Inelastic Scattering of 500-Mev Negative Pions in Emulsion Nuclei*

M. BLAU, *Brookhaven National Laboratory, Upton, New York*

AND

MARTIN CAULTON,† *Rensselaer Polytechnic Institute, Troy, New York*

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Inelastic scattering of 500-Mev negative pions has been investigated in 1700 meson-induced events in emulsion nuclei. Large energy losses and strong angular relationships of the emitted mesons have been observed, similar to those in experiments with lower energy mesons. The possible causes for this behavior are discussed. In 1–3 percent of the events, production of charged mesons has been found. The cross section for meson production on free nucleons is estimated to be between 3.5 and 10 mb, considering the possible absorption of one or both mesons. The angular and energy distributions of mesons and recoiling nucleons in events with meson production are discussed. Six events of π^0 production on free protons (or edge nucleons) have been found. The results are compared with observations on meson scattering and meson production in cosmic-ray experiments.

I. INTRODUCTION

INVESTIGATIONS on the interaction of nucleons with complex nuclei have contributed considerably to the knowledge of nucleon-nucleon collisions. Particularly, the ideas on meson production are, up to date, almost entirely based on these experiments.

It seemed promising to apply the same methods for high energy meson interactions—500-Mev negative pions—and to explore, in general, problems connected with these interactions.

Experiments using lower meson energies (30 to 210 Mev) have been performed by various authors[1–9] in cloud chamber and emulsion experiments. Elastic scattering, meson absorption, and inelastic scattering events have been found;[10] and the cross section and characteristics of these types of events have been discussed. It has been established that absorption of low energy mesons takes place in nucleon pairs or larger nucleon complexes. The process of inelastic meson scattering at all these energies is characterized by great energy losses and strong angular dependence and is not fully understood.

It was expected that at higher energies the prevailing interaction would be quasi-elastic scattering—elastic scattering on single nucleons within the nucleus. However, the interaction process turned out to be actually more complex. The investigation of this process was one of the objects of this paper. The main purpose, however, was the attempt to detect meson production by mesons and to find the laws governing this process.

II. EXPERIMENTAL PROCEDURE

A. Plate Exposure

Two different types of exposures were used.

(1) The plates were exposed to the "500-Mev meson beam" of the Brookhaven Cosmotron; mesons of 620-Mev/*c* momentum, analyzed and focused by the Cosmotron magnet, leave through a hole in the Cosmotron shield. These mesons were further deflected by a second analyzing magnet. The plates were placed parallel to the beam behind a lead collimator and shielded by lead bricks from background radiation.

(2) Particles emitted from the Cosmotron target (beryllium) at an angle of 32° with the proton direction pass directly through the Cosmotron shield. After collimation, particles of the desired momentum and charge were selected by an analyzing magnet. Again the plates were placed parallel to the direction of the selected beam and properly shielded. The "focused" beam had higher intensity than the "direct" beam, but the latter had less contamination. The angular spread of the focussed beam was approximately $\pm 4°$, which was the same as that exhibited by incident minimum tracks found on the exposed plates. The angular spread in the direct beam was less than $\pm 2°$.

400-micron Ilford G-5 emulsions with glass backing were used in the first series of experiments. In latter exposures stacks of a dozen 400-micron Ilford G-5 stripped emulsions were used. The processing of the emulsions followed standard development techniques.

B. Search

Meson interactions were found by area scanning under 300 times magnification. Under high magnification, only about 20 meters of minimum tracks have been followed, mainly to check the efficiency of the area scanning search and to compare the distribution of certain types of events found in both methods.

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† Now at Brookhaven National Laboratory.

[1] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. **80**, 924 (1950); Bernardini, Booth, and Lederman, Phys. Rev. **82**, 105 (1951); G. Bernardini and F. Levy, Phys. Rev. **84**, 610 (1951).
[2] H. Bradner and B. Rankin, Phys. Rev. **81**, 916 (1951).
[3] Blau, Oliver, and Smith, Phys. Rev. **91**, 949 (1953).
[4] G. Goldhaber and S. Goldhaber, Phys. Rev. **91**, 674 (1953).
[5] W. F. Fry, Phys. Rev. **91**, 1576 (1953).
[6] A. H. Morrish, Phys. Rev. **90**, 674 (1953).
[7] A. H. Morrish, Phil. Mag. **45**, 47 (1954).
[8] Byfield, Kessler, and Lederman, Phys. Rev. **86**, 17 (1952).
[9] J. O. Kessler and L. M. Lederman, Phys. Rev. **94**, 689 (1954).
[10] The term inelastic scattering is commonly used to describe stars with one emitted meson.

The efficiency in area scanning for picking up events with 2 or more black tracks was almost 100 percent, for 1 black prong only 50±10 percent. Events without black prongs and 1 or 2 light tracks have only been picked up occasionally. This fact immediately limits the scope of the experiments to inelastic scattering events.

In total, 1700 events have been found in about 8 cc of emulsion. In the beginning of this investigation all observed events were measured and the grain count and angular relation of light tracks determined. After 460 interactions were found, only stars were measured with at least one fast particle or a black track which seemed a meson by its apparent scattering. After a total of approximately 700 interactions were found, only special events (having at least two tracks, which were possible mesons) were measured and recorded. The other events were only counted, in order to keep account of the total number of observed events.

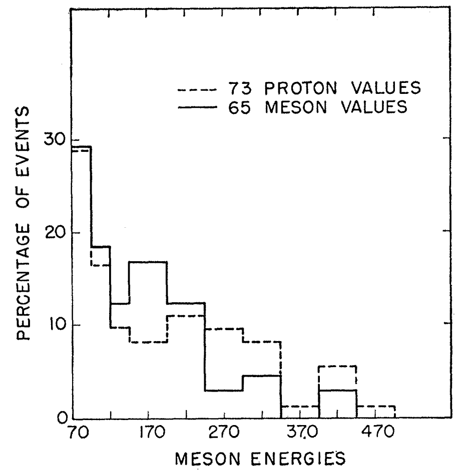

FIG. 1. Histogram of average multiple scattering angles (expressed in corresponding meson energies) for mesons and protons.

C. Measurements

Nature and energy of particles were determined by the usual methods: grain count, multiple scattering, and range measurements. Sample tracks of incoming mesons have been scattered for each set of exposures; the mean energy determined from scattering measurements was 520±30 Mev, in agreement with the value expected from experimental conditions (current of the analyzing magnet, position, etc.).

Grain count and scattering measurements on light tracks emitted in the interactions have been performed, whenever track length or ionization made this procedure meaningful. In this way for about 30 percent of all light tracks the nature and energy of the particle could be determined. In experiments with emulsion stacks the ionization loss per unit path length could be used as an additional criterion, especially in cases where excessive dip angle or distortion made scattering measurements unreliable. Scattering measurements on heavily ionizing tracks were performed, when they were suspected by apparent scattering to be π mesons or by other unusual features to be heavy mesons. However, no single case of a meson heavier than π could be established. Likewise, the investigation of several two-prong stars without an incoming particle, suspected to be Λ^0, gave no positive results.

D. Measurement Considerations

In the interactions described in this paper the presence of mesons with energies greater than 100 Mev (minimum grain count) can be established by kinematic considerations alone, since the maximum energy a proton can acquire in an elastic collision with 500-Mev mesons is 420 Mev (including 22-Mev Fermi energy), and therefore, the corresponding tracks have grain counts higher than minimum. Based on similar considerations, tracks emitted in the backward hemisphere, with grain counts less or equal to 1.4 minimum grain count, cannot be protons, but must be mesons.

In order to establish the energy distribution of the mesons, scattering measurements are necessary. The question arises, whether the scattering measurements made on 30 percent of light tracks (sample comprising about 1000 events) represent the true distribution of mesons in number and energy. Since the track lengths necessary for adequate scattering measurements increases with the particle energy, i.e., with smaller multiple scattering angles, it is important to investigate if the distribution in the measured sample is deficient of high-energy mesons. While the true energy distribution of mesons is not known, the energy distribution of protons can be calculated in an approximate manner.[11]

The probability of finding a track adequate for scattering measurements depends on: (1) the dip angle of track, (2) position in the plate, and (3) the mean multiple scattering angle of the track. (1) and (2) are obviously independent of the nature of the particle causing this track (whether meson or proton). (3), the multiple scattering angle of the most energetic recoil protons (420 Mev), is about equal to the multiple scattering angle of the incoming mesons (500 Mev), and, therefore, equal to or smaller than the multiple scattering angle of emitted mesons.

The histogram of protons—73 protons with energies >60 Mev—is plotted in Fig. 1 (dotted lines) *versus* the

[11] The calculations are based on the well-known energy dependance of mean free paths in nucleon matter for $p-p$ and $p-n$ collisions and the average number of collisions in emulsion nuclei [Bernardini, Booth, and Lindenbaum, Phys. Rev. **85**, 826 (1952); **88**, 1017 (1952)]. It is assumed that the fast protons are produced in elastic meson-nucleon collisions with energies corresponding to the experimentally observed angular distribution of the mesons (Fig. 2). The ratio of neutron to proton recoils has been determined by the ratio of neutrons to protons in emulsion nuclei and the statistical weight of $\pi^-+p\rightarrow\pi^-+p$ and $\pi^-+n\rightarrow\pi^-+n$ interactions.

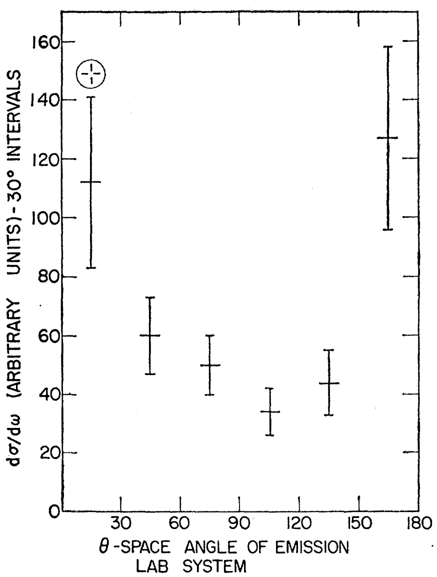

FIG. 2. Differential cross section of emitted mesons *versus* space angle of emission in laboratory system.

angle of multiple scattering; the scattering angle, however, is expressed in corresponding meson energies. In this sample, 8 percent of all protons (>60 Mev—corresponding to 70-Mev meson energy) have energies >280 Mev (corresponding in scattering angle to mesons >350 Mev). Calculating[11] the percentage of protons with energies >280 Mev among protons of energies >60 Mev yielded the value 7.5 percent.

The solid lines in Fig. 1 correspond to the energy distribution of mesons in a nearly equal sample (65 mesons). There is a greater number of large multiple scattering angles in the meson distribution than in the proton distribution.

Because of the approximate character of the calculation of fast emerging protons, the agreement between experimental and calculated values (7.5 percent and 8 percent, respectively) does not necessarily prove that the sample really embraces all fast protons. However, the fact that the meson sample has relatively fewer high energy particles than the proton distribution makes it probable that the former sample represents the true meson energy distribution.

Furthermore, the ratio (minimum tracks scattered)/(total number of minimum tracks) is nearly equal for forward (presumably higher energy mesons) and backward-scattered mesons.

On the other hand, some fast mesons, scattered strongly forward (small energy of the recoil nucleon) may have been missed because of the inefficiency in finding small events (1 and 0 prong stars). The percentage of missing forward-scattered (Fig. 2), and therefore, possibly high energy mesons (Figs. 3 and 4), has been estimated by comparing the frequency of finding small events in area scanning and scanning along incident tracks. The dotted lines in Fig. 2 and Fig. 4 are corrected for this loss assuming that the missing events are entirely connected with high energy meson emission; the dotted lines in Fig. 4, therefore, probably represent an overestimate of high energy mesons.

III. EXPERIMENTAL RESULTS AND DISCUSSION

From a phenomenological standpoint the interactions observed can be divided into 3 groups. (1) Stars with 1 meson—38±6 percent of all cases, (2) stars with 2 mesons—1–3 percent, and (3) stars without mesons. Presumably, in all three types of events the primary process is meson interaction with a single nucleon; interactions with nucleon complexes, if present at all, will be less probable because of the small wavelength of 500-Mev pions.

The number of stars with mesons—usually called inelastic scattering events—has increased in comparison to experiments with lower-energy mesons. Only 10 percent of all interactions with 70-Mev mesons[1] have mesons emerging, 22 percent with 135-Mev mesons,[4] and 31 percent with 210-Mev mesons.[7]

A. Stars without Mesons

In a certain percentage of mesonless stars charge exchange scattering may have occurred. In order to estimate this percentage the energy dissipation in stars with and without charged mesons has been compared and found distinctly different. The mean number of black prongs is 4.3±0.2 in mesonless stars and about 66 percent of all stars have a fast proton; in stars with mesons the mean prong number is 2.7±0.1, and only 40 percent have a proton more energetic than 30 Mev.

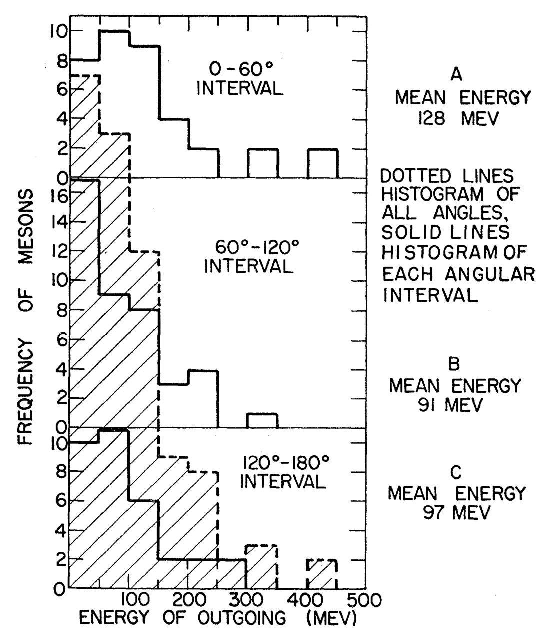

FIG. 3. Energy distribution of emitted mesons.

The mean energy of the emitted charged mesons is 110 Mev and the energy distribution is assumed to be equal for charged and neutral mesons;[12] therefore, the mean energy dissipation in mesonless stars should be greater by 110+140 Mev. This energy increase expressed in black and gray tracks has been estimated from the known prong distribution of sigma stars[13] and stars produced by negative mesons in the energy interval of 50–100 Mev.[1] According to this estimate, charge exchange should have occurred in 29 percent of all mesonless stars or in 18 percent of all interactions observed. Another rough estimate of the frequency of charge exchange can be obtained by considering the frequency of events with electron pairs. Among 1700 events 2–4 have been observed with pairs emerging from the vertex of the interaction.[14] Assuming these pairs to be conversion electrons from π^0 disintegrations, charge exchange would have taken place in 10–20 percent of all events. A value of 20 percent would be expected from statistical spin considerations,[15] the near equality of $\pi^+ + p$ and $\pi^- + p$ cross sections at this energy, and the ratio of neutrons to protons in emulsion nuclei.

After subtracting 20 percent of the events as charge exchange, 44 percent of the stars are still mesonless. This percentage is astonishingly high considering the high energy of mesons involved. It seems reasonable to assume that meson capture in nucleon pairs will occur only if the meson wavelength is comparable with the distance of nucleons within the nucleus (smaller meson energies).[16] Therefore, the meson must lose an appreciable amount of its original energy before being captured. If the energy degradation takes place gradually through repeated scatterings, the frequency of meson escape should be higher, considering the finite size of the nucleus.

B. Stars with One Meson

Figure 2 gives the angular distribution (differential cross section in arbitrary units) for 112 inelastically scattered mesons leaving the nucleus, and Fig. 3, the energy distribution of these mesons. A, B, and C in Fig. 3 refer to angular intervals 0–60°, 60–120°, and 120–180° (solid lines), while the dotted lines of the histogram comprise all three angular regions.

The energy distribution is peaked at low energies and only a few mesons have energies greater than 200 Mev. The distribution is quite similar in A, B, and C, with the exception of a few high energy mesons in A. It seems, therefore, that there is no relation between

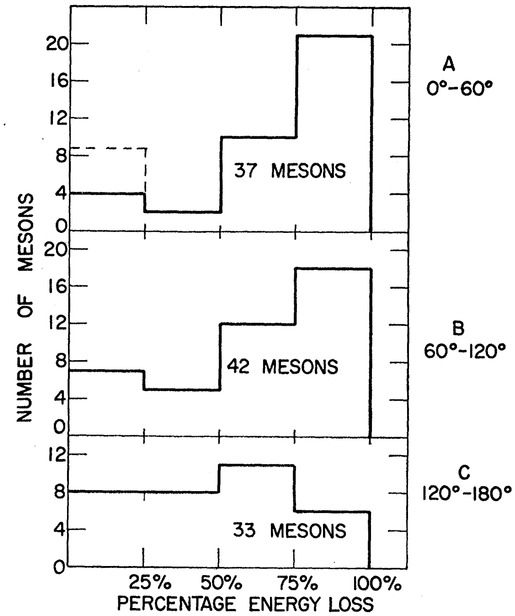

FIG. 4. Number of mesons *versus* percentage energy loss for three space intervals.

meson energy and angle of emission. One would, however, expect such a relation on the obvious assumption that the primary process within the nucleus will be meson-nucleon scattering. Therefore, the observed distribution strongly suggests that the original distribution is obliterated by other processes, for instance, repeated scattering or meson production and reabsorption. The fact that repeated scattering or meson reabsorption may have occurred in at least several of the events can be demonstrated by observation of fast protons in the backward hemisphere in 9 out of 112 cases. However, at least 3 of these cases can be interpreted as reabsorption of positive mesons since in addition to the backward ones, forward protons are observed and the angles between protons are ≥ 150 degrees.

1. *Energy Degradation of Observed Mesons*

The number of collisions necessary to explain the observed energy degradation would be rather high, especially if one considers that for high-energy mesons the probability of forward scattering (small energy loss) will be at least as high as that of backward scattering. For instance, three consecutive scatterings at 60° would decrease the initial energy to about 200 Mev; but only 14 percent (or 18 percent after correction) of all observed mesons have energies ≥ 200 Mev.

For mesons scattered in the forward direction (up to 60°), it is possible to estimate the probabilities for escape after one or two repeated collisions, respectively. In this angular interval the changes in energy are relatively small and lead to energy regions in which the mean free path in nuclear matter is nearly constant (small increase).

[12] Carlson, Hooper, and King, Phil. Mag. **41**, 701 (1950).
[13] Menon, Muirhead, and Rochat, Phil. Mag. **41**, 583 (1950).
[14] In two cases the nature of the particles causing the pair of minimum tracks could not be established with certainty. A small additional number of events with electron pairs having 1 or 0 black prongs may have been missed in area scanning.
[15] K. A. Brueckner, Phys. Rev. **86**, 109 (1952).
[16] Proton pairs accelerated in the absorption of a π^+ meson in a nucleon pair rarely have energies greater than 70 Mev.

If it is assumed that the mean free path in nuclear matter is given by $\lambda = 4\pi r_0^3/3\sigma_\mu$, where $\sigma_\mu = 26$ mb,[17] the probability for escape of the meson after one collision, P_1, or after two collisions, P_2, is given by

$$P_1 = \frac{2}{a^2}\cdot 2\left[1-\left(1+a+\frac{a^2}{2}\right)e^{-a}\right],$$

$$P_2 = \frac{2\cdot 3}{a^2}\left[1-\left(1+a+\frac{a^2}{2}+\frac{a^3}{2\cdot 3}\right)e^{-a}\right].$$

$P_T = 1-P_0 = \{1-(2/a^2)[1-(1+a)e^{-a}]\}$ is the probability for any number of collisions.[18] The quantity a is the nuclear diameter expressed in units of λ. For emulsion nuclei (averaging over heavy and light elements and considering their relative transparency), one obtains $P_1/P_T = 34.7$ percent. $P_2/P_T = 29$ percent. Therefore, $(P_1+P_2)/P_T = 63.7$ percent, or 63.7 percent of all forward scattered mesons should have energies ≥ 260 Mev (after 2 collisions). This percentage is an overestimate since initially backward-scattered mesons may enter the forward hemisphere by being scattered a second time at angles greater than 90°. However, since the mean free path for backward-scattered mesons is much smaller than for forward mesons, one would expect that mesons scattered twice at great angles will not contribute greatly to the frequency of mesons observed at forward angles.[19]

Figure 4 compares for 3 angular intervals the energy loss suffered by the emerging mesons. The energy loss in percent is defined by $L = 1 - W_{i\gamma}/W_{e\gamma}$, where $W_{i\gamma}$ is the kinetic energy of a meson observed at an angle γ and $W_{e\gamma}$ is the kinetic energy expected at this angle in the case of elastic scattering. (The Fermi momentum distribution has been taken into account.) The results are in obvious contradiction to the above calculations and considerations. Only 17 percent of all mesons or 10 percent in the angular interval 0–60° can be considered first or second collisions according to Fig. 4. If the events missed because of incomplete scanning efficiency are taken into account, the above percentages would be 22 percent or 25 percent, respectively. Since in about one-half of all events no meson leaves the nucleus, these figures can be smaller by one-half the stated amount.

Another fact, in disagreement with the great observed energy losses, is the small size of stars observed.

[17] L. Yuan and S. Lindenbaum, Phys. Rev. **92**, 1578 (1953), found a cross section of 25±3 mb for 450-Mev negative pions on hydrogen and 27 mb for positive mesons of equal energy. In the calculation of the total cross section, the mean cross section per nucleon has been assumed to be 26 mb.

[18] S. A. Wouthuysen, University of Rochester Technical Report No. 5 on the 130″ cyclotron (unpublished).

[19] The calculation for backward-scattered mesons is more difficult, because the mean free path is strongly dependent on energy for meson energies near 200 Mev.

2. *Angular Distribution of Mesons*

Figure 2 shows a strong angular dependence of inelastic scattered mesons and that again is difficult to reconcile with a model of frequent repeated scatterings.

Similar features (great energy losses and strong angular dependence of inelastic scattered mesons) have also been observed in experiments with mesons of lower energy.[1–8] Kessler and Lederman[9] compare for 120-Mev negative incident pions the angular distribution of mesons inelastically scattered in carbon and lead with the differential cross section of the elementary process $\pi^+ + p \rightarrow \pi^+ + p$ at equal energy. The distribution from carbon simulates closely the elementary process and even in the large nucleus, lead, the features of the elementary distribution are recognizable although here the distribution is smoother and obviously somewhat obliterated by multiple scattering processes. Emulsion experiments with 135-Mev negative mesons[4] show similar results. While the relative loss in meson energy is considerable, the absolute amount of energy loss in both experiments is relatively small. The energy of the emitted mesons may be depressed because of the momentum distribution within the nucleus.[20] On the other hand, the angular distribution (predominantly backward) may be partly affected by the small mean free path of the incident meson, favoring an interaction near the beginning of its travel through the nucleus; therefore, the scattered mesons may preferentially escape the nucleus in the backward direction.

With 210-Mev mesons,[7] great energy losses of emitted mesons are observed. Because of the small mean free path, repeated scatterings are expected. However, a definite angular distribution is found; the ratio of forward- to backward-scattered mesons increases as compared with lower energy experiments. This is indicative of the influence of a primary nucleon process.

For the experiments described here no comparison with the elementary scattering process can be made, since the differential scattering cross section for 500-Mev mesons is not known. Because of the great absolute energy loss suffered by the majority of mesons in the present experiment, any angular distribution differing from an isotropic one seems incompatible with the assumption of gradual energy loss by frequently repeated scatterings.

It is, therefore, believed that there exists another mechanism, by which the meson energy is reduced in larger steps in one single or at least relatively few collisions.

Meson production, eventually followed by reabsorption, could lead to sudden energy changes. The cross section for production of charged mesons has been estimated within rather wide limits[21] (14–40 percent of the elastic cross section). If the actual value is appreciably larger than the lower limit and if the π^0 production

[20] M. H. Johnson, Phys. Rev. **83**, 510 (1951).

[21] Section III: C-3 of this paper.

cross section is of comparable magnitude, the combined effect of meson production, scattering, and absorption may be sufficient to explain the experimental results—great energy losses and strong angular preference of mesons.

C. Events with Two Mesons—Meson Production by Mesons

1. *Production of Charged Mesons*

Among 1700 events, 20 cases with 2 mesons leaving the nucleus have been identified with certainty. There are 24 more cases which probably represent meson production. In the established events the mesons have been identified by grain count, scattering, and range. Fifteen of these events are tabulated in Table I. In some cases the minimum tracks at backward laboratory angles have been denoted mesons from kinematic considerations alone. Whenever the possibility existed that a track considered a meson could be a proton, the event was classified as only possible. It is likely that more than 50 percent of these possible cases represent meson production. About 10 more cases with steeply dipping tracks have been observed, which possibly could be events with meson production, but because of the uncertainty, these events have not been considered.

The events with two emitted mesons represent most probably meson production by mesons; meson production by recoil nucleons produced in the primary scattering process is very unlikely because of the low energy of these recoil nucleons.[22] Furthermore, the kinematics of only 15 out of 44 events would be in agreement with meson production by recoil nucleons.

Only 3 events, Numbers 2, 9, and 15 in Table I, can be explained by meson production on free protons, since no other tracks besides the two mesons are visible. These events have been analyzed. If the momenta and angles of the incoming and both emitted mesons are known, the momentum and the angle of the recoil nucleon can be found. An event, representing meson production on a single nucleon, balances if $T_{\mu 1}+T_{\mu 2}+T_N = T_{\mu_i}-140$ Mev$=360$ Mev. Here, $T_{\mu i}$, $T_{\mu 1}$, and $T_{\mu 2}$ are the kinetic energies of incoming and both emitted mesons, and T_N is the kinetic energy of the nucleon derived from the momentum diagram. In event 2 the sum of energies of both mesons and the calculated nucleon add up to 360 Mev and in No. 9 to 320 Mev, and therefore, these events agree kinematically with the assumption of meson production on a free proton. In event No. 15 the forward scattered particle was too short to be identified with certainty. However, since only one other particle (identified as a meson) is emitted, the event can be assumed to have occurred on a free proton. In this case the energy of one of the mesons together with both emission angles determines the kinematics of the event. The event balances with a meson energy for the forward track in good agreement with grain count measurements.

The energies of the emitted mesons, determined by the usual methods, are only known within a certain limit. For low-energy mesons, where both grain count and scattering measurements can be made, the uncertainty in energy is usually less than 10 percent. For high-energy mesons with minimum grain count, the upper energy limit is sometimes 35 percent higher than the mean value. In cases 2 and 9 and in many of the cases mentioned later, balance has been reached for meson energies near or at the calculated mean value. If higher energy values within the fiducial limits

[22] Argument presented in paper by Blau, Caulton, and Smith, Phys. Rev. 92, 516 (1953).

TABLE I. Description of established two-meson events (mesons in kinematic balance with a single nucleon encounter). Angles are given in degrees.

(1) Event[a]	(2) Kin. energy T (lab) Mev	(3) Lab angle θ	(4) Kin. energy T (c.m.) Mev	(5) C.m. angle $\bar{\theta}$	(6) Lab angle $\pi-\pi$	(7) Lab angle $\pi-N$	(8) C.m. angle $\pi-\pi$	(9) C.m. angle $\pi-N$	(10) Other tracks[b]
1 *I*	500	0							1 *B*
A (π^+)	8.4	39	5	125		31		35	
B	280	35	178	33	71	76	145	160	
N	55	41	37	126					
2 *A*	16	7	0.4	35		20		66	None
B	125	102	169	125	105	123	130	177	
N	220	20	48	52					
3 *A*	53	145	117	159		137		153	4 *B*
B	38	66	35	106	149	68	93	114	
N	230	2	55	6					
4 *A*	55	32	23	60		55		170	1 *R*
B	115	96	147	123	71	122	73	103	1 *B*
N	185	26	46	49					1 *e*
5 *A*	3.1	12	3.3	168		15		136	1 *B*
B	105	115	164	138	119	131	46	175	
N	250	15	51	37					
6 *A*	60	128	116	148		130		150	5 *B*
B	42	90	58	125	104	105	39	173	
N	250	12	48	33					
7 *A*	57	60	45	95		72		128	3 *B*
B	86	154	176	165	107	159	79	159	
N	230	13	42	35					
8 *A*	70	126	128	147		138		150	1 *R*
B	40	95	60	128	82	108	58	153	3 *R*
N	280	13	62	31					
9 *A*	2.8	46	7	154		72		60	None
B	280	14	152	24	32	39	129	170	
N	34	25	21	147					
10 *A*	90	70	84	100		86		144	1 *B*
B	49	159	119	168	90	176	68	148	
N	230	17	47	43					
11 *A*	120	62	99	90		100		175	2 *B*
B	94	51	64	79	12	90	14	168	
N	145	39	60	92					
12 *A*	2.5	124	22	166		145		146	2 *B*
B	122	95	154	121	30	115	45	168	1 *R*
N	240	20	56	49					
13 *A*	4	52	8	146		74		141	1 *R*
B	150	84	164	108	50	109	46	171	
N	210	25	54	61					
14 *A* ?[c]	40	43	20	81	*AB* 62	47	*AB* 78	105	1 *B*
B	3.1	95	17	155	*AC* 46	92	*AC* 141	95	
C	95	41	54	66	*BC* 75	48	*BC* 126	115	
N	92	12	4	83					
15 *A*	100	156	198	165		162		155	None
B	17	17	2	76	149	20	110	72	
N	260	5	46	13					

[a] In column (1), *I*—incident particle; *A*, *B*, *C*—mesons; *N*—nucleon.
[b] In column (10), *B*—black track, *R*—recoil, and *e*—electron.
[c] Track *A* causes a star after traveling 958 microns.

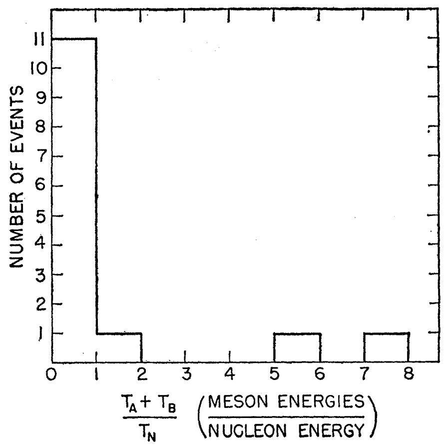

FIG. 5. Distribution of meson and nucleon energies in events with meson production in laboratory system. (Ratio of sum of meson energies to nucleon energy.)

(67 percent probability) have been used, this procedure seemed justified because of cell length or other considerations connected with the measurement. An event was assumed to be balanced when the sum of energies of both mesons and the nucleon energy did not differ by more than 10 percent from the calculated value. The energy values in Table I correspond to energy values for which "balancing" was found.

In all the other "established events" in Table I, evaporation particles in addition to both mesons are emitted. Meson production may have occurred on protons or neutrons, with the exception of 2 cases where the charge of one of the mesons could be identified as positive, so that collision with a proton is certain. Under the assumption that these tracks are caused by subsequent interactions of the recoil nucleon a kinematic investigation similar to that described has been made. Energy and momentum balance within the error limit has been found for the events of Table I.

Event No. 14 in Table I is a case where possibly 3 mesons emerge from the vertex. B and C have been identified as mesons; track A has 1.8 times minimum grain count and travels 958μ before causing a star; the star has only a few black prongs and could have been caused by either a 40-Mev meson or 260-Mev proton. If A is assumed to be a meson, a single nucleon is needed to balance energy and momentum. Total energy is $500-2(140)=220$ Mev. In columns 5, 6, and 7 of Table I, the energies and angles in the center-of-mass system are listed. Five more events with unmistakably identified mesons could not be balanced; in these events the energy of both mesons was small, and therefore, one or both of the mesons might have suffered a subsequent scattering before emerging. One of these events has 8 black tracks and 3 others have fast protons; in two of these cases emission of a π^0 is not excluded.

In the case of "possible events," energy and momentum balance was attempted, whenever energy determination of the emitted particles was possible. Eleven of these events could be balanced and nucleon energies and angles have been calculated. In 6 events with minimum tracks (multiple scattering angle not measurable) balance was not even attempted because the energy of these mesons is not known. In these cases only emission angles have been calculated in the laboratory and c.m. systems;[23] 5 more cases could not be balanced, and finally in 2 cases not enough information was available for an analysis.

In most of the events described, the nucleon receives in the laboratory system a great amount of the energy available. Figure 5 is a histogram showing the frequency of events *versus* the ratio $(T_{\mu 1}+T_{\mu 2})/T_N$, the sum of the kinetic energy of both mesons divided by the nucleon energy. In the two events with a ratio ≥ 5, one of the mesons is produced with nearly the maximum available meson energy. One of these events is No. 9 without evaporation tracks while both of the other "proton events" lie in the interval with a ratio around 0.5. The angular distribution of both mesons is plotted in Fig. 6 (laboratory system) and Fig. 7 (c.m. system). The dotted lines comprise both established and probable events. No differentiation between produced and original mesons can be made; only 2 cases of positive mesons have been observed, and both are emitted backwards in the c.m. system.[24] Figures 8(a) and 8(b) show for 14 events the distribution of the angles between both

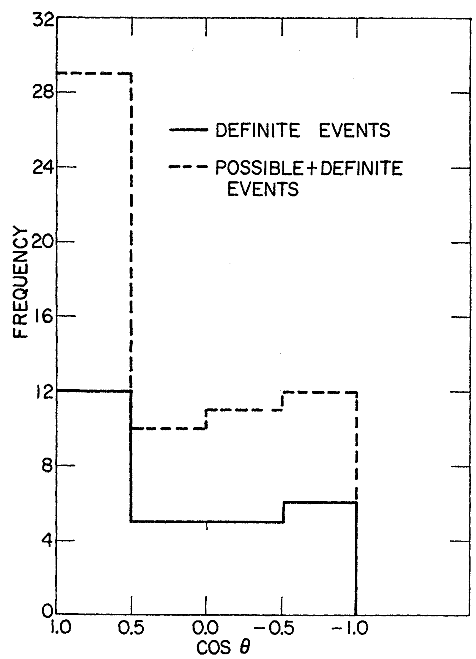

FIG. 6. Angular distribution of mesons in events with meson production—laboratory system.

[23] The relation between laboratory and c.m. angles depends very little on energy for meson energies greater than 80 Mev.

[24] One event observed with incident mesons of 750 Mev, without evaporation tracks, also has a positive meson emitted backward.

mesons in the laboratory and c.m. systems. The statistics are too poor to draw any conclusion, although small angles between mesons (c.m. system) seem to be more frequent. Finally, Fig. 9 gives the histogram of nucleons in the c.m. system. (Dotted lines refer again to established+possible events.) The trend in forward emission of nucleons follows from the backward trend of meson emission. In two of the alleged proton events the nucleon is emitted forward, while in the case of No. 9 with a high ratio (meson energies/nucleon energy) the nucleon is in the backward hemisphere.

The differentiation between events with evaporation tracks and the "free proton events" without visible prongs has been made for the following reason. It is felt that in some of the former cases the nucleus excitation might not be caused entirely by the recoil nucleon but also by subsequent scattering of one or both of the emitted mesons. The argument of balance would not be stringent, if something like coincidence balance exists. Calculations have been made on constructed and observed cases in order to determine the probability of chance balance. If the energy of both of the mesons is ≥ 100 Mev, chance balance seems impossible; for 1 meson ≥ 100 and the other <100, chance balance is possible; that means that there exists another meson energy and angle from which one of the mesons could have been scattered to its actual position. The limits for chance balance are very narrow from a theoretical standpoint, but are widened by uncertainties in energy and angular (for high dip angles) measurements. If, however, the second meson has a very small energy, then even if it should have been scattered from an original position, parameters like nucleon energy or angle will be only slightly affected.[25] Most suspicious are events with both mesons of energies below ~100 Mev; then, cases can be constructed allowing for both mesons the possibility of having been scattered from another produced angle and energy. Five cases out of the 14 events used for the histograms (Figs. 6–9) belong in this group. Assuming that there are cases where the energy connected with the emitted mesons was originally higher, then the energy of the recoil nucleons would have been overestimated, and, consequently, the angle of emission (c.m. system) would have been shifted towards the forward direction. The nucleon angular distribution may actually become more isotropic and the ratio of backward- to forward-emitted mesons smaller.[26] The angular distribution of nucleons and mesons again may have been altered to some degree by the momentum distribution within the nucleus. This could affect the "free proton events" in the same way, since there is a certain possibility that the events took place on bound nucleons (edge of nucleus) and not on free protons. Crussard, Walker, and Koshiba,[27] studying meson production (charged and neutral mesons) with

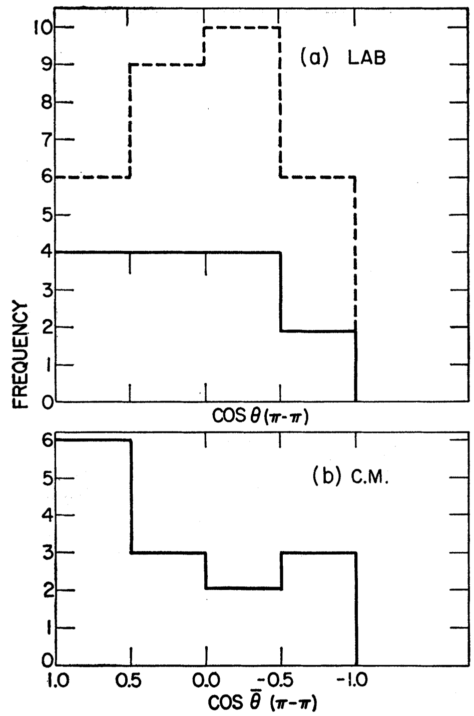

FIG. 8. Distribution of angles between the two emitted mesons in cases of meson production. (a) Laboratory system; (b) c.m. system.

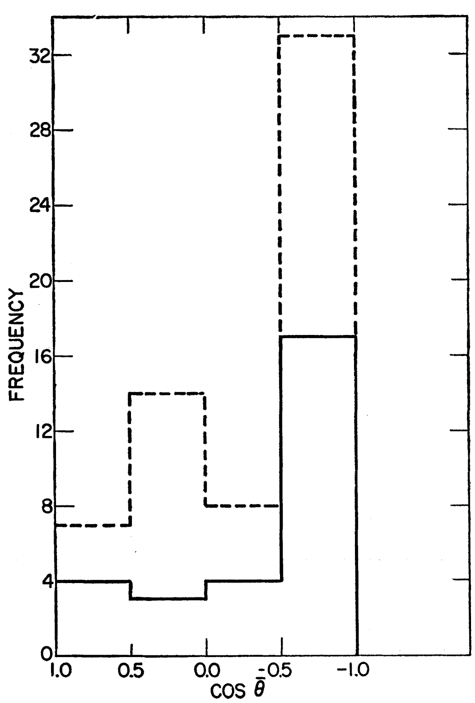

FIG. 7. Angular distribution of mesons in events with meson production—c.m. system.

[25] This argument is not valid if the original meson has suffered more than 1 scattering; the high capture cross section for mesons in this energy interval and the small star sizes observed do not favor such an assumption, however.

[26] Lal, Pal, Peters, and Swami, Proc. Indian Acad. Sci. 36, 75 (1952).

[27] Crussard, Walker, and Koshiba, Phys. Rev. 94, 736 (1954).

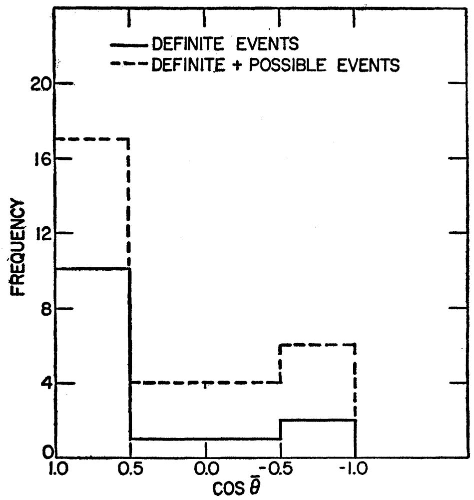

FIG. 9. Angular distribution of recoil nucleons in events with meson production (c.m. system).

1.5-Bev negative mesons, found predominantly backward emission of nucleons. Here only events without evaporation tracks have been considered. One-half of these events occur on free protons; this conclusion has been reached by taking into account the known cross section for 1.5-Bev mesons.

It cannot be decided if the different angular distribution of the recoil nucleons found with 500-Mev mesons is attributable to: (1) the difference in energy, (2) the fact that the production takes place in complex nuclei, or (3) the fact that in some cases coincidence balance leads to false conclusions. Backward asymmetry of emitted mesons in showers produced by high-energy mesons has been observed by Lal *et al.*[26]

2. *Production of Neutral Mesons*

Very little can be said about neutral meson production in the reaction $\pi^- + p \rightarrow p + \pi^- + \pi^0$; reactions on free protons are necessary for the unambiguous identification of this process, and such reactions can only rarely be found in area scanning techniques.

In all, 6 events corresponding to the above reaction were found; the respective energies and angles are given in Table II. In 5 of the 6 events the proton is emitted in the backward direction in the c.m. system. Strongly peaked backward emission of the protons in π^0 production has been found by Crussard *et al.*[27] with 1.5-Bev negative pions. However, the number of events here is too small to draw any conclusions. Furthermore, the area scanning technique will favor events with low-energy protons (backward in the c.m. system) which give black or dark grey tracks.

It is difficult to evaluate the number of cases where π^0 emission may have occurred in collisions with bound protons or neutrons (events with evaporation tracks). In a certain percentage of events with charged mesons, the energy degradation observed may have been caused by this type of collision. At least 6 percent of all events with a single charged meson most probably belong to this type of interaction. This value is found by considering only events with a single evaporation prong and a forward emitted meson (charged),[28] which apparently has lost a large amount of energy. From statistical considerations[29] the number of events with two charged mesons should be about equal to the frequency of events with 1 charged and 1 neutral meson.

3. *Approximate Cross Section for Production of Charged Mesons*

As stated before, in only 1–3 percent of all events production of charged mesons has been found.[30] It is thought that this figure can at the most be doubled in order to account for inefficiency in scanning. This, however, is only valid for meson production in nuclei with at least 1 evaporation track; events occurring in hydrogen or edge nucleons may have been missed in a greater proportion.

It is obvious that the actual fraction of interaction leading to meson production will be higher than 1–3 percent, since both or at least one of the mesons can be captured within the nucleons, and therefore, not be observable. The absorption coefficient will be appreciable, if one takes into account the low energy of mesons (mean energy) observed in this process.

TABLE II. Description of events representing π^0 production on a free proton. ($\pi^- + p \rightarrow p + \pi^- + \pi^0$.) Angles are in degrees.

Event	Lab energy Mev	Lab angle θ	C.m. angle $\bar{\theta}$	Lab angle π-π
1 π^-	90	63	93	
π^0	200	56	81	104
p	86	23	99	
2 π^-	80	34	58	
π^0	280	12	19	47
p	5	10	177	
3 π^-	165	48	72	
π^0	76	81	112	37
p	138	10	42	
4 π^-	240	15	24	
π^0	165	37	47	51
p	6	46	112	
5 π^-	150	38	59	
π^0	150	47	71	50
p	71	47	120	
6 π^-	100	32	53	
π^0	256	16	25	49
p	6	6	178	

[28] Backward mesons can be associated with fast recoil neutrons to take up the energy. Since discernment of π^0 production among such events is not possible, they are not considered.

[29] C. N. Yang and E. Fermi (private communication). See Blau, Caulton, and Smith, Phys. Rev. **92**, 516 (1953).

[30] Calculations based on $\pi - \mu - e$ decays observed in plates and stacks lead to a value of 0.4±0.1 percent for the production of positive mesons alone (in the energy interval 0–30 Mev).

An estimate of the probability of meson production per nucleon can be obtained by considerations similar to those in the case of photomeson production.

Francis and Watson[31] describe the relation between the photomeson production cross sections σ_π from a nucleus of atomic weight A, and σ_f, the cross section for production on free nucleons. The equation

$$\sigma_\pi = A\eta\sigma_f(\lambda/V_A)\sigma_{\text{abs}}$$

represents this relationship, where λ is the mean free path in nuclear matter, σ_{abs} is the absorption cross section for mesons, V_A is the nuclear volume, and η is a factor smaller than one.

In applying this equation to the present case, the value of λ, 3×10^{-13} cm, found by Kessler and Lederman[9] for 120-Mev mesons, has been used since this energy is comparable with the mean energy of emitted mesons. σ_π is assumed to be 2 percent of σ_{total}, where $\sigma_{\text{total}}=610$ mb[32] calculated from the mean free path of 500-Mev mesons[33] averaging over all emulsion nuclei, taking into account their transparency. Furthermore, one has to consider that not only the produced, but also the scattered mesons are subject to additional scattering and absorption (square of absorption factor). Finally, contrary to the problem of photomeson production, the attenuation of the incident mesons has to be accounted for. This has been done in an approximate manner by multiplying the number of nucleons per atom by a factor P_A. P_A is the probability that a 500-Mev meson suffers exactly one collision in passing through a nucleus of atomic mass number, A. This assumption implies that mesons having suffered more than 1 collision in passing through the nucleus no longer have sufficient energy to produce further mesons.

If one takes into account heavy and light emulsion nuclei and their respective abundance in the emulsion, the final result becomes:

$$0.02\times610\times10^{-27}=3.4\sigma_{pr},$$

and σ_{pr}, the cross section for production of charged mesons per nucleon, is 3.5 mb or 14 percent of the total meson-nucleon interaction cross section at 500 Mev. The calculated meson production cross section probably has been underestimated, since the mean free path λ may be smaller than 3×10^{-13} cm.

A probable overestimate of the meson production cross section based only on experimental data can be obtained by the following considerations.

With 135-Mev incident meson energy,[4] only 22 percent of all interactions in the emulsion have a single meson leaving the nucleus. Since in the case of meson production, the probability that two mesons leave the nucleus has to be considered, one would expect that only 5 percent of all cases with meson production can be observed and that actually in 40 percent of all interactions production of charged mesons takes place. This estimate would lead to a cross section of 10 mb for production of charged mesons. The value 10 mb, however, is considered an overestimate since an incident meson, on the average, has to traverse a larger path within the nucleus than either of the mesons emitted in the case of meson production.

The actual value of the meson production cross section (charged mesons) will lie between 3.5 and 10 mb. From statistical considerations,[29] the cross section for meson production by mesons is expected to be 12 percent of the total cross section.

D. Comparison with Cosmic-Ray Experiments

1. *Meson Scattering*

The mean energy of mesons emitted as shower particles in cosmic-ray experiments is 640 Mev.[34] Therefore, a comparison with experiments using only slightly lower energy mesons should be of interest.

In cosmic-ray investigations it had been assumed that for mesons the interaction mean free path is geometric over a wide range of energies. With artificial mesons (based mainly on counter measurements), strong energy dependence of the cross section has been found. For 500-Mev mesons the mean free path in nuclear emulsions is about twice geometric. Some calculations connected with transition effects and the mean free path of the star-producing components will have to be revised because of these data.

Interactions of single mesons have been studied by the Bristol group. Lock and Yekutieli[35] compile results on this subject; 86 meson interactions in the energy range of 0.1 to 1 Bev are discussed. The conclusion is reached that mesons below 160 Mev are strongly absorbed, while at higher energies, charge exchange prevails. This conclusion is based on the relatively low excitation energy of stars induced by mesons of energy higher than 160 Mev. It is assumed that more than 50 percent of all mesons suffer charge exchange, a value which seems high in comparison to observations with artificial mesons.

Sixteen meson induced events have been found (in the majority of the cases the incoming meson energy was higher than 300 Mev), where an identified meson leaves the nucleus. As in the cases with artificial mesons, great energy losses in the emitted mesons have been observed; an attempt was made to explain these energy losses on the basis of repeated scattering. This explanation makes it necessary to assume a high interaction cross section for mesons and this assumption is in dis-

[31] N. C. Francis and K. M. Watson, Phys. Rev. **89**, 328 (1953); **92**, 291 (1953); compare with I. Reff, Phys. Rev. **91**, 150 (1953).
[32] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **92**, 1578 (1953), see also reference 17.
[33] 610 mb is in fair agreement with an experimental value found by comparing the number of stars and inelastic events with the number of incident particles corrected for μ-meson and electron contamination.

[34] M. Sands, Phys. Rev. **77**, 180 (1950).
[35] W. O. Lock and G. Yekutieli, Phil. Mag. **43**, 231 (1952).

agreement not only with the cross section found for artificial mesons in this energy interval, but also with observations on mesons in showers produced by high energy nucleon-nucleon collisions; the mean energy of these shower particles is 640 Mev, and therefore, comparable with the energy of the single mesons, observed by the Bristol group[36] and in the experiments with 500-Mev mesons.

From the number of mesons scattered backward in nucleon-nucleon collisions, the interaction cross section of shower particles is estimated to be not greater than 10 percent of the geometrical cross section. The number of black and grey tracks in stars connected with shower particles increases only very slowly with the increasing number of shower particles and that again favors the assumption of a small interaction cross section and a small probability for meson reabsorption.

The discrepancy between the interaction of single mesons and mesons produced in "showers" is difficult to understand. Several hypotheses[36] have been put forward to clarify this problem, but none of them is entirely satisfactory. The mean free path for mesons of energy ≥ 300 Mev is equal or even smaller than the mean free path of relativistic nucleons; therefore, mesons produced in nucleon-nucleon collisions traverse in the average the same nuclear path as secondary mesons scattered or produced in meson-nucleon collisions.

The difference in the behavior of single incident mesons and shower mesons may be connected with the production mechanism of the latter, the formation of excited nucleons. Not enough is known about this process to discuss the consequences this phenomenon may have on the scattering of produced mesons. If it should be possible to assume that the excited nucleons have a finite lifetime $\sim 10^{-23}$ sec, for example, then excited nucleons (great mass, and, therefore, less subject to scattering), not single mesons, will traverse at least part of the nuclear path.

One has reason to believe that also in meson-nucleon collisions excited nucleon formation may take place[37]; however, the probability of this process will be smaller (only one nucleon as compared with two in nucleon-nucleon collisions).

2. *Meson-Meson Production*

Indirect evidence on meson-meson production has been obtained in absorption experiments. Rosser and Swift[38] exposed sensitive emulsions at mountain altitudes below and above 30 cm of lead. By comparing the ratio of charged and neutral primaries producing shower particles ($n_s \geq 2$), a ratio twice as large has been found in absorber plates. This effect, if explained entirely on the basis of meson-meson production, would lead to a production cross section nearly equal to the geometric cross section of the average emulsion nucleus. This result is in disagreement with observations on artificial mesons.

One event of meson-meson production initiated by a 1-Bev meson has been identified by Camerini *et al.*[36] The cross section of meson production per nucleon has been estimated to be 10 percent of the elastic cross section.

Lal *et al.*[26] found 7 meson showers produced by relativistic shower particles from very high-energy primary collisions. The showers are of the jet type (few evaporation tracks) and have a large angular spread. Since this type of shower is not observed in nucleon collisions, production by mesons has been assumed. The low excitation of the nucleus makes it improbable that scattering may have occurred. Therefore, some of the mesons are emitted originally with rather large angles to the primary meson. In the c.m. system more than half of all mesons are emitted in the backward hemisphere.

From experiments with artificial mesons of lower energy, not enough information is yet available to decide if, actually, the produced mesons are emitted preferentially in the backward direction.

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[36] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950); Camerini, Davies, Fowler, Franzinetti, Lock, Perkins, and Yekutieli, Phil. Mag. **42**, 1261 (1951).

[37] Crussard, Walker, and Koshiba (private communication).

[38] W. G. Rosser and M. I. Swift, Phil. Mag. **42**, 856 (1951).