An Analysis of Some Cosmic Ray Meson–Production Events. II.

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Three cases of meson production by cosmic rays are described. In each one, the momentum of the primary particle was measured by a magnetic method using two cloud chambers. The analysis confirms the existence of a large spread in the number of secondary particles and in the energy carried away by π-mesons.

BOTH cloud chamber and emulsion techniques have been used to study the interaction between cosmic ray particles and nuclei. Up to now, the energy of the primary particles has been measured indirectly through the angles in which the secondary particles were emitted. This method can lead to appreciable errors, especially for complex nuclei, since the errors increase with increasing mass of the target nucleus. It would be interesting to measure the energy of the primary particle directly. In order to do this, we modified our previously described apparatus[2] * by adding a second cloud chamber as shown in Fig. 1. The work was carried out during the winter of 1955–1956. For the second cloud chamber, d= 30 cm, and the illuminated region was 10 cm deep. After passing through the upper cloud chamber, charged particles are deflected by the field of the electromagnet (whose strength was about 10^4 Oe) and are then detected above the Be slab in the lower cloud chamber. If the particle initiates a shower in the beryllium slab (thickness 9.2 gm/cm^2), then the origin of the shower can be found by projecting the tracks of the secondary particles backwards. The displacement between the point where the shower started and the direction of the primary particle, as found from the track in the upper chamber, determined the momentum and charge of the primary. The relative orientation of the two chambers was adjusted by using mesons of the hard component, which had energies more than 5 bev, The same pictures were used to find the largest momentum we could measure with the two camera method. In our case, p_{max} turned out to be 50 bev/c.

It should be noted, however, that the use of two cloud chambers decreased the sensitivity of the apparatus considerably. We here able to obtain only four pictures for which the momentum of the primary could be obtained and which showed more

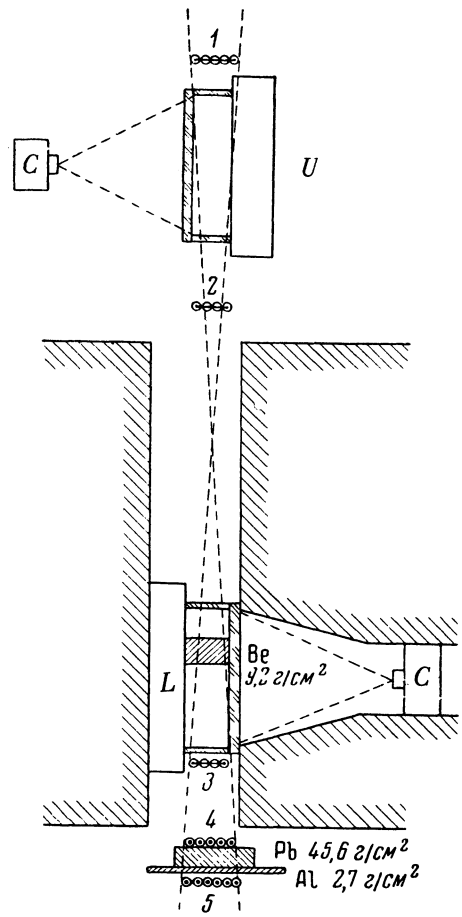

FIG. 1. Schematic drawing of apparatus. U—upper cloud chamber, L—lower cloud chamber, C—picture taking equipment.

than four charged particles. The characteristics of the showers are summarized in the Table. In three of the showers it was possible to both find

*Denoted in the following by I.

out how the energy of the primary particle was distributed among the secondary ones, and also the angular distribution of the particles in the center-of-mass system. This assumes that the generating particle interacted with only one nucleon in the beryllium nucleus. Since, for energies up to about 5 bev, the meson production cross section for nucleon-nucleon and nucleon–π–meson collisions is about $1/2\,\sigma_{\text{geometric}}$ of the nucleon[3], this assumption seems to be justified.

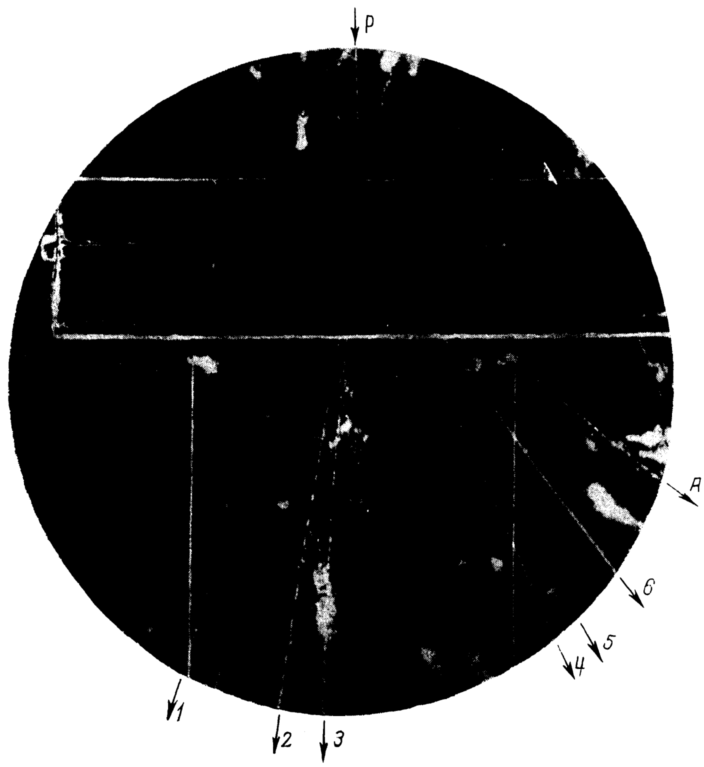

FIG. 2. Shower No. 27.16, initiated by a primary particle which made a track in the upper cloud chamber U, then stopped in the beryllium slab placed in the lower cloud chamber L. Particle A does not go through the origin of the shower.

Shower No. 27.16: This shower is illustrated in Fig. 2. Since there was no more than 8 gm/cm^2 of material above the apparatus, the (positive) incident particle is probably a proton. Energy and momentum are conserved if we assume that a nucleon-nucleon collision occurs, and that a neutron carried away 2.3 bev/c of momentum in some direction making a small angle with the primary direction. The reaction is then $p + p \rightarrow 3\pi^+ + 2\pi^- + p + n$.

Charge conservation eliminates a p–n interaction.

It should be noted that the angle of emission and the momentum of the proton in the laboratory frame, as computed using Eqs. (4) and (5) in I, agree well with experiment.* Thus,

$$\theta_{L\,\text{calc.}} < 38°;\quad \theta_{L\,\text{obs.}} = 23°;$$

$$4\times10^8 < p_{L\,\text{calc.}} < 8\times10^8 \text{ ev}/c;$$

$$p_{L\,\text{obs.}} = 5\times10^8 \text{ ev}/c.$$

The emission angles and momenta, in the center-of-mass system, for the particles in this reaction are given in Table I, while the angular distribution is shown in Fig. 3. From this Figure we see that the particles are emitted almost isotropically in the center-of-mass system. Consideration of the energy balance shows that almost all the kinetic energy of the primary proton was used up in creating π-mesons. The fast nucleons take away only a fairly small fraction (about 43%) of the total primary energy. Reference 4 describes a similar

*In the following, a subscript L indicates the laboratory and C the center-of-mass reference frames.

Picture number	Particle number	sign	Ionization	Momentum, in laboratory coordinates $p \times 10^{-8}$ ev/c	Angle of emission relative to the primary. Lab. coord. $\theta^{\circ}{}_L$	Momentum in the center-of-mass system. $P_c \times 10^{-8}$ ev/c	Total energy in the center-of-mass system $E_c \times 10^{-8}$ ev/c	Angle of emission relative to the primary.c.o.m.coord. $\theta^{\circ}{}_c$	Kind of particle
I	II	III	IV	V	VI	VII	VIII	IX	X
27.16	primary	+	~ 1 *min.*	56 ± 6	—	15,4	18	—	proton
	1	+	~ 1 *min.*	$2,8^{+0.8}_{-0.4}$	28	1.4	2	104	π-meson
	2	?	~ 1 *min.*	>13	15	4.3	4,5	52	π-meson (from conservation laws)
	3	+	~ 1 *min.*	$2^{+0,3}_{-0.2}$	20	1,0	1.6	111	π-meson
	4	+	~ 1 *min.*	11^{+7}_{-3}	22	4.4	4,5	67	π-meson (from conservation laws)
	5	?	~ 1 *min.*	—	23	—	—	—	(π?)
	6	+	~ 5 *min.*	$3,0^{+0,3}_{-0.2}$ taking the range in Be into account $p = 5.0 \cdot 10^8 \frac{ev}{c}$	28	9	13	165	proton

68.18	primary	—	~ 1 *min.*	~65	—	17	17	—	π-meson
	1	—	~ 1 *min.*	—	34	—	—	—	π-meson
	2	—	~ 1 *min.*	1,5±0,2	17	1.1	1,8	149	π-meson
	3	?	~ 1 *min.*	>25	11	7	7,1	41	(π?)
	4	+	~ 1 *min.*	$2,7^{+0,4}_{-0,3}$	9	0.4	1.5	83	π-meson
	5	+	~ 8 *min.*	$2,5^{+0,4}_{-0,21}$ taking the range in Be into account $p = 3,8 \cdot 10^8 \frac{\text{ev}}{c}$	22	10	13.7	172	proton
6.116	primary	?	~ 1 *min.*	>540	—	>50	>51	—	(proton?)
	1	+	~ 1 *min.*	11^{+4}_{-2}	10	2	2.4	107	(π?)
	2	+	~ 1 *min.*	$5^{+1}_{-0,5}$	2	0,5	1,5	169	π-meson
	3	—	~ 1 *min.*	$9,5^{+3}_{-2}$	2	0,6	1.5	39	π-meson
	4	?	~ 1 *min.*	⩾38	8	>4,5	4,7	70	(π?)
	5	+	~ 1 *min.*	$5^{+1}_{-0,5}$	15	2	2.4	135	π-meson

shower, in which an n–p interaction ($E_0 = 5.6$ bev) produced 5 π-mesons. In this case, the π-mesons carried away 70% of the kinetic energy of the primary nucleon, while $\epsilon < 0.52$.

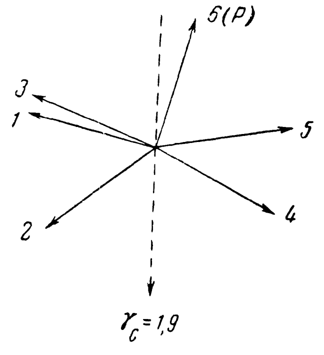

FIG. 3. Angular distribution (in the center-of-mass system) for the particles in shower No. 27.16.

Shower No. 68.18: in this case the primary particle is negative and is presumably a π–meson formed in the graphite layer above the apparatus. Its energy was about 6.5 bev. The analysis of this case is less clear–cut than the previous one because the momenta of the primary and secondary particles are less well known. The shower apparently was produced by the reaction $\pi^- + n \to 2\pi^+ + 3\pi^- + p + m\pi^0$, where m is the number of neutral π-mesons.

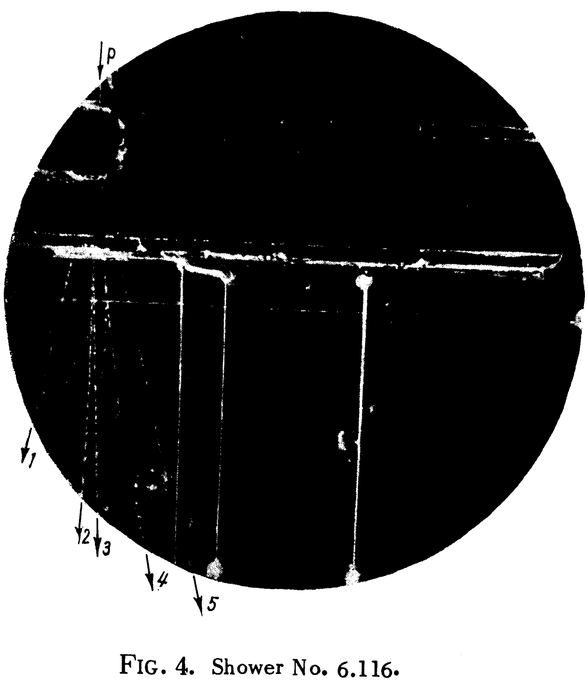

FIG. 4. Shower No. 6.116.

As in the previous case, particles are emitted symmetrically in the center-of-mass system. It is interesting to note that in contrast to the shower first described, a large part of the energy is concentrated not on the nucleons but on particle No.3 (Table I), which appears to be a π-meson. This particle was emitted at 11° to the direction of the primary and carried more than 40% of the primary energy.

Shower No. 6.116 (Fig. 4): The momentum of the primary particle was $\gtrsim 54$ bev/c. Inasmuch as this particle, with such a large momentum, was not accompanied by another charged particle in the upper chamber, it was probably a proton. Calculations based on Eqs. (4) and (5) of I show that neither particle *1* nor particle *4* (Table I) can be protons. Assuming this, either of the following reactions could account for the process:

$$p + n \to 3\pi^+ + 2\pi^- + n + n + k\pi^0$$

$$p + p \to 3\pi^+ + 2\pi^- + p + n + k\pi^0.$$

The δ-nucleon must be emitted at an angle $\theta_\delta < 63°$ (in the laboratory system) and cannot have a momentum larger than 4×10^8 ev/c (such a proton has a large chance of stopping in the Be). In the center-of-mass system, the corresponding statement is that the δ-nucleon must be emitted at an angle $\theta_{\delta c} < 175°$. Within experimental error, energy and momentum balance in this case for the charged π-mesons alone. If the π^0-mesons are emitted with the same energies in the center-of-mass system as the π^+–mesons, then the nucleon emitted forward makes an angle of about 5° (in the center-of-mass system) with the direction of the primary and carries away about 80 per cent of the energy of the primary nucleon. Thus, in this shower only a small fraction of the total energy goes into π-mesons. It should be noted that the number of π^+-mesons in this shower is the same as in shower No. 27.16 ($n_s = 5$), although the primary energies differ by a factor of about 10.

The events described indicate that in the interaction of a proton with a light nucleus (Be), relatively many particles may be produced ($n_s = 5$ at $E_0 = 5.7$ bev) with large energy loss, or relatively few particles ($n_s = 5$ at $E_0 > 54$ bev) with small energy loss.

In conclusion, we present shower No. 27.34

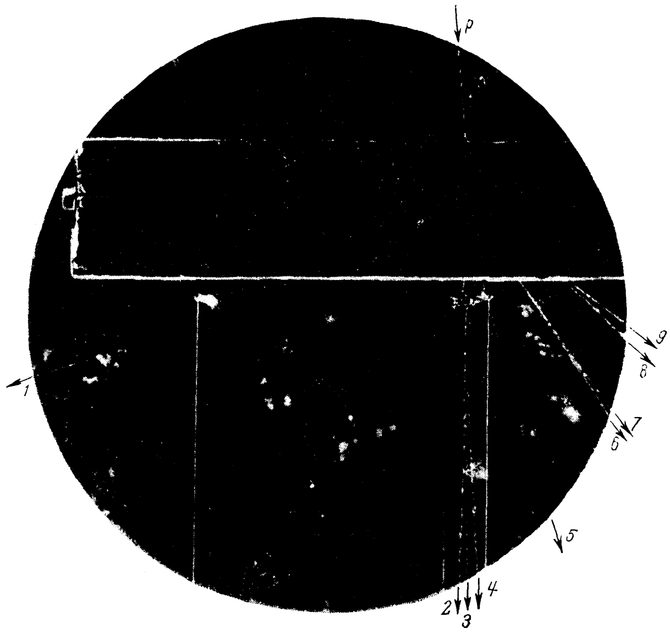

FIG. 5. Shower No. 27.34. Particles 3–4, 6–7 and 8–9 form three narrow pairs, with angles between particles in a pair no larger than 2°.

(Fig. 5), which was initiated by a 6 bev proton. This shower is interesting because of the nine relativistic secondaries, 6 form 3 narrow pairs, the angle in each pair being no larger than 2°. The tracks were distorted by turbulence, so that it was not possible to measure the momenta of the secondary particles.

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4 Fowler, Maenchen, Powell,Saphir and Wright, Phys. Rev. 101, 911 (1956).

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