}	7	„	π	
	4	?	>38	5	„	?	
	5	—	$16^{+17}_{-5.5}$	9	„	π	
	6	—	$7^{+2.5}_{-1.5}$	3	„	π	
	7	?	—	13	„	?	short track
	8	?	>24	14	„	?	
	9	—	$0,57\pm0.01$	9	„	δ-electron	
50.38 Shower without accompaniment	1	?	>40	6	~ min.	?	
	2	—	19^{+18}_{-6}	3	„	π	
	3	?	>40	3	„	?	
	4	?	>30	4	„	?	
70.52 Shower without accompaniment	1	—	$2+0.1$	41	~ min.	π	
	2	?	—	40	~ 5 min.	proton	
	3	+	$10^{+4.5}_{-1.5}$	2	~ min.	?	
	4	+	9^{+4}_{-1}	14	„	?	
	5	?	>9	48	„	?	
74.39 Shower without accompaniment	1	—	$4.5^{+1.2}_{-0.9}$	30	~ min.	π	
	2	+	10^{+12}_{-3}	16	~ min.	?	
	3	+	$8.5^{+3}_{-1.5}$	25	~ min.	?	
	4	+	3.9 ± 0.4	10	~ min.	π	
87.52 Shower without accompaniment	1	—	2.3 ± 0.2	6	~ min.	π	
	2	?	>29	5	„	?	
	3	+	15^{+15}_{-5}	6	„	?	
	4	?	>25	13	„	?	
	5	?	—	11	„	?	short track

TABLE II (continued)

No. of photograph	No. of particles	Sign	Momentum, $10^8\ \frac{\text{eV}}{c}$	Angle in l. s. θ_L degrees	Ionization	Nature of particle	Comment
1	2	3	4	5	6	7	8
89.51	1	—	$4\ 5^{+2}_{-1}$	77	~ min.	π	
Shower without accompaniment	2	?	>14	16	„	?	
	3	?	—	21	„	?	tracks 3–7 almost run together
	4	?	—	2	„	?	
	5	?	—	2	„	?	
	6	?	—	2	„	?	
	7	?	—	2	„	?	
	8	+	$10^{+5}_{-2.5}$	2	„	?	
	9	+	$18^{+14}_{-4.5}$	5	„	?	
60.89 Shower without accompaniment	1	?	>13	48	~ min.	?	
	2	+	$3\ 7^{+0.8}_{-0.6}$	31	„	π	
	3	—	$6^{+4}_{-1.5}$	14	„	π	
	4	+	11.5^{+16}_{-3}	2	„	?	
	5	—	25^{+80}_{-11}	2	„	π	
	6	?	>38	6	„	?	
	7	?	—	11	„	?	short track
	8	?	> 9	25	„	?	
93.46 Shower without accompaniment	1	?	> 7	22	~ min.	(π?)	
	2	?	>39	7	„	?	
	3	—	23^{+34}_{-8}	8	„	π	
	4	+	$13^{+5.5}_{-2.5}$	20	„	?	
	5	—	5,2±0.5	4	„	π	
	6	+	10^{+6}_{-2}	13	„	?	
	7	+	12^{+6}_{-3}	32	„	?	
95.87	1	?	—	71	~ min.	?	short tracks
	2	?	—	32	„	?	
	3	+	$8^{+1.3}_{-3}$	26	„	(π?)	
	4	+	12^{+38}_{-5}	16	„	?	
	5	?	>26	13	„	?	
	6	?	>25	4	„	?	
	7	?	>29	2	„	?	
	8	?	>27	3	„	?	
	9	+	$13.5^{+12}_{-4.5}$	5	„	?	
	10	+	11^{+6}_{-3}	6	„	?	
	11	—	$7.8^{+1.9}_{-1.1}$	18	„	π	
	12	—	$5\ 7^{+1.1}_{-0.7}$	24	„	π	
	13	+	8^{+5}_{-2}	45	„	(π?)	

TABLE II (continued)

No. of photograph	No. of particles	Sign	Momentum, $10^8\,\frac{eV}{c}$	Angle in l.s. θ_L degrees	Ionization	Nature of particle	Comment
1	2	3	4	5	6	7	8
98.80 Shower without accompaniment	1	?	—	14	~ min.	?	short track
	2	?	>17	8	„	?	
	3	—	1.2 ± 0.05	8	„	π	
	4	—	10^{+3}_{-2}	16	„	π	
	5	?	>38	4	„	?	
	6	+	17^{+13}_{-5}	14	„	?	
	7	?	—	45	„	?	short track
98.87 Shower without accompaniment	1	?	>3	37	min.	(π?)	
	2	—	1.0 ± 0.3	5	„	π	
	3	+	>37	9	„	?	
	4	+	$10.5^{+4.5}_{-2.5}$	12	„	?	
	5	+	13^{+6}_{-3}	10	„	?	
	6	?	>3	55	„	(π?)	
44.55 Shower is formed by a neutral particle	1	—	$2.0\pm0,2$	5*	min.	π	
	2	+	13^{+32}_{-5}	4	„	?	
	3	+	$6.5^{+3.5}_{-1.5}$	5	„	π	
	4	?	—	2	„	?	tracks of particles 4–9 almost run together
	5	?	—	2	„	?	
	6	?	—	2	„	?	
	7	?	—	2	„	?	
	8	?	—	2	„	?	
	9	?	—	2	„	?	
	10	+	$11.5^{+8.5}_{-3.5}$	2	„	?	
	11	?	>27	3	„	?	
	12	+	$15^{+9.5}_{-4.5}$	4	„	?	
	13	?	>27	6	„	?	
Showers formed in graphite by charged particles							
16.X.53 No. 9 Shower without accompaniment	1	—	$5^{+1.5}_{-1.0}$	25	~ min.	π	
	2	?	>23	10	„	?	
	3	+	12^{+36}_{-5}	6	„	?	
	4	?	>14	15	„	?	
14.20	1	+	7^{+4}_{-2}	50	~ 2 min.	proton	
	2	?	—	25	min.	?	
	3	+	$6.5^{+3}_{-2.5}$	18	„	π	
	4	+	20^{+20}_{-9}	11	„	?	
	5	?	>23	2	„	?	

*From the direction of the motion of the neutral generating particle we get the direction of the total momentum of the charged particles.

TABLE II (continued)

No. of photograph	No. of particles	Sign	Momentum, $10^8 \frac{eV}{c}$	Angle in l.s. θ_L degrees	Ionization	Nature of particle	Comment
1	2	3	4	5	6	7	8
14.20 .	6	—	$13^{+16}_{-4.5}$	2	min.	π	
	7	—	12^{+12}_{-4}	2	„	π	
	8	—	12^{+11}_{-4}	6	„	π	
	9	?	>23	13	„	?	
	10	—	4^{+2}_{-1}	28	„	π	
	11	+	12^{+22}_{-45}	19	„	?	
	12	?	—	32	„	?	short track
	13	+	14^{+20}_{-7}	30	„	?	
	14	—	$12^{+2.1}_{-4.5}$	31	„	π	
22.44-a Shower without accompaniment	1	+	$3.8^{+0.8}_{-0.6}$	33	min.	π	
	2	?	>22	14	„	?	
	3	+	$5.5^{+4.5}_{-2}$	5	„	π	
	4	+	8.5^{+6}_{-3}	4	„	?	
	5	?	>22	6	„	?	
	6	?	>7	8	„	(π?)	
	7	?	>6	9	„	(π?)	

protons.* We can then find the amount of energy transferred to pions in the backward cone in the c.o.m. system: therefore, if the emission of the secondary particles is symmetric we can also obtain the amount of energy α_C transferred to all mesons,

$$\alpha_C = 1{,}5\,\Sigma E_{iC}^{\pi\pm} / \gamma_C Mc^2. \tag{3}$$

We consider that the neutral pions make up one third of all mesons. The amount of energy retained by each nucleon will be

$$\varepsilon_C = E_{NC} / \gamma_C Mc^2 = 1 - 1{,}5\Sigma E_{iC}^{\pi\pm} / \gamma_C Mc^2.$$

Transforming to the laboratory system of coordinates, under the assumption of nucleon-nucleon interaction, we find that the fraction of energy retained by a fast nucleon is equal to

$$\varepsilon = \frac{E_N}{E_0} = \frac{\gamma_C}{2\gamma_C^2 - 1} [\varepsilon_C \gamma_C + \beta_C \sqrt{\varepsilon_C^2 \gamma_C^2 - 1} \cos\theta_{NC}], \tag{4}$$

where E_N is the total energy of the nucleon in the l.s. after the interaction, E_0 is the initial total energy of the nucleon in the l.s., θ_{NC} is the emergence angle of the nucleon in the c.o.m. system. Making use of Eq. (4), we can find the limits, for a shower with known γ_C, within which the quantity ϵ will lie in its dependence on the angle θ_{NC}. Table IV gives the estimates of the amount of energy ϵ retained, obtained by this method. Analyzing Table IV, we see that for all cases, the energy of a fast nucleon is less than 60% of the energy of the primary nucleon.

It should be noted that the data we have obtained bear an approximate character, inasmuch as in showers with a small number of particles, an appreciable scatter is possible both in the values of the energy transferred to the pions in the backward cone, and in the values of the energy pos-

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*In certain cases when relativistic particles, emerging at large angles in the l.s., possess a momentum $p > 8 \times 10^8$ ev/c, we consider them to be protons. As will be evident in what follows, this leads to an increased amount of energy concentrated on a single nucleon.

sessed by the π^0–mesons.

5. ANGULAR DISTRIBUTION OF PARTICLES IN THE CENTER-OF-MASS SYSTEM

For showers whose energy is determined by the method just described, we can obtain the angular distribution of all shower particles in the center-of-mass system. Such a distribution for 68 particles which gave tracks with minimum ionization is presented in Fig. 5. The broken curve corresponds to the isotropic distribution of the particles. In the limits of statistical errors, the angular distribution that we obtained coincides with the isotropic.

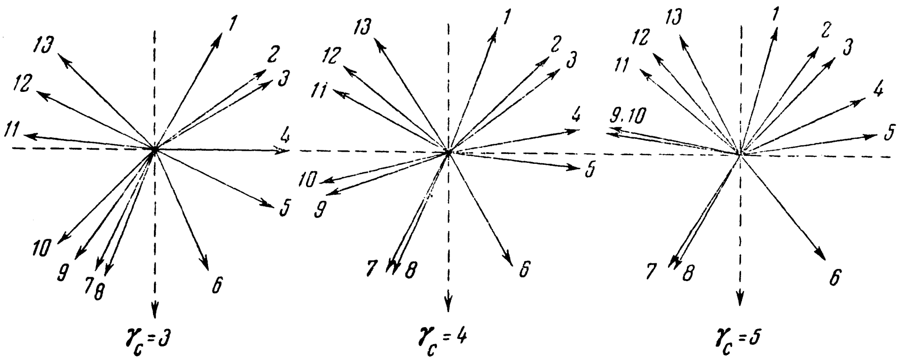

FIG. 4. Angular distribution of the shower particles in the c.o.m. system for shower No. 95.87. In finding the angles for particles 1 and 2, it is assumed that the momentum of these particles is equal to 5 bev/c.

TABLE III

No. of shower	Total no. of particles in shower	γ_C	E_0' 10^{-9} ev for $N+N$ collisions
43.27	7	2.5	10.8
60.89	8	3.5	22
70.52	5	2	6.6
89.51	9	5	49
93.46	7	3.5	22
98.80	7	3	16
95.87	13	4	29*
98.87	6	2	6.6
44.55	13	6	66
22.44-a	7	4	29
74.39	4	1.5	3.5

*It is possible that this is not a nucleon-nucleon interaction.

In one shower (No. 70.52) a slow δ-proton was registered; in the others, δ-protons were not seen. However, it is possible, making use of Eq. (1), to attempt to determine the angles and momenta in the l.s. of those nucleons which emerge in the forward direction in the c.o.m. system. Actually,

$$E_\delta - p_\delta c \cos\theta_\delta = Mc^2 - \Sigma\,(E_i - pc\cos\theta_i).$$

As before, we neglect π^0–mesons, and consider all secondary charged particles which produce minimum ionization in the gas of the chamber to be π–mesons (the presence in the medium of fast charged particles of one proton has slight effect on the result).* We denote

$$Mc^2 - \Sigma\,(E_i - p_i c\cos\theta_i)$$

by B. Then,

$$p_\delta c = [B\cos\theta_\delta \tag{5}$$

$$\pm\sqrt{\cos^2\theta_\delta B^2 - \sin^2\theta_\delta\,(M^2c^4 - B^2)}\,]\,/\sin^2\theta_\delta.$$

It therefore follows that

$$\operatorname{ctg}\theta_\delta \geqslant \sqrt{M^2c^4 - B^2}\,/\,B. \tag{6}$$

Equation (6) determines the maximum angle for which δ-nucleons can emerge in the laboratory system. Here

$$(M^2c^4 - B^2)\,/\,2B < p_\delta c \tag{7}$$

$$< \sqrt{(E_0 + Mc^2 - \varepsilon E_0 - 1{,}5\,\Sigma E_i)^4 - M^2c^4}.$$

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*Consideration of π^0–mesons and of a fast nucleon leads to some diminution of the limit angle θ_δ.

TABLE IV

No. of shower	γ_C	without consideration of π^0-mesons			with consideration of π^0-mesons		
		α_C	$\varepsilon(\theta_{NC}=0)$	$\varepsilon(\theta_{NC}=90°)$	α_C	$\varepsilon(\theta_{NC}=0)$	$\varepsilon(\theta_{NC}=90°)$
43.27	2,5	0,35	0.58	0,35	0,5	0,43	0,27
60.89	3.5	0,34	0,65	0,35	0.5	0,46	0,26
70.52	2	0,5	0,29	0,29	—	—	—
89.51	5	0.4	0.6	0.3	0.6	0.37	0.2
93.46	3,5	0.27	0.7	0.36	0.4	0.57	0.31
95.87	4	0.5	0.48	0.26	0.75	0.13	—
98.87	2	0.3	0.65	0.35	0.45	0 43	0.31
22.44-a	4	0,27	0.70	0,4	0,4	0,6	0,3

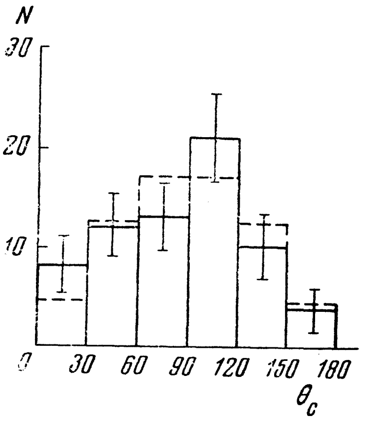

FIG. 5. Angular distribution in the c.o.m. system of shower particles which produce relativistic ionization in the gas of the chamber.

The upper limit for p_δ is determined from the law of conservation of energy, in which we take for ϵ the minimum values from Table IV, and in the composition of ΣE_i, we do not include the value of the energy of the fastest particle of the shower. Here we obtain a reduced value of p_δ. Equations (6) and (7) allow us to determine the minimum angle at which a δ-nucleon emerges in the c.o.m. system. The limiting angles of emergence of δ-nucleons in the l.s., and c.o.m. system, $\theta_{\delta L}$ and $\theta_{\delta C}$, for showers with known γ_C are given in Table V.

The values of the limiting angles $\theta_{\delta C}$ of Table V are significantly reduced, inasmuch as in their determination we have made use of the reduced values of momenta of the δ-nucleons in the l.s. This applied particularly to the showers 44.55 and 89.51 in which about half of the particles possess unmeasured momenta.

TABLE V

No. of shower	$\theta_{\delta L}^{\circ}$	$p_\delta \cdot 10^{-8}$ eV/c	$\theta_{\delta C}^{\circ}$
43.27	$\leqslant 37$	5—18	> 130
70.52	$\leqslant 34$	6—15	> 125
89.51	$\leqslant 26$	9—220	> 90
93.46	$\leqslant 30$	11—50	> 120
98.80	$\leqslant 40$	4—18	> 140
98.87	$\leqslant 34$	6—25	> 120
44.55	$\leqslant 62$	1,5—270	> 115
22.44-a	$\leqslant 48$	6—105	> 125

It then follows from Table V that the emergence of δ-nucleons in the c.o.m. system takes place anisotropically.

6. CONCLUSIONS

We can now make some conclusions relative to the character of the interactions isolated by our apparatus.

1. The angular distribution of the shower particles (pions) in the c.o.m. system of two colliding nucleons is close to isotropic.

2. The scattering of nucleons in the c.o.m. system occurs anisotropically, principally in the direction of motion of the primary nucleon.

3. The fraction of energy retained by the fastest nucleon does not exceed 60%. It should be noted that these conclusions cannot be extended to all interactions of nucleons with $E_0 \geq 5$ bev with Be nuclei, inasmuch as the cases that we have analyzed, which differ in the comparatively large number of secondary particles, form an insignificant fraction of the total number of interactions. Comparison of the value of the amount of energy transferred to the pion, which is obtained for the cases analyzed, with the significantly smaller value of this same quantity which follows from analysis of processes of passage of cosmic ray nucleons through the atmosphere,[2] points up the presence of large fluctuations in the characteristics of nuclear interactions.

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[1] Wright, Saphir, Powell, Maenchen and Fowler, Phys. Rev. 100, 1802 (1955); Fowler, Maenchen, Powell, Saphir and Wright, Phys. Rev. 101, 911 (1956); Materials of the Rochester Conference, April, 1956.

[2] N. L. Grigorov, Uspekhi Fiz. Nauk 58, 599 (1956).

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