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EXPLOSION SHOWERS PRODUCED BY HIGH-ENERGY COSMIC RAY PARTICLES

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Experimental results on 43 showers produced by nucleons of $10^{10}-10^{14}$ ev and on 20 showers produced by particles with $Z \geq 2$ are presented. An asymmetry has been observed in the angular distribution of shower particles with respect to the direction $\pi/2$ in the center-of-mass system in showers produced by nucleons with energy $> 10^{11}$ ev. This fact is not consistent with the concept of shower production on nuclei in nucleon-nucleon collisions and with the predictions of the hydrodynamical theory of multiple particle production proposed by Belen'kii and Landau.

THE present work is devoted to the study of explosion showers produced by high-energy cosmic ray particles by means of an emulsion chamber. Preliminary results obtained for 29 showers were published earlier.[1] The purpose of the present article is to consider the energy dependence of the various characteristics of explosion showers in the region $10^{10}-10^{13}$ ev.

The emulsion chamber consisted of 100 layers 10 cm in diameter. Total thickness of the chamber was equal to 4.5 cm Emulsion NIKFI type R was used. The chamber was irradiated in the stratosphere at 27 km altitude for seven hours in May 1956. Explosion showers with more than five relativistic tracks, concentrated in a sufficiently narrow cone, were found by scanning. There was no discrimination with respect to the number of black and grey tracks in finding the showers. Jets of relativistic particles consisting of more than five tracks were also noted in scanning. Further investigation showed that five of these events represented explosion showers while the remaining 200 jets were identified as electron-photon showers. Charge of the shower producing particle was determined in each case of detected explosion shower (as single, double, or multiple) and the angular distribution of shower particles with respect to the axis was measured.

1. MEASUREMENT OF THE ANGULAR DISTRIBUTION OF SHOWER PARTICLES

For shower particles of the "wide cone," making an angle larger than 5° with shower axis, the angle α in the emulsion plane and the inclination β were measured with an accuracy of 1°. The angular distribution about the shower axis was determined by means of the special device shown in Fig. 1. Each shower particle was marked on an aluminum sphere and the angles α and β were read off the divisions 1 and 2 respectively. The angle ϑ between the particle trajectory and shower axis was found using a plexiglass hemisphere with the latitude (ϑ) and longitude (φ) marked on it, and which could be fitted to the aluminum sphere.

Measurements of the angle ϑ for shower particles with $\vartheta < 5°$ were carried out by means of finding the points of intersection of the tracks with a plane perpendicular to shower axis. An example of such construction for the determination of angular distribution of particles in a shower of 3.7×10^{12} ev is shown in Fig. 2, which represents the

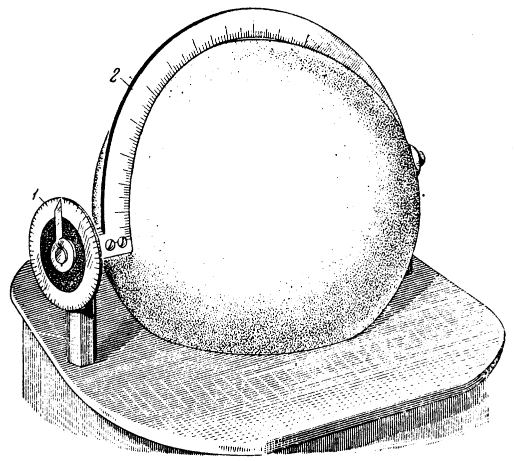

Fig. 1. Apparatus for measurement of the angle between shower axis and direction of emission of shower particles.

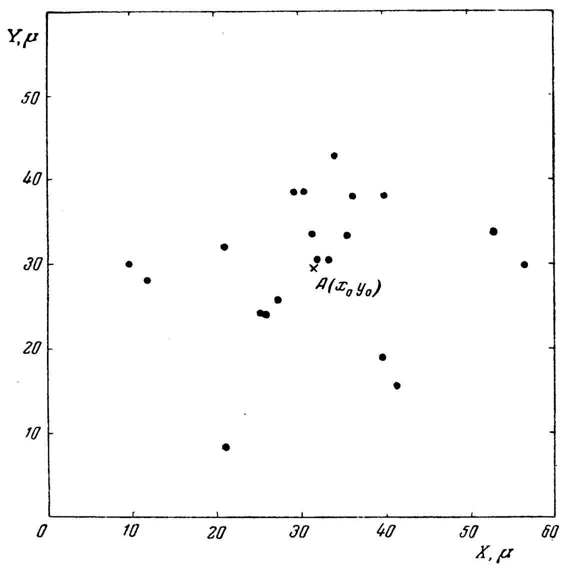

Fig. 2.

plane perpendicular to shower axis at a distance of 200 μ from the shower origin. The point $A(x_0, y_0)$ corresponding to the intersection of the shower axis with the XY plane was determined as

$$x_0 = \sum x_i / n, \quad y_0 = \sum y_i / n,$$

where n is the number of shower particles. The distance between the plane XY and the point of origin of the shower was selected so that the accuracy of angle measurements for most shower particles would not be worse than 5 — 10 percent.

2. DETERMINATION OF SHOWER ENERGY

If we assume that the observed showers were produced as the result of nucleon-nucleon collisions, then it follows from the symmetry of angular distribution of shower particles in the center-of-mass system (c.m.s.) about the direction $\theta = \pi/2$* that the energy of the primary particles in c.m.s., $\gamma_c = 1/\sqrt{1-\beta_c^2}$, can be written in the form

$$\gamma_c = \cot \vartheta_{1/2}, \tag{1}$$

where $\vartheta_{1/2}$ is the angle containing half of the shower particles.

A second method of determination of γ_c, which permits a better use of the data on angular distribution, and makes it possible to determine the statistical error due to the finite number of shower particles, has been proposed by Castagnoli et al.[2] According to their calculations, we have

$$\ln \gamma_c = -\overline{\ln \tan \vartheta} \pm (\sigma / \sqrt{n_s}), \tag{2}$$

where n_s is the number of shower particles and σ is of the order of unity.

The value of γ_c can also be found, for a symmetrical distribution with respect to $\theta = \pi/2$ in the c.m.s., from the integral angular distribution of shower particles. Let us denote the integral angular distribution of shower particles by F. We then have

$$F(\lambda) = \frac{1}{\sum n_s} \int_{-\infty}^{\lambda} \frac{dn_s}{d\lambda} d\lambda, \tag{3}$$

where $\lambda = \ln \tan \vartheta$. $F(\lambda)$ is normalized to unity, i.e.,

$$\int_{-\infty}^{+\infty} F(\lambda)\, d\lambda = 1.$$

It is evident that, for a symmetrical angular distribution, $F/(1-F) = 1$ for $\theta = \pi/2$, i.e., $F/(1-F)$ is such a function of λ that for $\ln[F/(1-F)] = 0$ its argument, according to Eq. (1), is $\lambda_0 = \ln \tan \vartheta_{1/2} = -\ln \gamma_c$. In this way the determination of γ_c is reduced to plotting $\ln[F/(1-F)]$ as a function of $\lambda = \ln \tan \vartheta$ and finding the value λ_0 for which $\ln[F/(1-F)] = 0$.

All these methods of finding γ_c yield results that vary by 20 — 30%, and which are within the statistical accuracy of measurements. It can be seen from Table I that the values of γ_c obtained according to Eq. (2) are lower than those of the two other methods.

It should be noted that the assumption that showers produced on the emulsion nuclei originate in nucleon-nucleon collisions may not correspond to reality. Belen'kii and Landau[3] treated the case of multiple particle production according to the hydrodynamical model, assuming the interaction be-

*Where, as in the following, θ denotes the emission angle of a shower particle in the c.m.s. and ϑ the emission angle of shower particle in the laboratory system.

TABLE I

$E_0=10^{10}$—10^{11} ev

No.	Primary particle	n_h+n_g	n_s	$\vartheta_{1/2}$, deg.	γ_c ($\vartheta_{1/2}$)	γ_c ($\bar{\lambda}$)	γ_c (F)	$\bar{\gamma}_c$	E_0, ev	k	l	P_s	E, ev
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	p	14+6	23	11.5	4.9	4.8	6.0	5,2	$5,3\cdot10^{10}$	3,05	8,5	0,05	$4,5\cdot10^{11}$
2	p	15+5	24	10	5.5	4.6	7,6	5,9	$6,9\cdot10^{10}$	3.07	8	0,42	$5.5\cdot10^{11}$
3	p	4+2	8	11	5.1	4.7	—	4,9	$4.7\cdot10^{10}$	0,41	3	0,32	$1,4\cdot10^{11}$
4	n	7+3	13	26	2.0	2,1	2,9	2,3	$1,0\cdot10^{10}$	2,24	6	0,54	$6,0\cdot10^{10}$
5	p	13+5	14	16.5	3,4	2.8	3,6	3,3	$2,1\cdot10^{10}$	1,93	5,5	0,68	$1,2\cdot10^{11}$
6	p	8+8	8	18	2.1	2.0	3.5	2,9	$1.6\cdot10^{10}$	1,13	3,5	0,85	$5,7\cdot10^{10}$
7	p	9+3	12	11	5.1	3,6	5,1	4,6	$4,1\cdot10^{10}$	1,02	4	0.05	$1.6\cdot10^{11}$
8	n	11+2	23	18	3.1	2.5	3.2	2,9	$1,6\cdot10^{10}$	3,68	9.5	0,09	$1,5\cdot10^{11}$
9	p	10+7	25	16.0	3.5				$4.0\cdot10^{10}$	3,42	9	0,68	$3,6\cdot10^{11}$
10	n	6+6	15	16.5	3.4				$2,2\cdot10^{10}$	2,20	6	0.07	$1,3\cdot10^{11}$
11	n	6+9	22	14.5	3.9				$2.9\cdot10^{10}$	2.94	8	0.28	$2,3\cdot10^{11}$
12	n or p	14+6	21	16.5	3.4				$2,2\cdot10^{10}$	2.36	8	0,001	$1,8\cdot10^{11}$
13	p	5+3	22	17	3,3				$2.1\cdot10^{10}$	3,28	9	0,24	$1,9\cdot10^{11}$
14	α	1+2	35	10,7	5.3	4.7	6,4	5,5	$6,0\cdot10^{10}$	3,85		0.67	
15	α	12+3	42	10,6	5,3	5.9	8.3	6.5	$8,4\cdot10^{10}$	3,95		0,14	
16	α	17+9	36	9.0	6.3	5,1	6.5	5,6	$6,2\cdot10^{10}$	4,45		0.50	
17	α	9+4	17	8.0	7.1	5,0	7,9	6.6	$8.6\cdot10^{10}$	2.20		0,42	
18	Z	8+26	87	12,2	4.6					12,3		0.32	
19	α	12+3	20	13.0	4,3	4,3	5.0	4,9	$4.4\cdot10^{10}$	2.35		0.24	
20	α	16+8	45	23.5	2.2	1.9	2.3	2.1	$0,9\cdot10^{10}$	8,40		0,06	
21	α	16+15	35	19.5	2.7	2.4	3,0	2.7	$1,4\cdot10^{10}$	5,85		0,85	
22	Z	17+6	74	10.5	5,3	5.7	7.2	6.0	$7,0\cdot10^{10}$	9,75		0.81	
23	α	16+8	26	23.0	2,3	2.4	2.5	2.4	$1,1\cdot10^{10}$	4.75		0,08	
24	α	10+6	16	15.0	3,7	3.6	4,2	3.8	$2,8\cdot10^{10}$	1,89		0.67	
25	α	15+10	28	9.5	5.9	5,7	6,8	6.1	$7,1\cdot10^{10}$	3.30		0.92	
26	Z	12+8	41	15,0	3.7	3,2	3.8	3.6	$2,4\cdot10^{10}$	6,10		0.54	
27	α	9+3	13	20,0	2.7	3.2	3,6	3.2	$1,9\cdot10^{10}$	1,68		0.081	
28	α	13+5	29	17,0	3.3	3.4	4.0	3.6	$2.4\cdot10^{10}$	4,00		0.42	

$E_0=10^{11}$—10^{12} ev

No.	Primary particle	n_h+n_g	n_s	$\vartheta_{1/2}$, deg.	γ_c ($\vartheta_{1/2}$)	γ_c ($\bar{\lambda}$)	γ_c (F)	$\bar{\gamma}_c$	E_0, ev	k	l	P_s	E, ev
1	p	5+2	23	3.3	17,1	16.6	13,6	15,8	$5.0\cdot10^{11}$	2.50	5	0.32	$2,5\cdot10^{12}$
2	p	3+4	15	3,5	17.1	13.9	20.0	17,0	$5.8\cdot10^{11}$	0,64	3	0.90	$1,7\cdot10^{12}$
3	p	5+3	14	4.7	12,3	10.4	14.1	12,5	$3,1\cdot10^{11}$	0.59	3.5	0.20	$1.1\cdot10^{12}$
4	p	3+2	18	6,5	11,9	11,0	15.1	12,7	$3.2\cdot10^{11}$	1.10	4.5	0,60	$1,4\cdot10^{12}$
5	p	5+3	15	5,5	10.4	7,0	12.6	10,0	$2.0\cdot10^{11}$	1.84	4	0.67	$8,0\cdot10^{11}$
6	p	12+7	24	6,9	8.3	6.1	8.0	7.5	$1,1\cdot10^{11}$	2.57	8	0.60	$9,0\cdot10^{11}$
7	p	9+7	14	5,1	11.2	11.2	15,1	12.5	$3.1\cdot10^{11}$	0,82	3.5	0,01	$1,1\cdot10^{12}$
8	p	13+10	19	2,5	22.9	12.2	15.8	17,0	$5.7\cdot10^{11}$	1,91	4	0.67	$2.3\cdot10^{12}$
9	p	1+2	29	6.5	8.8	7,1	8.7	8,2	$1.3\cdot10^{11}$	3.45	2.5	0,40	$1,2\cdot10^{12}$
10	p	1+1	12	8,1	7.0	5,9	8,3	7.1	$1.0\cdot10^{11}$	1.32	4	0.32	$4,0\cdot10^{11}$
11	p	13+2	30	7.5	7.5	7.6	7,2	7.4	$1,1\cdot10^{11}$	3.70	12	0.60	$1,3\cdot10^{12}$
12	n	10+1	23	7,0	8,1	5.1	8,5	7.2	$1.0\cdot10^{11}$	2.80	8	0,54	$8\ \cdot10^{11}$
13	p	3+0	8	6.5	8,8	6.9	9.1	7,9	$1,2\cdot10^{11}$	0.80	2,5	0.85	$3\ \cdot10^{11}$
14	n	4+1	7	3.5	16,3	9.1	12,0	12,3	$3.0\cdot10^{11}$	0.40	1,5	0.94	$4,5\cdot10^{11}$
15	p	10+6	35	6.7	8.3	8.4	15,0	10,6	$2.2\cdot10^{11}$	4.16	10	0.23	$2.2\cdot10^{12}$
16	n	7+5	32	5.4	10,6	9,9	15.0	11.8	$2,8\cdot10^{11}$	3.62	8,5	0,54	$2.4\cdot10^{12}$
17	p	1+1	20	2.0	28,6	15.6	19.5	21,3	$9.1\cdot10^{11}$	1.67	4	0.42	$3,6\cdot10^{12}$
18	n	1+0	10	3,2	17.5	12,6	20,0	16,7	$5,6\cdot10^{11}$	0,40	2	0,80	$1,1\cdot10^{12}$
19	p	1+2	19	6,5	8,8	9.2	11,0	9,7	$1,9\cdot10^{11}$	2,0	5.5	0.80	$1,0\cdot10^{12}$
20	p	10+1	29	5,4	10,5	10,5	13,2	11,4	$2.6\cdot10^{11}$	2,74	8	0,98	$2,1\cdot10^{12}$
21	p	12+3	11	5.7	9,5	6,3	9,6	8,5	$1.4\cdot10^{11}$	0,99	3	0.85	$4,2\cdot10^{11}$
22	Z	1+1	22	6.8	8,4	7.3	10,0	8,6	$1,5\cdot10^{11}$	1.43		0.001	
23	α	3+1	27	4.0	14.3	11,1	12,6	12,5	$3,2\cdot10^{11}$	1,28		0.48	
24	α	0+2	29	6.5	8.8	9,2	10,0	9,2	$1,7\cdot10^{11}$	3,4		0,09	
25	Z	4+0	57	3,7	15,4				$4,7\cdot10^{11}$			0,05	

$E_0=10^{12}$—10^{13} ev

No.	Primary particle	n_h+n_g	n_s	$\vartheta_{1/2}$, deg.	γ_c ($\vartheta_{1/2}$)	γ_c ($\bar{\lambda}$)	γ_c (F)	$\bar{\gamma}_c$	E_0, ev	k	l	P_s	E, ev
1	n	5+8	35	1.0	55	20	53	43	$3,7\cdot10^{12}$	3,95	5	0,5	$1,9\cdot10^{13}$
2	p	2+3	27	2,1	27	32	32	30	$1,8\cdot10^{12}$	2,65	4,5	0,1	$8,1\cdot10^{12}$
3	p	0+0	9	1,7	34	27	37	33	$2,1\cdot10^{12}$	0,14	1,5	0,04	$3,2\cdot10^{12}$
4	p	5+3	27	2.4	24	17	25	22	$9,6\cdot10^{11}$	2,82	5,5	0.8	$5,3\cdot10^{12}$
5	p	2+4	27	1.0	57	36	50	48	$4,6\cdot10^{12}$	1.0	4	0,2	$1,8\cdot10^{13}$
6	p	6+4	20	2.6	22	20	25	22	$9,6\cdot10^{11}$	1,85	4	0,7	$4,0\cdot10^{12}$
7	p	1+2	43	1.3	43	36	40	40	$3.2\cdot10^{12}$	2,48	7	0.75	$2,2\cdot10^{13}$
8	α	7+3	33	2.3	24	21	30	25	$1,3\cdot10^{12}$	2.95		0,03	

$E_0=10^{13}$—10^{14} ev

No.	Primary particle	n_h+n_g	n_s	$\vartheta_{1/2}$, deg.	γ_c ($\vartheta_{1/2}$)	γ_c ($\bar{\lambda}$)	γ_c (F)	$\bar{\gamma}_c$	E_0, ev	k	l	P_s	E, ev
1	p	11+3	16	0,70	81	50	120	84	$1,4\cdot10^{13}$	1,11	1,5	0.40	$2,1\cdot10^{13}$
2	p	5+4	9	0.25	227	141	300	222	$9,9\cdot10^{13}$	0,09	1	0.75	$9\ \cdot10^{13}$

tween the primary nucleon and the nucleus as a whole, in head-on collisions. They obtained the following formula for the angular distribution of particles in the c.m.s.:

$$dN \sim \exp\left(\sqrt{L^2 - \ln^2 \tan\frac{\theta}{2}}\right) d\left(\ln \tan\frac{\theta}{2}\right). \qquad (4)$$

Here $L = \ln[(1+\ell)/4\gamma_c]$, ℓ is the tunnel length, i.e., the number of nucleons on the chord corresponding to the trajectory of the primary particle through the nucleus. According to Eq. (4), $dN/d\theta$ is symmetric about $\theta = \pi/2$. It follows that, if the theory is correct, γ_c can be determined by the same method as for nucleon-nucleon collisions.

In the following we shall ascribe to showers values of γ_c, calculated according to formulae (1) and (2) and from the condition $\ln[F/(1-F)] = 0$, which correspond to the assumption that the distribution of shower particles is symmetric about $\theta = \pi/2$. It should be noted that the experimental data available are not in agreement with this assumption (cf. Sec. 3) and the accuracy of shower energy determination by the above method should not be overestimated.

The shower energy in the laboratory system, E_0, can be determined in a unique way only for the case of nucleon-nucleon collisions:

$$\gamma = 2\gamma_c^2 - 1 \approx 2\gamma_c^2, \qquad (5)$$

where $\gamma = E_0/Mc^2$. For collisions between the primary nucleon and nucleons contained in the tunnel, the shower energy in the laboratory system is found from the relation

$$\gamma = 2\gamma_c^2 l, \qquad (5')$$

where ℓ is the tunnel length and $\gamma = E/Mc^2$.

3. EXPERIMENTAL RESULTS AND THEIR EVALUATION

Experimental results on 43 showers produced by nucleons and 20 showers generated by α particles and nuclei are summarized in Table I. The showers are divided into three energy groups. Shower energies were calculated according to Eq. (5). Such a procedure is rather arbitrary, since Eq. (5) corresponds to the case of nucleon-nucleon collisions. Energies of nucleon-produced showers, calculated according to Eq. (5′) are shown in Fig. 4. The value of γ_c in Eq. (5′) was found under the assumption that the angular distribution of shower particles in the c.m.s. is, as in the case of nucleon-nucleon collisions, symmetrical with respect to $\theta_{cm} = \pi/2$ (the Belen'kii-Landau theory). It follows, however, from the experimental results of the present work that such an assumption does not conform to reality. It is therefore not clear which method of energy determination is advisable. In the following, dealing with energy dependence of various characteristics of explosion showers, we shall use for that purpose Eq. (5), although the resulting absolute energy values are evidently too low. The nature of primary particles is given in the second column of the table. Singly-charged particles were assumed to be protons, and the neutral ones — neutrons. The number of black and grey tracks ($n_h + n_g$) and the number of shower particles (n_s) are given in the third and fourth columns respectively; the values of γ_c calculated according to Eqs. (1) and (2) and from the condition $\ln[F/(1-F)] = 0$, and also the mean values $\bar{\gamma}_c$ calculated using the above methods are given in columns 6 — 9. k is the coefficient of inelasticity given by the equation[4]

$$k = 1{,}5 n_s \gamma_c \sin \vartheta_{\max} / 2\mu (\gamma_c - 1), \qquad (6)$$

where ϑ_{max} is the maximum angle between a shower particle and shower axis, and μ is the ratio of the nucleon mass to the π-meson mass. The tunnel length ℓ is a function of γ_c and n_s, according to the relation $n_s = f(\gamma_c, \ell)$ from the statistical theory of multiple particle production. For large γ_c (> 10) the relation is of the form*

$$n_s = 0.9 l^{3/4} (1 + l)^{1/4} \sqrt{\gamma_c} + \frac{l+1}{2}, \qquad (7)$$

where the coefficient 0.9 is chosen for fit with curves for small values of γ_c, obtained from statistical weight calculations.

A. Angular Distributions of Shower Particles in the C.M.S.

The direction of motion of a relativistic particle in the laboratory system is connected with the direction of motion in the c.m.s. by the following relation:

$$\cot \vartheta = \gamma_c \frac{\cos\theta + (\beta_c/\beta)}{\sin\theta}, \qquad (8)$$

where β_c is the velocity of the c.m.s. and β is the particle velocity in the c.m.s. In the extreme relativistic case, $\beta_c \approx \beta \approx 1$, i.e.,

$$\cot \vartheta = \gamma_c \frac{\cos\theta + 1}{\sin\theta} = \gamma_c \cot(\theta/2). \qquad (8')$$

*Results of calculations of statistical weights, and formula (7), were kindly communicated by D. S. Chernavskii.

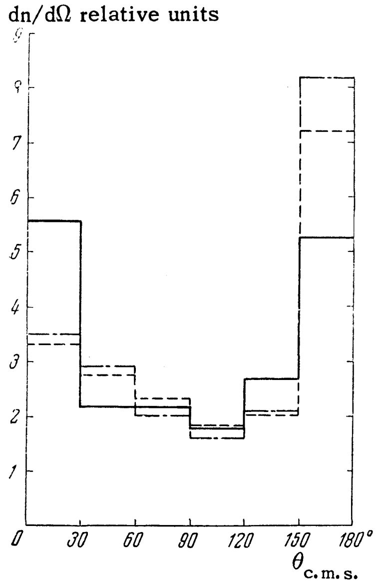

Fig. 3. Angular distributions of shower particles in c.m.s. Solid line – $E_0 = 10^{10} - 10^{11}$ ev, dashed – $E_0 = 10^{11} - 10^{12}$ ev, dot-dash – $E_0 = 10^{12} - 10^{14}$ ev. All distributions pertain to nucleon-produced showers.

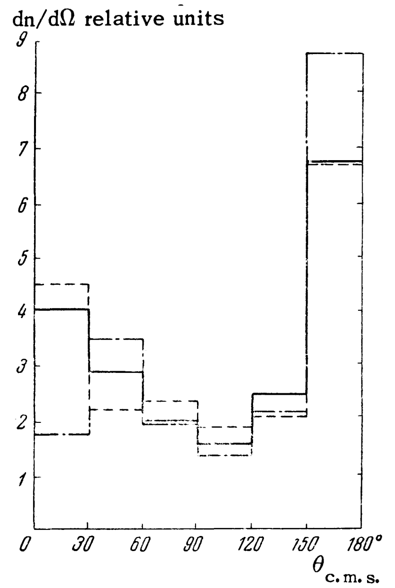

Fig. 4. Angular distributions of shower particles in c.m.s. for nucleon-produced showers. Shower energy calculated according to Eq. (5′). Solid line – E = $10^{11} - 10^{12}$ ev, dashed – E = $10^{12} - 10^{13}$ ev, dot-dash – E = $10^{13} - 10^{14}$ ev.

TABLE II. Angular distribution of particles in c.m.s., in nucleon-produced showers, for three regions of energy E_0 calculated under the assumption of a nucleon-nucleon collision [Eq. (5)].

E_0, ev \ $\theta_{c.m.s.}$		0–30°	30–60°	60–90°	90–120°	120–150°	150–180°	$N\ (\theta<90°)$	$N\ (\theta>90°)$
10^{10}–10^{11}	N	34	38	50	42	48	31	122	121
	$dN/d\Omega$	5.4 ±0.92	2.21±0.35	2.13±0.30	1.79±0.27	2.79±0.39	4.92±0.91		
10^{11}–10^{12}	N	34	77	91	67	57	75	202	199
	$dN/d\Omega$	3.28±0.56	2.72±0.3	2.35±0.24	1.73±0.2	2.01±0.26	7.22±0.83		
10^{12}–10^{14}	N	19	43	41	33	31	45	103	109
	$dN/d\Omega$	3.47±0.8	2.87±0.44	2.00±0.31	1.61±0.28	2.07±0.37	8.19±1.2		

TABLE III. Angular distribution of particles in c.m.s., in showers produced by particles with Z ≥ 2.

E_0, ev \ $\theta_{c.m.s.}$		0–30°	30–60°	60–90°	90–120°	120–150°	150–180°	$N\ (\theta<90°)$	$N\ (\theta>90°)$
10^{10}–10^{11}	N	47	103	117	107	100	59	267	266
	$dN/d\Omega$	3.4 ±0.5	2.73±0.27	2.28±0.21	2.0 ±0.2	2.66±0.27	4.29±0.56		
10^{11}–10^{14}	N	18	35	30	34	26	25	83	85
	$dN/d\Omega$	4.13±0.97	2.94±0.50	1.85±0.34	2.09±0.36	2.19±0.43	5.75±1.2		

The angular distribution function $f(\theta)$ in the c.m.s. was found for each shower using Eq. (8′). To obtain better statistical results, summary distributions were constructed for showers of various energy regions. These distributions are given in Tables II, III, and IV and in Figs. 3 and 4. The errors given in the tables represent statistical deviations $\sqrt{N_i}$, where N_i is the number of particles within a given angle interval $\Delta\theta_{c.m.}$. The total number of particles propagating in the forward and

TABLE IV. Angular distribution of particles in c.m.s., in nucleon-produced showers, for three regions of energy E calculated for tunnel-effect interaction [Eq. (5′)].

E, ev \ $\theta_{c.m.s.}$		0–30°	30–60°	60–90°	90–120°	120–150°	150–180°	$N\ (\theta<90°)$	$N\ (\theta>90°)$
$10^{11}-10^{12}$	N	32	63	59	45	54	53	154	152
	$dN/d\Omega$	4.05 ± 0.71	2.92 ± 0.36	2.0 ± 0.26	1.54 ± 0.23	2.5 ± 0.34	6.7 ± 0.91		
$10^{12}-10^{13}$	N	45	60	88	71	56	67	193	194
	$dN/d\Omega$	4.5 ± 0.67	2.2 ± 0.28	2.35 ± 0.25	1.9 ± 0.22	2.05 ± 0.27	6.7 ± 0.81		
$10^{13}-10^{14}$	N	6	32	25	17	20	29	63	66
	$dN/d\Omega$	1.79 ± 0.73	3.5 ± 0.62	2.0 ± 0.4	1.36 ± 0.33	2.2 ± 0.49	8.7 ± 1.61		

backward directions [$N(\vartheta < 90°)$ and $N(\vartheta > 90°)$] is the same for showers with even number of particles and differs by one in showers with odd n_s. The number of particles per steradian in relative units $dN/d\Omega \sim N/\sin\bar{\theta}$, where $\bar{\theta}$ is the mean angle of a given interval $\Delta\theta$ is shown in the figures.

It can be seen from Tables II and III that $f(\theta)$ is substantially anisotropic and for showers generated by nucleons of $10^{11}-10^{13}$ ev asymmetric with respect to the direction $\theta = \pi/2$. The angular distributions (in the c.m.s.) given in the tables were obtained by means of Eq. (8′), γ_c being defined as $\gamma_c = \cot\vartheta_{1/2}$. For such definition of γ_c the number of particles in angle intervals $0-\pi/2$ and $\pi/2-\pi$ was assumed to be equal. It follows therefore, from the asymmetry of the angular distribution for the above definition of γ_c, that $f(\theta)$ cannot be made symmetric for any value of γ_c. It is interesting to note that this asymmetry is absent for showers with $E_0 = 10^{10}-10^{11}$ ev, and is less marked for showers generated by heavy particles, although the latter conclusion is not sufficiently founded, in view of the small number of observed cases in the region $10^{11}-10^{1}$ ev. An analogous conclusion about the asymmetry with respect to $\theta = \pi/2$ can be drawn dividing the showers according to energy E (cf. Table IV and Fig. 4). One would expect the observed asymmetry to be caused by secondary interactions of shower particles with nucleons in the nucleus. In the same way, one could explain the fact that the inelasticity coefficients k calculated according to Eq. (6) were found in most cases to be larger than unity. Under this assumption one would expect the asymmetry about $\theta = \pi/2$ to decrease for showers with smaller values of $n_h + n_g$ and with $k < 1$. It follows from Table V, however, that the asymmetry of the angular distribution does not exhibit the expected behavior. This fact indicates that secondary interactions are not responsible for the asymmetric angular distribution of shower particles about $\theta = \pi/2$.

The observed asymmetry could be also due to shower production as the result of several collisions of the primary with nucleons of the nucleus. It is evident that the asymmetry should then increase with the number of shower particles. The results of the experiment, however, contradict this explanation. It can be seen from Table VI that $dN/d\theta$ is independent of the number of particles in the shower n_s. It must be concluded that the asymmetry of $f(\theta)$ with respect to $\theta = \pi/2$ is not due to secondary processes, but is inherent in the process of shower production. This result contradicts the hydrodynamical theory of shower production in head-on collisions, which predicts a symmetrical angular distribution of shower particles about the direction $\pi/2$ in the c.m.s. [cf. Eq. (4)].

D. S. Chernavskii (private communication) proposed a possible explanation of the observed aymmetry of angular distribution in explosion showers, indicating that a part of the shower particles can be produced in interaction between nuclear matter and the π-meson cloud of the incident nucleon. These particles can be associated with additional tunnels in the same nucleus which are characterized by a different value of γ_c (since the mass of a π meson is less than that of a nucleon). It can be easily seen that such mechanism leads to the excess of shower particles propagating backwards in the c.m.s.

Mean values of the angle $\vartheta_{1/2}$, denoted by $\bar{\vartheta}_{1/2}$, for showers with various number of particles n_s and different $n_h + n_g$ are given in Table VII. It can be seen that the mean angle of emission of shower particles does not depend markedly on the above parameter. In other words, possible secondary interactions of shower particles with nucle-

TABLE V. Distribution of shower particles in c.m.s., $dN/d\theta$, for showers with various k and ($n_h + n_g$). Data refer to the total number of shower particles within a given interval $\Delta\theta$ ($E_0 = 10^{11} - 10^{14}$ ev).

Condition \ θ	0–30°	30–60°	60–90°	90–120°	120–150°	150–180°
$k>1$	51	88	98	77	67	93
$k<1$	2	32	32	23	21	27
$k<0.4$	1	4	12	6	6	4
$n_h+n_g\leqslant 3$ ($\bar{k}=1.9$)	10	23	40	25	30	21
$n_h+n_g<3$ $k<1$	0	3	9	5	6	3

TABLE VI. Distribution of shower particles in c.m.s., for showers with different n_s. $\bar{n}_s$ denotes the mean value of n_s for a given energy region. Data refer to the total number of shower particles within a given interval $\Delta\theta$.

Δθ		0–30°	30–60°	60–90°	90–120°	120–150°	150–180°
$E_0=10^{10}$–10^{11} ev, $\bar{n}_s=18$	$n_s<\bar{n}_s$	5	9	21	18	10	7
	$n_s>\bar{n}_s$	29	28	25	19	34	25
$E_0=10^{11}$–10^{12} ev, $\bar{n}_s=19$	$n_s<\bar{n}_s$	13	33	32	24	21	35
	$n_s>\bar{n}_s$	21	44	57	45	36	40
$E_0=10^{12}$–10^{14} ev, $\bar{n}_s=24$	$n_s<\bar{n}_s$	3	10	13	11	7	10
	$n_s>\bar{n}_s$	16	33	28	22	24	35
$E_0=10^{11}$–10^{14} ev, $\bar{n}_s=21$	$n_s<\bar{n}_s$ $k<1$	1	19	24	18	17	15

TABLE VII. Mean values of the angles of emission of shower particles $\bar{\vartheta}_{1/2}$

E_0, ev	$\bar{n}_s$	$\bar{\vartheta}_{1/2}$	$\overline{\vartheta_{1/2}\,(n_s<\bar{n}_s)}$	$\overline{\vartheta_{1/2}\,(n_s>\bar{n}_s)}$	$\overline{\vartheta_{1/2}\,(n_h+n_g\leqslant 3)}$	$\overline{\vartheta_{1/2}\,(n_h+n_g>3)}$
10^{10}–10^{11}	17.7	15.3	16.5	14.3	—	—
10^{11}–10^{12}	19.4	5.34	5.12	5.63	5.48	5.29
10^{12}–10^{14}	23.8	1.45	1.30	1.56	1.51	1.43
10^{11}–10^{14}	20.7	4.17	4.04	4.35	4.48	4.06

ons of the nucleus do not change appreciably the value of $\vartheta_{1/2}$.

The anisotropy of the angular distribution of shower particles in the c.m.s. can be characterized by the value Δ defined as follows:

$$\Delta = \left[\sum_i (\bar{\lambda} - \lambda_i)^2 n_i \Big/ \sum n_i\right]^{1/2}, \qquad (9)$$

where $\lambda_i = \ln \tan \vartheta_i$, $\bar{\lambda} = \overline{\ln \tan \vartheta_i} = \ln \gamma_c$, and n_i is the number of shower particles in the i-th interval of the variable λ. It is evident that large values of Δ correspond to a larger measure of anisotropy in the angular distribution $f(\theta)$ i.e., to greater emission probability of shower particles at angles close to $\theta = 0$ and $\theta = \pi$ in the c.m.s. It can be easily shown that for a distribution isotropic in the c.m.s. $\Delta_{is} = 0.3$. Table VIII illustrates the variation of Δ for showers with different values of n_s and $n_h + n_g$.

Mean values of Δ for various energy regions calculated according to the hydrodynamical theory of Belen'kii and Landau from distribution (4), $\bar{\Delta}_{theor}$, are also given in the table. In calculating Δ_{theor} it was taken into account that the mean tunnel length for nuclei of the emulsion is $\ell = 3.25$. In addition to Δ_{exp} calculated according to Eq. (9),

TABLE VIII. Mean values of Δ and $\Delta(\lambda < \bar{\lambda})$ [cf. Eq. (9)] for showers of various energies.

E_0, ev	n_s, n_h+n_g	$\bar{\Delta}_{\text{exptl.}}$	$\bar{\Delta}_{\text{exptl.}}$ $(\lambda<\bar{\lambda})$	$\bar{\Delta}_{\text{theoret.}}$
10^{11}—10^{12}	$n_s<\bar{n}_s$	0.52	0.42	0.48
	$n_s>\bar{n}_s$	0.54	0.48	0.47
	$n_h+n_g\leqslant 3$	0.45	0.33	0.47
	$n_h+n_g>3$	0.56	0.49	0.48
10^{12}—10^{14}	$n_s<\bar{n}_s$	0.63	0.50	0.72
	$n_s>\bar{n}_s$	0.73	0.66	0.65
	$n_h+n_g\leqslant 3$	0.39	0.38	0.66
	$n_h+n_g>3$	0.77	0.64	0.69
10^{11}—10^{14}	$n_s<\bar{n}_s$	0.54	0.43	0.55
	$n_s>\bar{n}_s$	0.62	0.56	0.53
	$n_h+n_g\leqslant 3$	0.44	0.34	0.52
	$n_h+n_g>3$	0.62	0.54	0.55
	$n_s<\bar{n}_s$ $n_h+n_g\leqslant 3$		0.32	

values of $\Delta(\lambda < \bar{\lambda})$ calculated according to the same formula for values $\lambda < \bar{\lambda}$ are given in Table VIII. These values correspond to small angles of emission of shower particles (if the assumption of a symmetrical distribution of shower particles in the c.m.s. about $\theta = \pi/2$ were correct, then the values $\lambda < \bar{\lambda}$ would correspond to angles of emission $\theta < 90°$ in the c.m.s.). It can be maintained that $\Delta(\lambda < \bar{\lambda})$ characterizes better the anisotropy of the angular distribution of shower particles produced in the primary interaction, since Δ calculated according to Eq. (9), taking into account all values of λ, may be in error due to secondary interactions of shower particles with nucleons of the nucleus.

It can be seen from Table VIII that the anisotropy increases considerably with increasing n_s and, especially, $n_h + n_g$. This cannot be explained by secondary interactions of shower particles, since the increase in $\bar{\Delta}$ with n_s and $n_h + n_g$ should influence $\Delta(\lambda < \bar{\lambda})$ to a larger extent than Δ, calculated for all values of λ.

If we assume that a large value of $n_h + n_g$ indicates, on the average, that the primary particle traversed the center of the nucleus, then it follows from the above results that the anisotropy of shower particles increases with tunnel length ℓ. This result contradicts the predictions of the hydrodynamical theory — a decrease in Δ with increasing ℓ.

B. Inelasticity Coefficient

As it has been shown above [cf. Eq. (6)], data on the angular distribution of shower particles make it possible to calculate the inelasticity coefficient k. The values of k for the observed showers are given in Table I. It should be noted, however, that in defining k in the above manner it is assumed that all particles have the same energy. Since it is very probable that this is not the case, the resulting inelasticity coefficients are only approximate. Since k depends strongly on the maximum angle of emission of shower particles, it can be considerably influenced by secondary interactions of shower particles with nucleons of the nucleus. In the calculation of k according to Eq. (6), it is assumed that showers originate in nucleon-nucleon collisions. For collisions between a nucleon and the nuclear matter of the tunnel, Eq. (6) should be modified by introducing the tunnel length ℓ into the denominator. This would cause a considerable decrease in the values of k. All these factors render the determination of k from Eq. (6) unsatisfactory.

The inelasticity coefficient should, according to its definition, be always less than one. It can be seen from Table I that this is not so for calculations based upon Eq. (6). This fact, as it has been mentioned above, is evidently due to the assumptions made in deriving Eq. (6) and to the influence of secondary interactions of shower particles.

The abnormally high values of k for showers generated by heavy particles are clearly connected with the fact that in those events showers originate in interactions between several pairs of nucleons.

C. Azimuthal Asymmetry of Shower Particles

A marked asymmetry of shower particles with respect to the azimuth φ has been observed for several showers. The values of P_6, given in the

TABLE IX. Mean numbers of shower particles in nucleon-produced showers

E_0, ev	$\bar{\vartheta}_{1/2}$	$\bar{n}_s$	$\bar{n}_s(n_h+n_g<3)$	$\bar{n}_s(n_h+n_g>3)$	$n_s(\vartheta_{1/2}<\bar{\vartheta}_{1/2})$	$n_s(\overline{\vartheta_{1/2}>\bar{\vartheta}_{1/2}})$	$\delta(\bar{n}_s)$	$\delta(n_h+n_g<3)$	$\delta(\vartheta_{1/2}<\bar{\vartheta}_{1/2})$
10^{10}—10^{11}	15.3	17.7	—	17.7	19.0	16.6	6.1		7.2
10^{11}—10^{12}	5.34	19.4	16.3	20.6	15.3	21.9	8.2		5.3
10^{12}—10^{14}	1.45	23.8	26.0	23.1	26.2	20.8	11.2		13.4
10^{11}—10^{14}	4.17	20.7	18.8	21.4	20.5	20.9	9.2	12.1	10.1

thirteenth column of Table I, represent the Pearson probabilities that a given value of asymmetry in the distribution $f(\varphi)$ will be observed in a given shower, under the assumption that the asymmetry is due to statistical fluctuations. The values $P_6(\chi^2)$ were determined from tables for various values of χ^2 which were found from the formula

$$\chi^2 = \frac{m}{n_s}\left(\sum_{i=1} n_i^2\right) - n_s, \tag{10}$$

where n_s is the total number of shower particles in a shower, m is the number of intervals of angle φ, and n_i is the number of shower particles in the i-th interval $\Delta\varphi$. The values P_6 given in Table I are calculated for $m = 6$. It should be mentioned that cases of large asymmetry were observed both for showers produced by nucleons and by heavy particles. The results on azimuthal asymmetry are, of course, preliminary and a considerable increase in the number of observed cases is necessary for a final conclusion about the existence of such asymmetry.

D. Relation Between the Number of Shower Particles and the Shower Energy

The mean number of shower particles in nucleon-generated showers of various energy regions are given in Table IX. The values of δ, defined below, are also given in the table.

$$\delta = \left\{\sum_i (\bar{n}_s - n_{si})^2 \Big/ \left[\left(\sum_i n_{si}\right) - 1\right]\right\}^{1/2} \tag{11}$$

δ determines the mean spread in the number of shower particles for individual showers.

It can be seen from Table IX that the number of shower particles n_s depends very little on the angle $\vartheta_{1/2}$. It follows that if the determination of shower energy from the angular distribution of shower particles, by the method described in Sec. 2, yields a correct answer for E_0, then the experimental dependence obtained, $n_s = f(E_0)$, is substantially different from the theoretical prediction* $(\bar{n}_s)_{theor} \sim \sqrt[4]{E_0}$. Table IX illustrates also the weak dependence of $\bar{n}_s$ on $\vartheta_{1/2}$ and on the number of black and grey tracks associated with the shower. This fact indicates that secondary interactions of shower particles with nucleons of the nucleus do not influence greatly the shower production mechanism. It should be noted that the relation $n_s \sim \sqrt[4]{E}$ follows from sufficiently general considerations, and the discrepancy between the experimental and theoretical expressions for $n_s = f(E_0)$ can be regarded, together with the asymmetry of angular distribution (cf. Subsec. A) as a proof against the nucleon-nucleon theory of shower production.

Shower energies calculated under the assumption of interaction between the incident nucleon and nucleons of the tunnel are given in column 14 of Table I. Mean lengths $\bar{l}$ of the tunnel calculated under that assumption for various energy regions are given in Table X. The mean number of shower particles is also given in the table for different energies of the primary particles.

Were the tunnel-effect model of shower production correct, $\bar{l}$ would be the same for all energy regions and equal to the mean tunnel length for emulsion, $\bar{l}_{em} = 3.25$. It can be seen from Table X that $\bar{l}$ does not remain constant for showers of different energies. The small number of observed events, however, does not permit us to draw final conclusions. The difference between the absolute

TABLE X. Mean tunnel lengths for various energies of primary particles.

ΔE, ev	$\bar{E}$, ev	No. of showers	$\bar{n}_s$	$\bar{l}$
10^{11}—10^{12}	$3.7\cdot10^{11}$	18	17.2	6.1
10^{12}—10^{13}	$2.5\cdot10^{12}$	18	21.7	5.5
10^{13}—10^{14}	$3.4\cdot10^{13}$	5	26.0	3.7

*Cf. Ref. 3, for example.

TABLE XI. Angular distributions of shower particles in c.m.s. calculated according to Eq. (8′). Data refer to the number of shower particles within given intervals $\Delta\theta$.

No.	Primary particle	0–30°	30–60°	60–90°	90–120°	120–150°	150–180°
			$E_0=10^{10}$–10^{11} ev				
1	p	8	3	1	2	3	6
2	p	6	4	2	1	5	6
3	p	0	2	2	3	1	0
4	n	2	2	3	4	2	0
5	p	0	2	5	4	2	1
6	p	1	1	2	1	1	2
7	p	0	2	4	2	3	1
8	n	2	7	3	3	5	3
9	p	4	6	3	4	5	3
10	n	2	0	5	4	1	3
11	n	2	3	5	3	6	2
12	n or p	3	3	5	2	7	1
13	p	3	3	5	5	4	2
14	α	2	10	5	7	4	6
15	α	6	12	3	8	10	3
16	α	5	5	8	6	5	7
17	α	1	3	5	3	3	2
18	Z	3	13	27	19	16	8
19	α	1	5	4	4	3	3
20	α	3	11	7	9	5	7
21	α	3	7	7	4	10	3
22	Z	8	17	10	16	14	6
23	α	2	2	9	5	6	2
24	α	2	4	2	1	4	3
25	α	2	0	12	6	6	1
26	Z	3	7	10	10	5	6
27	α	3	2	2	1	4	1
28	α	3	5	6	8	5	1
			$E_0=10^{11}$–10^{12} ev				
1	p	3	2	7	5	2	4
2	p	0	5	2	4	0	4
3	p	0	3	4	2	4	1
4	p	4	2	2	3	3	3
5	p	0	6	2	1	1	6
6	p	0	5	7	3	5	4
7	p	0	4	3	2	3	2
8	p	4	2	3	1	1	8
9	p	1	3	11	4	6	4
10	p	1	4	1	2	1	3
11	p	4	6	5	7	2	5
12	n	1	8	2	2	4	6
13	p	0	1	2	2	1	1
14	n	0	1	2	1	0	1
15	p	0	9	8	13	1	4
16	n	6	5	5	2	8	5
17	p	2	1	7	3	3	4
18	n	0	0	5	1	3	1
19	p	4	2	4	3	4	2
20	p	4	5	6	5	5	4
21	p	0	3	3	1	0	4
22	Z	0	6	5	3	6	2
23	α	2	4	7	4	6	4
24	α	1	8	5	10	2	3
25	Z	9	11	9	12	7	9
			$E_0=10^{12}$–10^{13} ev				
1	n	2	9	6	3	2	12
2	p	8	3	2	3	5	6
3	p	0	2	2	2	2	1
4	p	3	2	8	6	3	5
5	p	1	9	3	3	4	7
6	p	2	4	4	5	1	4
7	p	2	10	9	7	10	5
8	α	6	6	4	5	5	7
			$E_0=10^{13}$–10^{14} ev				
1	p	1	1	5	1	3	4
2	p	0	3	2	3	1	1

value of $\overline{l}$ and $\overline{l}_{em}$ does not contradict the theory, since the theoretical relation $n_s = f(\overline{l}, \gamma_c)$ includes a constant, which has to be determined experimentally.

The values of δ given in Table IX show that the spread in n_s for individual showers is considerably greater than statistical fluctuations $\delta_{fluct} \approx \sqrt{\overline{n}_s}$. A large value of δ can be explained by shower production in interactions of the primary nucleon with tunnels of different lengths.

The number of shower particles in showers generated by particles with $Z \geq 2$ is considerably greater than $\overline{n}_s$ in nucleon-produced showers. This can be explained by assuming that in the former case shower production is due to interaction between several nucleons and the nucleus.

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APPENDIX

Since valid conclusions about showers produced by high-energy cosmic ray particles can be drawn only on the basis of a large statistical material, the authors have thought it useful, for reference purposes, to include data on the angular distribution of shower particles, in the c.m.s., for each observed event. Angular distributions in the c.m.s. were calculated from data on the distribution in the laboratory system according to Eq. (8′), γ_c being determined from the relation $\gamma_c = \cot \vartheta_{1/2}$. The numeration of showers in Table XI corresponds to that of Table I.

It should be noted that for several showers the values n_s given in Table I are slightly larger than the total number of shower particles in Table XI. This is due to the fact that some particles propagate at an angle $\vartheta > 90°$ in the laboratory system, and have not been considered in calculations of the angular distribution according to Eq. (8′).

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ASYMMETRY IN THE ANGULAR DISTRIBUTION OF $\mu^+ \to e^+$ *DECAY ELECTRONS OBSERVED IN PHOTOGRAPHIC EMULSIONS*

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Herewith are presented the results of measurements of the angular distribution of $\pi \to \mu \to e$ decay electrons observed in a photographic emulsion located either inside a magnetic screen or in a magnetic field $H \sim 1100$ G, longitudinal with respect to the μ-meson motion. The electron angular distributions were found to be describable by a relation of the form $1 + a \cos \theta$. The parameter a was found to be equal to $-(0.092 \pm 0.018)$ and $-(0.16 \pm 0.04)$ for the cases when the emulsion was inside the magnetic screen and the magnetic field respectively.

In the fundamental work of Lee and Yang[1] and Landau,[2] it was shown that a possible method for testing parity nonconservation in weak interactions is to study the asymmetry in the angular distribution of the electrons emitted in the decay of polarized μ mesons. The two-component neutrino theory, developed by the same authors, leads to the conclusion that the μ meson formed in the $\pi \to \mu$ decay should be fully polarized in the direction of its motion. According to this theory, the electron angular distribution from the $\mu \to e$ decay is described by the relation

$$f(\theta) = 1 + (\lambda / 3) \cos \theta, \qquad (1)$$

where θ is the angle between the electron momentum and the μ-meson spin. The constant λ depends on the relative amount of vector and axial vector coupling in the β decay of the μ meson and can vary between -1 and $+1$.

The first experimental confirmation of parity nonconservation in the $\pi \to \mu \to e$ chain came from Garwin et al.[3] Thereafter a rather large number of papers appeared devoted to a more accurate determination of the constant λ, using photoemulsions, counters and bubble chambers. It was established in these experiments that in the $\mu^+ \to e^+$ decay the positrons are emitted predominantly backwards, i.e., $\lambda < 0$. It also follows from these experiments that the asymmetry in the angular distribution of electrons from $\mu \to e$ decay depends sensitively on the substance in which the μ meson decays. This indicates the existence of a partial depolarization of the μ mesons and consequently the electron angular distribution from the $\mu \to e$ decay may be written in the form

$$1 + a \cos \theta, \quad a = (\lambda / 3)(1 - \gamma), \qquad (2)$$

where γ is the depolarization coefficient of the μ mesons. The experimentally obtained angular distributions of electrons from $\mu \to e$ decay agree qualitatively with formula (2) throughout the electron energy spectrum. However, more definite quantitative conclusions can be reached only by substantially increasing the statistical accuracy.

In this work we studied the angular distribution of $\mu^+ \to e^+$ decay electrons in emulsions. A 7×4×1 cm emulsion chamber consisting of 23 layers of NIKFI type R photoemulsion was irradiated with