num. One can, however, obtain other information from a study of these numbers. As is shown in Table IV, the ratio of numbers of interactions having multiplicity $\geqslant 2$ is 2.3 ± 0.6, which is well in agreement with the ratio 2 expected for geometric cross sections. In the case of higher multiplicity interactions, however, the ratio[13] is 4.9 ± 1.1. (Note that, from Fig. 3, a ratio 4 corresponds to vanishingly small cross sections, assuming the ratio to be unbiased by the selection of events.)

One concludes that the measured ratio 4.9 reflects the effect of different detection probabilities for interactions of different multiplicities. The change in ratio with multiplicity is, in consequence, proof that nuclear interactions of high energy neutrons produce, on the average, a higher multiplicity of penetrating particles in lead than in aluminum. The same result has been obtained by Lovati and his co-workers.[5]

[13] This number differs from the one in Table IV because it includes the interactions of high multiplicity occurring in the lowest three plates.

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A Cloud-Chamber Study of Nuclear Interactions in Lead and Aluminum. Part II*

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The results of the cloud-chamber Experiment B described in Part I are used to discuss some properties of the particles produced in nuclear interactions. Evidence is presented showing that the electronic showers produced in nuclear interactions are all photon-initiated. Upper limits on the proportion of directly produced electrons are found to be 20 percent in interactions in aluminum and 41 percent in lead. The possibility that the photons are decay products of neutral π-mesons is strongly indicated, although no definite proof can be given. It is shown that the mean free paths for nuclear interaction of secondary penetrating particles are 172 ± 30 g/cm^2 in lead and 164 ± 50 g/cm^2 in aluminum. Assuming that the penetrating particles consist of equal numbers of π-mesons and protons, one obtains an upper limit of 250 g/cm^2 for the mean free path for interaction of π-mesons in lead.

I. INTRODUCTION

We shall be concerned in this paper (Part II) with the study of the secondary particles produced in interactions observed in Experiment B (see Part I). In Sec. II, we shall discuss the production of the electronic component, stressing the likelihood that all of the electronic showers originate as photons. In view of recent evidence[1,2] on the existence of the neutral π-meson, it will be of interest to investigate this hypothesis in relation to the evidence obtained in this experiment.

In Sec. III, we shall show that the secondary pene-penetrating particles produce nuclear interactions in lead and aluminum with cross sections near the geometric values. It will be seen that the bias introduced by the counter selection system is important even in the case of the simple selection system used in this experiment, and therefore that the difficulty of computing corrections for this effect may account for the fact that our results are at variance with those obtained in similar cloud-chamber experiments.[3–5]

We present in Figs. 1–4 some examples of nuclear interactions which are thought to be of unusual interest.

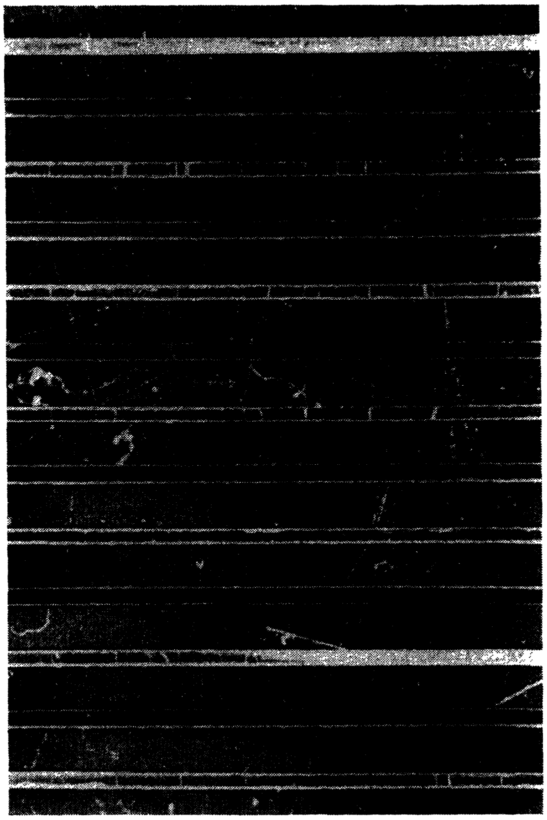
II. SOME GENERAL PROPERTIES OF SECONDARY PARTICLES

Let us first note some general properties of the secondary particles produced in the nuclear interactions of Experiment B. We are concerned here only with the penetrating particles (particles of minimum ionization traversing two lead plates without multiplication) and the electronic showers (of two or more electrons). The discussion in this paragraph and in Sec. III will be limited to a group of 82 nuclear interactions resulting in the production of more than two penetrating particles. The numbers of penetrating particles and showers observed in these cases are given in Table I. The average multiplicity of the penetrating particles is seen to be 4.5. The angle of emission of a penetrating particle is defined as the angle of its track with the average direction of the group. The average value of these angles was found to be 16°. The electronic showers are grouped

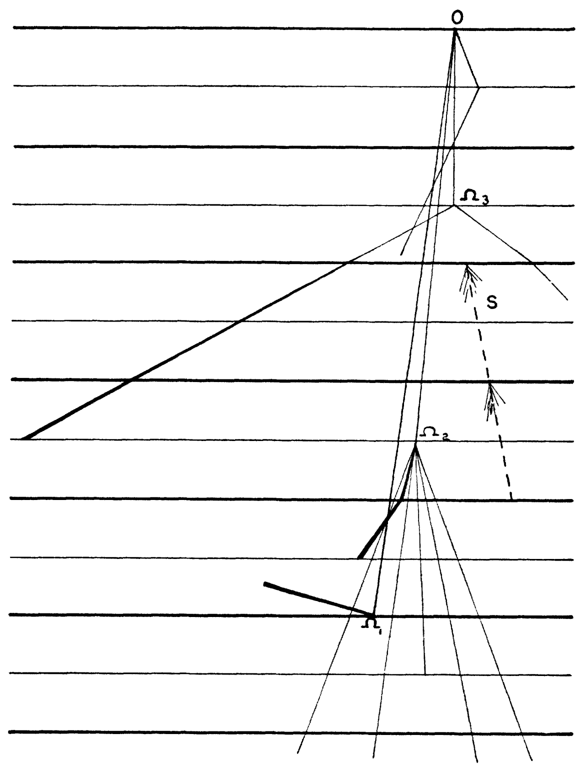
TABLE I. Production of penetrating particles and electronic showers in nuclear interactions of types 3, 3′, 4, 4′, and 5.

Number of interactions	Penetrating particles	Average angle of production	Electronic showers (number of electrons) >10	5 to 10	3 to 5	no penetration <3
82	355	16°	22	58	43	25

* This work was supported in part by the joint program of the ONR and AEC.
† Now at the University of Rochester, Rochester, New York.
[1] Steinberger, Panofsky, and Steller, Phys. Rev. 78, 802 (1950).
[2] Carlsen, Hopper, and King, Phil. Mag. 41, 701 (1950).
[3] W. B. Fretter, Phys. Rev. 76, 511 (1949).
[4] Lovati, Mura, Salvini, and Tagliaferri, Phys. Rev. 77, 285 (1950).
[5] W. W. Brown and A. S. McKay, Phys. Rev. 77, 347 (1950).



(a)



(b)

FIG. 1. In this picture, one finds an exceptionally clear example of the production of a photon in a nuclear interaction. It is also one of several pictures which indicate rather convincingly that π-mesons interact with nuclei. Three penetrating particles were produced in the first plate (lead) by an incident neutron, and were emitted within a cone of 13°. They all suffered nuclear collisions in other plates (Ω_1, Ω_2, Ω_3). The interaction at Ω_1 produced only one visible secondary particle, a low energy nucleon emerging upward from the plate. The particle which is thought to have triggered the cloud chamber was one of five penetrating particles produced at Ω_2. The third interaction (Ω_3) occurred in an aluminum plate; one observes, besides the two minimum ionization particles emitted at large angles, an electronic shower S which begins in the lead plate immediately below Ω_3, and whose axis reprojects exactly to Ω_3. This is taken as evidence of the production of a photon.

It is hardly possible that all three penetrating particles produced in the primary interaction were protons. If we choose this interpretation, we should have to assume either that the incident neutron had an extremely high energy (and therefore that relativistic contraction explains the small angular divergence of the particles), or that the protons resulted from a minimum of four elastic collisions within one nucleus (in which case the small divergence is very improbable). We believe, therefore, that at least one of these particles was a π-meson.

in Table I according to the number of electrons observed in a region near the maximum of the shower. This number is significant only if the development of the shower is observed in the well-illuminated part of the chamber. In this case the maximum may extend over a region of five or six intervals, and the average number of electrons in these intervals can be related to the energy of the shower. We have used the Tamm and Belenky[6] formula to deduce the energy of the showers; this amounts to multiplying the average number of electrons by 100 Mev. In most cases, the energies of the showers could not be estimated with any certainty; the figures tabulated in Table I give, therefore, only a crude estimate of the energy spectrum of the showers. The average number of showers per primary interaction was 1.9. It may be noted that both the angle of emission of penetrating particles and the multiplicities of particles and showers are probably underestimates, since particles emitted at wide angles could not be identified.

(A) The Origin of the Electronic Showers

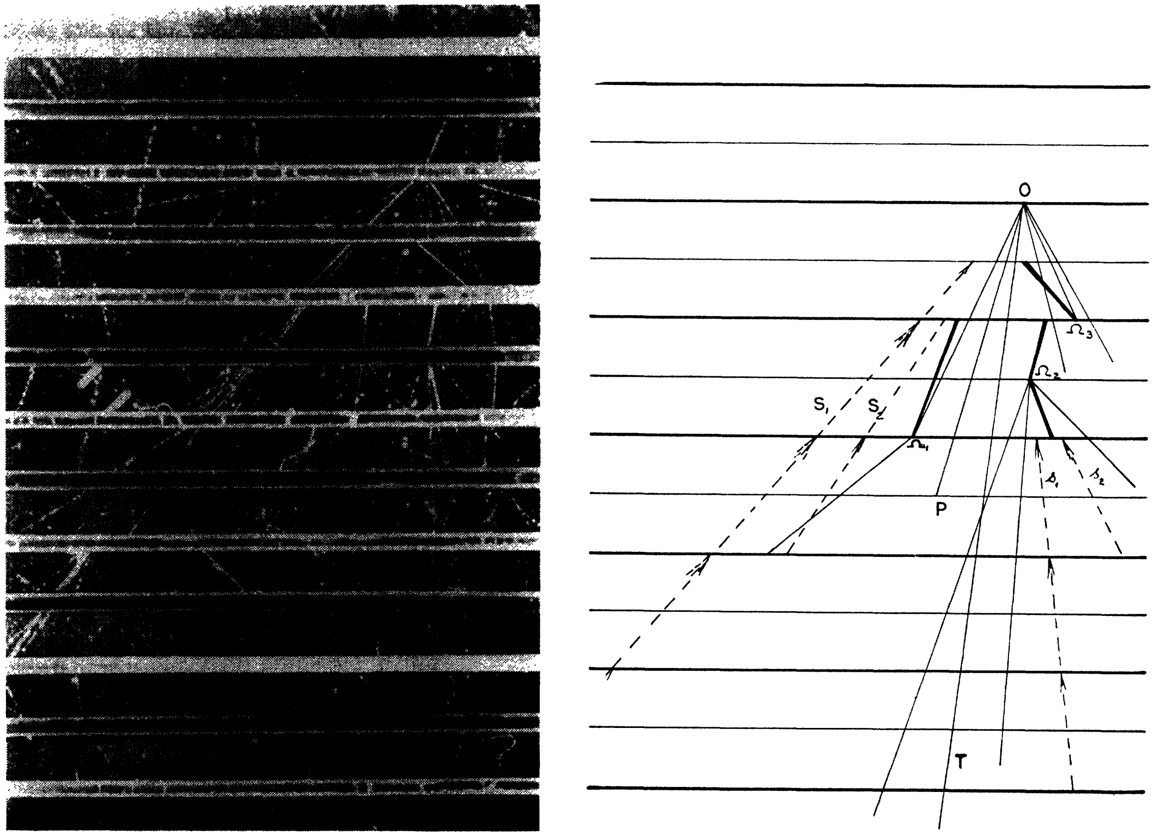
The following analysis will show that all of the showers observed may be considered to be photon-initiated.[7] This conclusion extends to higher energies the results obtained by York, Moyer, and Bjorklund[8] at 350 Mev and confirms the observation of Kaplon, Bradt, and Peters.[9] We shall also present evidence on the possible production of the photons by a neutral meson and give an estimate of the relative number of

[6] I. H. Tamm and S. Belenky, J. Phys. U.S.S.R. 1, No. 2 (1939).

[7] B. P. Gregory and J. H. Tinlot, Phys. Rev. 77, 299 (1950).

[8] York, Moyer, and Bjorklund, Phys. Rev. 76, 187 (1949).

[9] Kaplon, Peters, and Bradt, Phys. Rev. 76, 1735 (1949).



(a) (b)

FIG. 2. This picture is a fairly representative example of the high multiplicity interactions of Experiment B. Proceeding from left to right, we find:

(a) Two electron showers S_1 and S_2 beginning in the fourth (aluminum) and fifth (lead) plates. These showers presumably were produced by two photons originating in the primary interaction, 0, in the third plate. It is therefore possible to look for correlation of the photons according to the neutral meson hypothesis, as described in Sec. II. The difficulty of estimating the energies of the photons is evident. For instance, one counts the number of electrons in S_1 in the intervals below the third plate, and obtains the following sequence: 0, 2, 5, 7, 2, 2, 5, 4. Qualitatively, the shower seems about to end near the seventh plate, but begins again at the ninth plate. Similar fluctuations in the development of showers were often observed. It is seen that large errors may be made in estimating the energy of a shower when one cannot follow its development through a number of lead plates. In this case, we estimate the number of electrons at the maximum of S_1 to be 4 to 7, and the energy of the photon to be between 400 and 700 Mev. In the case of S_2, no good measure of energy could be made, since the shower left the illuminated region after traversing only four intervals. We may, however, compute the expected energy of the second photon from the knowledge of the energy of the first photon and the angle in space between the two showers ($19°\pm2°$), under the assumption that the two photons are decay products of a neutral π-meson. The energy of the second photon should then be between 230 and 550 Mev, a result which is consistent with the appearance of S_2. The neutral meson relation cannot, however, be proved in this case.

(b) Three penetrating particles produced at 0. The first interacts at Ω_1, the second leaves the illuminated region at P, and the third particle, OT (not clearly visible on the photograph), appears to have triggered the cloud chamber.

(c) A nuclear interaction at Ω_2 (presumably caused by a neutron produced at 0) which produces two penetrating particles and two photons, which materialize in the lead plate below Ω_2. As in the previous case, it is possible to define the energy of one photon (400 to 600 Mev) and the angle between the two showers ($28°\pm2°$), but not the energy of the second photon. On the neutral meson hypothesis, the expected energy of the second photon is 150 to 250 Mev.

(d) A particle which traverses one aluminum plate and then interacts (Ω_3). This particular interaction was rejected for the analysis of Sec. III, since the particle which produced it would have left the illuminated region before traversing two lead plates, and therefore would not have been recorded as a penetrating particle.

penetrating particles and neutral mesons produced in this set of nuclear interactions.

(a) *Production of Photons in Nuclear Interactions*

We consider now a set of 80 electronic showers which penetrated at least one lead plate, had five or more electrons, and whose axes reprojected to the origins of nuclear interactions; these showers were produced in nuclear interactions occurring in the illuminated region (see Table IV, Part I). The requirement on penetration assured that the axis and direction of each shower could be defined. It was found that the axes of these showers reprojected exactly to the origin in all but a few obvious cases of atmospheric showers not directly related to the nuclear interactions. One may thus conclude that the shower-initiating particle (whether

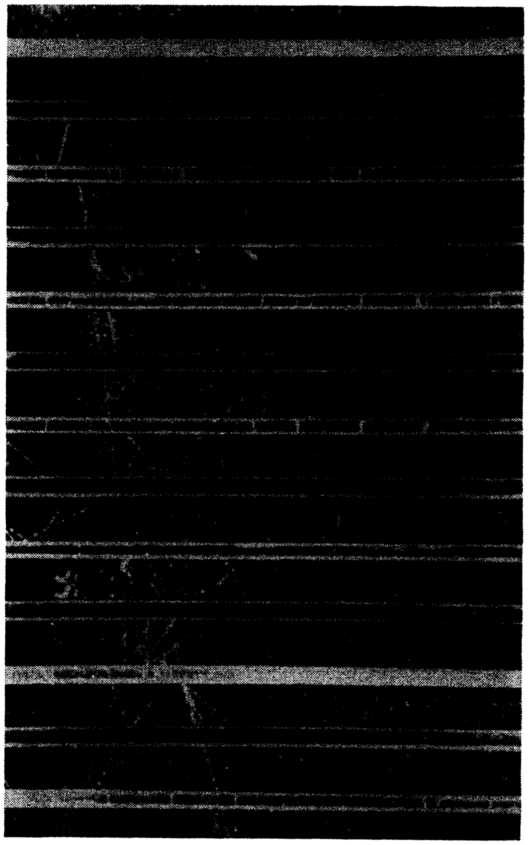


FIG. 3. This picture is representative of the large group showing low multiplicity interactions. A penetrating particle, whose track is somewhat obscured by electronic showers, penetrates five lead plates without scattering. The development of the showers is exceptionally clear. These showers are evidence of the production of two photons in the second (aluminum) plate. The energies of the photons are accurately defined (400 Mev and 900 Mev), but the angle between the showers is difficult to measure. On the neutral meson hypothesis, the angle should be 14°. The measured value is between 8° and 13°, and thus not in contradiction with the predicted value. The picture can be interpreted as showing the production by a high energy neutron of a single neutral meson of about 1300-Mev energy, and one charged meson, or possibly a recoil proton. In either case, the energy of the incident neutron must be at least 2 Bev.

photon or electron) was produced at a distance from the origin of the nuclear interaction small compared with the thickness of the plates. Examples of the appearance of such showers are given in Figs. 1, 2, and 3.

The "beginning" of each shower (the plate at which electrons first appear) was located whenever possible. When the complexity of the event obscured the development of the shower, the "beginning" of the shower could be located only to within a group of plates. The resulting data are given in Table II. For comparison, the average probabilities of materialization of a photon produced at a random depth in the plate of origin (plate No. 1) are listed in the second row of Table II.

One first notes that, within the statistical uncertainties, the experimental numbers fit well with the predicted numbers for production of photons only. The evidence is most striking when the interaction occurred in aluminum. In 22 of these cases, electron showers began in plates below the one of origin, while in no case could we identify an energetic electron emerging from the aluminum plate. The upper limit on the number of directly produced electrons is given by the number of uncertain cases (6) of column 7. We therefore set a limit of 20 percent for electron-initiated showers produced in interactions in aluminum. The interpretation of the data on interactions occurring in lead is more difficult, because of the larger number of uncertain cases[10] (columns 7 and 8). Let us assume purely photon-initiated showers. Then the 18 cases of

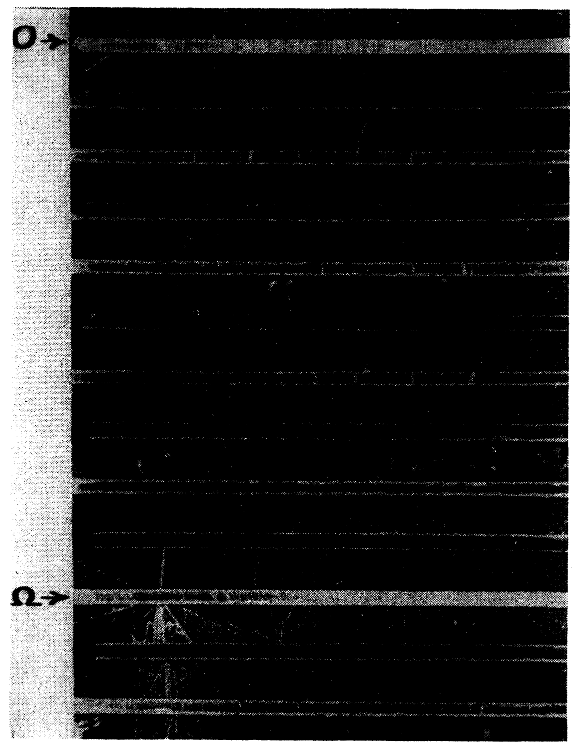


FIG. 4. In this unusual example, we observe two nuclear interactions (at 0 and Ω), the first of which is very simple, and the second very complex. The average direction of the particles produced at Ω lies along the line 0Ω, and the tracks are of the same "age." The interactions are therefore almost certainly associated. The penetrating particle produced in the interaction at 0 is emitted at an angle of 10° from the direction 0Ω. It is thus probably a meson, although it could be a knock-on proton resulting from two elastic collisions within one nucleus. The most likely interpretation of this picture is the following.

A neutron interacts in the first plate to produce one meson (energy unknown, but greater than 300 Mev), and a neutron of several Bev energy. The meson undergoes nuclear scattering in the sixth (aluminum) plate, but is not visibly scattered in five lead plates. The neutron interacts in the eleventh plate with great loss of energy. This picture is thus another example of low multiplicity meson production at very high energy.

[10] The increase in uncertainty was due to the greater complexity, on the average, of the interactions in lead; for example, one found (Sec. III, Part I) that the average number of penetrating particles produced in lead is greater than that produced in aluminum.

showers beginning below the plate of origin (certainly photon-initiated) correspond to a total of 33 photons, 11 of which should have produced showers beginning in plate No. 1. Instead, one finds a possible maximum of 34 such showers, if one adds the 15 uncertain cases (column 7) to the 19 showers definitely observed to begin in plate No. 1. Thus, the proportion of electrons directly produced in lead is, at the most,

$$(34-11)/(34-11+33)=41 \text{ percent.}$$

It is certainly more probable that some of the uncertain cases correspond to photon-initiated showers. In fact, one may in a reasonable way apportion among the other columns the number of uncertain cases of column 7, and so explain all of the showers as photon-initiated.

(b) *Production of Neutral Mesons*

If a neutral meson decays into two photons of energies E_1 and E_2, the angle ψ between the directions of emission of the two photons is determined, and is given by the relation,

$$(2\sin\tfrac{1}{2}\psi)^2=[\mu c^2]^2/E_1E_2.$$

As was indicated previously, we observed in a considerable number of cases two or more electron showers produced in one nuclear interaction. In these instances, one could estimate the energies and the angle ψ between pairs of showers and see if the above relation could be satisfied, assuming a neutral meson mass equal to that of the charged π-meson. Agreement was indeed possible in a number of examples, one of which has been published previously.[7] However, the probable errors on the estimated energies of the showers and, in some cases, on the angle ψ were found to be quite large. (Examples of the probable errors are given in Figs. 2 and 3.) We were brought to the conclusion that the examples in which the relation was satisfied could not be considered as proof of the existence of the neutral meson. Nevertheless, we believe that the following results give considerable support to the neutral meson hypothesis:[11]

(1) In the 13 cases in which the two showers penetrated at least one lead plate, 11 were found to satisfy the energy-angle relation for production by a neutral π-meson.

(2) In the 12 cases in which only one shower was observed, these showers had energies of less than 500 Mev. This is not surprising, since low energy mesons would produce photons at wide angles, and thus the probability of observing both of the resulting showers would be small.

If we assume hereafter that the neutral meson is responsible for the production of pairs of photons, we can compute estimates of the energy spectrum, the lifetime, and the absolute number of the mesons produced in the group of interactions under consideration.

[11] We wish to emphasize that the findings of Steinberger, *et al.* (reference 1), seem to be conclusive, but that the process investigated here is one of considerably higher energy.

TABLE II. Starting point of showers produced in nuclear interactions. Plate No. 1 is the plate in which the nuclear interaction occurred, Plate No. 2 is one immediately below, and so on.

Interactions in lead								
Beginning of shower	Plate No. 1 Pb	Plate No. 2 Al	Plate No. 3 Pb	Plate No. 4 Al	Plate No. 5 Pb	Other plates (below No. 5)	No. {1 or 2 or 3	No. {3 or 4 or 5
Observed number of showers	19	1	10	0	4	0	15	3
Calculated probability for materialization of a photon (%)	35	4	36	1	14	10	···	···
Interactions in aluminum								
Beginning of shower	Plate No. 1 Al	Plate No. 2 Pb	Plate No. 3 Al	Plate No. 4 Pb	Plate No. 5 Al	Other plates (below No. 5)	No. {1 or 2	No. {2 or 3 or 4
Observed number of showers	0	13	0	5	0	0	6	4
Calculated probability for materialization of a photon (%)	3	58	2	21	1	15	···	···

The data of Table I give a rough energy spectrum of the electronic showers; from this, one can deduce the general form of the energy spectrum of the neutral mesons. This spectrum was needed for developing the following arguments, but is otherwise of no interest, since the selection of nuclear interactions is strongly dependent on the triggering requirements.[12] If a neutral meson is produced by a nuclear interaction in a lead plate, the probability that one of the decay photons will materialize in this same plate will depend on the lifetime and the energy of the meson. We may refer to the observed number of such cases (Table II), and make use of the computed energy spectrum. The largest value of the mean life compatible with the observations was found to be

$$\tau=10^{-12} \text{ sec.}$$

The average energy of the mesons considered in this computation was about 1 Bev. This lifetime is consistent with the estimate of Kaplan, Bradt, and Peters.[9] The total number of neutral mesons produced, corresponding to the numbers of showers listed in Table I, follows immediately from the knowledge of the spectrum, if one assumes a reasonable lower limit on the observable energy. It is probable that electronic showers of energy less than 150 Mev were not detected. The number of neutral mesons corresponding to the 148 electronic showers is then 110. This gives a ratio of neutral mesons to penetrating particles of 1:3.

[12] For example, the spectrum is found to have a much smaller number of low energy mesons than is predicted by Sands [Phys. Rev. 77, 180 (1950)], and does not agree with the spectrum measured recently by Carlsen, *et al.* (reference 2).

TABLE III. Mean free path for interaction of secondary particles.

Type of primary interaction: (Part I, Table IV)	Lead Traversals g/cm²	Lead Nuclear interactions (ionizing particle)	Lead Nuclear scattering	Lead Nuclear interactions (non-ionizing particle)	Aluminum Traversals g/cm²	Aluminum Nuclear interactions (ionizing particle)	Aluminum Nuclear scattering	Aluminum Nuclear interactions (non-ionizing particle)
One penetrating particle (Types 1 and 1′)	710	0	0	2	265	1	0	0
Two penetrating particles (Types 2 and 2′)	730	0	0	1	278	1	0	1
Interactions of high multiplicity (Types 3, 3′, 4, 4′, 5)	2634	12	4	2	931	5	1	3
Origin of primary interaction outside illumination	3383	13	6	4	1211	5	2	1
Sum of 3rd and 4th row	6017	25	10	6	2142	10	3	4

III. NUCLEAR INTERACTIONS OF SECONDARY PENETRATING PARTICLES

Several authors[3–5], have measured the collision mean free path for the secondary particles comprising the penetrating showers by observing the behavior of these particles while traversing the plates in a cloud chamber. The same technique is used to obtain the results presented in this section. It is found, in common with these observers, that the main problems in interpreting the data involve corrections for possible errors of two types: (1) the effect of the finite thickness of the plates in the chamber in obscuring secondary interactions, and (2) the bias on the events observed caused by the requirements of the counter control triggering system.

Considerations of the first type usually arise in defining criteria for identifying secondary interactions. We shall show that the thickness of the plates used for this experiment was sufficiently small to cause little difficulty in identifying secondary interactions. The problem of analyzing the effects of the triggering system is much more involved. The necessary corrections will be shown to be small, but only for the cases of primary interactions of high multiplicity.

(A) Selection and Grouping of Primary Interactions

For reasons to be made evident in the succeeding paragraphs, the primary nuclear interactions were grouped according to the number of secondary penetrating particles. The pictures considered in the analyses to follow include those of primary interactions occurring in the illuminated region (listed in Table IV of Part I), and also those showing secondaries of interactions occurring outside the illuminated region. The minimum requirements for identifying an interaction of the latter type was a combination of penetrating particles and electronic showers totaling three or more, clearly diverging from a point in the material of the cloud chamber. We believe that the selection and grouping of pictures was independent of the secondary interactions.

(B) Definition of Traversals and Identification of Secondary Interactions

As a first step in determining the amount of lead and aluminum traversed by the penetrating particles (hereafter called the traversal of the particles), the track of each particle was located in space. We counted the traversal and interactions of such a particle only if its track (or its extension, if it interacted) traversed two lead plates within the illuminated region. In some cases, portions of the track of a particle were not used for computing traversal if the track was obscured by the superposition of tracks of other particles or electronic showers; nuclear interactions of particles in such regions were likewise ignored. The angle of incidence of the track with the plates was taken into account in measuring the actual amount of material traversed.

We identified secondary nuclear interactions other than scattering or nuclear stopping according to the criteria used in Experiment A (Part I). The cases of nuclear scattering were also identified whenever possible by the use of the criterion given in Part I, but extended to accept cases of large scattering associated with small scattering angles before and after. We selected in this way four interactions of type (1) and five interactions of type (2) as described in Fig. 2, Part I. Four other interactions could not be identified by this rule. A description of each case may best explain our choice:

In two cases the particle was deflected by an angle of more than 50° but was not scattered in one adjacent lead plate. (In one of these cases, the ionization changed abruptly after the scattering.)

In one case a proton was clearly identified through three lead plates after suffering a scattering of 27° in an aluminum plate.

In one case a particle stopped in a lead plate with the emission of a low energy particle in the backward direction.

It is felt that the number of these cases incorrectly identified, or of other cases missed, is small, since very few examples of large scattering were found which are not included in the above list.

The problem of defining nuclear "stopping" did not arise, because in no case was it found that a particle of minimum ionization which had traversed one lead plate without scattering was stopped in a succeeding plate without the emission of a nuclear secondary particle. The number of particles which stopped through nuclear interaction before traversing one lead plate (and which therefore could not have been identified) is thus believed to be very small. This result is similar to that found in Part I in the case of primary protons. The results of the survey of secondary interactions (uncorrected) are tabulated in Table III. The number of interactions of secondary neutrons was also recorded. Although the identification of neutron interactions is more difficult than that of interactions of ionizing particles, the data will be useful for estimating the ratio of secondary protons and π-mesons.

(C) Correction for the Effect of the Triggering Requirement

If we ignore the effect of the triggering process on the selection of events, we obtain the mean free path for interaction of the secondaries simply by dividing the total traversal by the number of interactions. This mean free path differs from the true collision mean free path principally because of two opposing effects: (1) a particle capable of triggering the counter telescope may interact without producing other particles which can trigger (absorption), and (2) a penetrating particle may produce by nuclear interaction a particle which can trigger (creation).

Since the probability of expanding the chamber is an increasing function of the number of triggering particles, absorption will increase the measured mean free path, while creation will decrease it.

We can estimate the magnitudes of these two effects and the resulting corrections to be made on the measured mean free path by assuming the effects to be independent. Let us consider how the probability of "single" triggering is altered by absorption. (Since, as shown in Sec. III-3, Part I, "single" triggering is dominant for both low and high multiplicity events, the discussion will be valid for the majority of the primary interactions.) We define a triggering particle as a penetrating particle emerging from the primary nuclear interaction and aimed at the bottom tray of the telescope. Let x be the equivalent lead thickness which a particle traverses in the chamber, y be the thickness of lead shielding in the telescope, and N be the number of triggering particles produced in a primary nuclear interaction. To correct for absorption with a mean free path λ, one must reduce the total traversal of the N particles by multiplying by the factor,

$$F(N)=\frac{1-[1-e^{-(x+y)/\lambda}]^{N-1}}{1-[1-e^{-(x+y)/\lambda}]^{N}}.$$

To calculate the values of F we may assume λ to be the geometric mean free path (167 g/cm² Pb, 82 g/cm² Al); averaging over the quantities x and y, we obtain

$$N=1, \quad F_1=0$$
$$N=2, \quad F_2=2/3$$
$$N=3, \quad F_3=6/7.$$

Other causes of triggering (electronic showers or neutron produced secondary interactions) will tend to decrease the necessary correction.

To correct for the effect of creation of triggering particles by secondary interactions one must reject a certain number of such interactions. The upper limit on this correction is obtained by rejecting all of them.

We can now proceed to apply these corrections to the different groups of primary interactions listed in Table III. Let us consider first the interactions of total multiplicity one or two. In these cases the biggest contribution to the total traversal is due to the triggering particles and the correction for absorption as calculated above is so large that the validity of the method is questionable. Moreover, of the two observed secondary interactions (for 1440 g/cm² Pb and 543 g/cm² Al), one "creates" a triggering particle. The correction for creation is also difficult.

Let us now group together the two sets of nuclear interactions listed in lines 3 and 4 of Table III. For each picture we can count the number N of triggering particles and apply a correction $F(N)$ on the corresponding traversal. For interactions originating outside of the illuminated region, the triggering particles were not visible in most cases and the correction was considered negligible.

The total correction for absorption was found to be 380 g/cm² of lead and 140 g/cm² of aluminum compared to a total traversal of all particles of 6015 g/cm² of lead and 2140 g/cm² of aluminum. One must reject in addition one interaction of a triggering particle in which case another secondary interaction created a triggering particle. The resulting correction on the mean free path is -5 percent.

Only two secondary interactions out of a total of 50 produced a triggering particle. The upper limit to the correction due to creation is therefore $+4$ percent.

The following conclusions were therefore drawn:

For all pictures of group I (low multiplicities) the corrections are extremely large and no useful result may be drawn from the data. The entire set of pictures was therefore discarded.

All other interactions were considered. The preceding analysis shows that the two errors due to absorption and creation cancel each other. Moreover, their magnitudes are small compared to the statistical error. We believe, therefore, that no appreciable error in the mean free path is introduced by the triggering requirements, if consideration is restricted to primary interactions producing more than two penetrating particles.

The figures of the last line of Table III give, therefore, the correct mean free path for interaction:

$$\lambda_{Pb}=172\pm30 \text{ g/cm}^2$$
$$\lambda_{Al}=164\pm50 \text{ g/cm}^2.$$

(D) Ratio of Mean Free Paths in Lead and Aluminum

It is seen that the mean free path in lead corresponds to the geometric cross section, while the one obtained for aluminum corresponds to one-half the geometric cross section. Although this result has a rather large statistical uncertainty, it seems to indicate some transparency of the aluminum nucleus. From the curves of

Fig. 3 (Part I) one finds that the mean free paths corresponding to a nucleon-nucleon cross section of 0.02 barn are

$$\lambda_{Pb} = 200 \text{ g/cm}^2$$
$$\lambda_{Al} = 140 \text{ g/cm}^2.$$

These numbers are quite consistent with the experimental values obtained above. It should therefore be emphasized that a mean free path in lead of more than 200 g/cm² is neither consistent with the experimental result, nor necessary to conform to the requirements of the theory of transparency.

(E) Mean Free Path for Nuclear Interaction of π-Mesons

It is not possible to establish the proportion of mesons and protons for the group of particles whose interactions were considered in this experiment. There is abundant evidence, however, that π-mesons are produced in nuclear interactions of primary particles whose energy is greater than a few hundred Mev.[13,14] Evidence of three types obtained in this experiment indicates that the group of penetrating particles considered includes considerable numbers of mesons:

(1) Relative numbers of electronic showers and penetrating particles.

As shown in Sec II-1, there is no contradiction in assuming the photons producing electronic showers to be the disintegration products of neutral π-mesons. The ratio of the computed numbers of neutral π-mesons to ionizing penetrating particles is about 1:3.

(2) Coulomb scattering of the penetrating particles.

Fifty of the 200 penetrating particles considered for study of secondary interactions suffered appreciable Coulomb scattering. Since consideration was restricted to particles of minimum ionization, it is believed that the majority of the scattered particles were mesons.

[13] O. Piccioni, Phys. Rev. **77**, 1, 6 (1950).
[14] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

(3) Relative numbers of interactions of ionizing and non-ionizing secondary particles.

The ratio of these numbers is 35:10 (Table III). The ratio of secondary protons to secondary neutrons produced in nuclear interactions of the energies involved in Experiment B is expected to be of the order of one.

From the above it seems reasonable to assume a value of one for the ratio of mesons to protons. The mean free path for interaction for mesons is then found to be between 160 g/cm² and 250 g/cm² of lead. The upper limit is not very sensitive to the assumed ratio of mesons to protons.

(F) Summary of Evidence Relating to Secondary Interactions

The following conclusions can be drawn on the basis of the discussion in the above sections (A) through (E):

(1) The most reasonable values of the mean free path for interaction of the penetrating particles produced in the nuclear interactions of Experiment B are 200 g/cm² of lead, and 140 g/cm² of aluminum.

(2) A reasonable upper limit on the mean free path for interaction of π-mesons in lead is 250 g/cm².

(3) The characteristics of the secondary interactions observed are very similar to those observed for primary cosmic-ray protons. In particular, one notices a similar scarcity of nuclear "stopping"; the number of nuclear scatterings is likewise small (about $\frac{1}{4}$ of all the secondary interactions).

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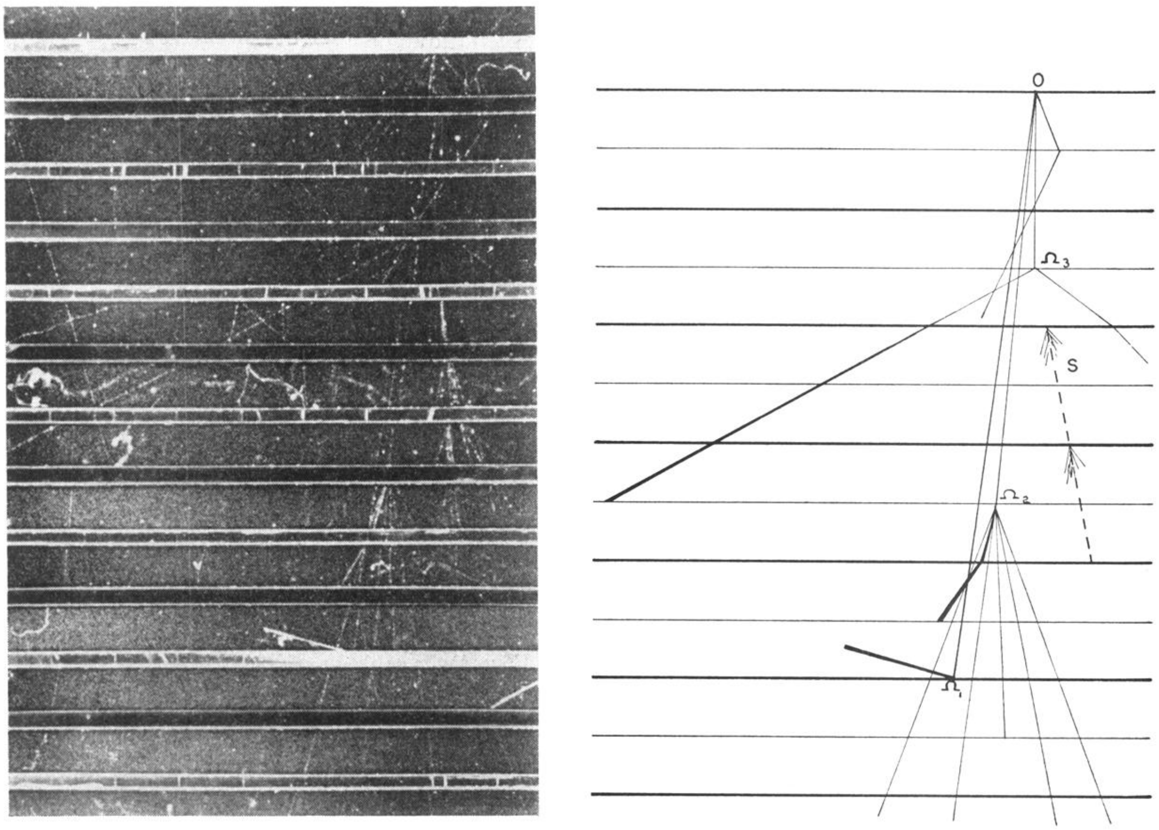
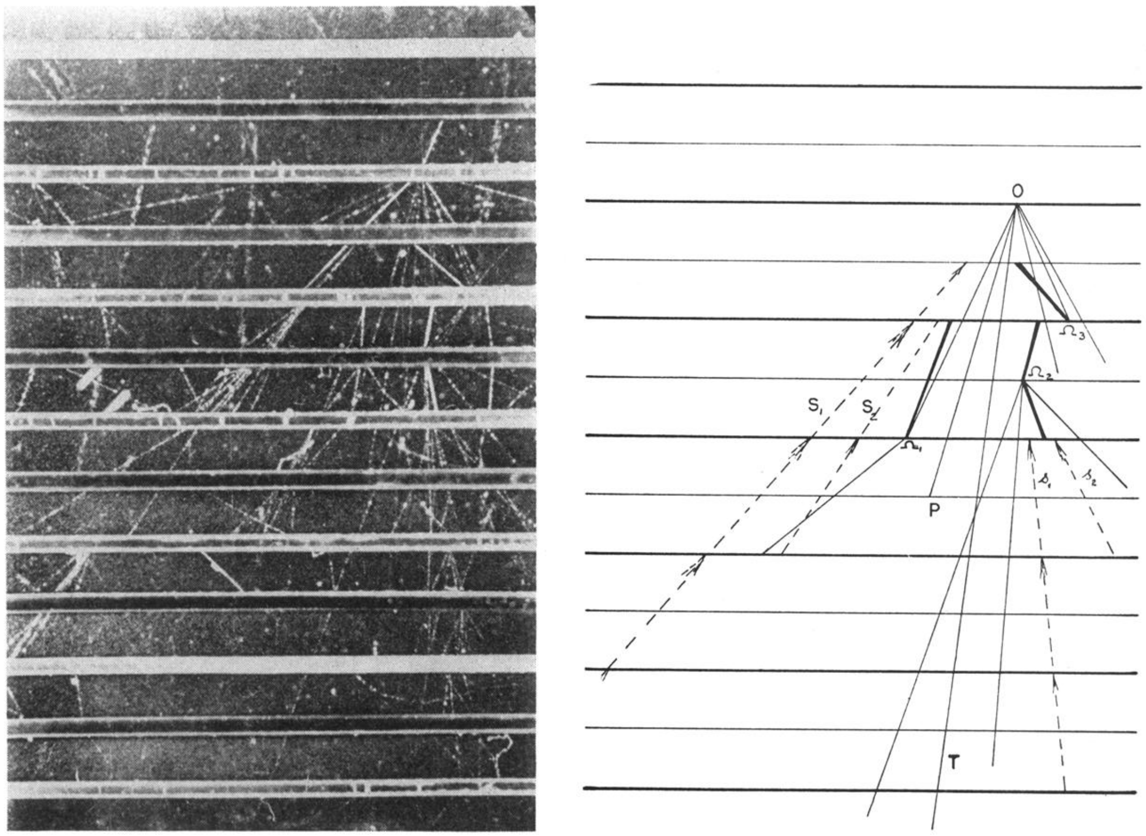


(a) (b)

FIG. 1. In this picture, one finds an exceptionally clear example of the production of a photon in a nuclear interaction. It is also one of several pictures which indicate rather convincingly that π-mesons interact with nuclei. Three penetrating particles were produced in the first plate (lead) by an incident neutron, and were emitted within a cone of 13°. They all suffered nuclear collisions in other plates (Ω_1, Ω_2, Ω_3). The interaction at Ω_1 produced only one visible secondary particle, a low energy nucleon emerging upward from the plate. The particle which is thought to have triggered the cloud chamber was one of five penetrating particles produced at Ω_2. The third interaction (Ω_3) occurred in an aluminum plate; one observes, besides the two minimum ionization particles emitted at large angles, an electronic shower S which begins in the lead plate immediately below Ω_3, and whose axis reprojects exactly to Ω_3. This is taken as evidence of the production of a photon.

It is hardly possible that all three penetrating particles produced in the primary interaction were protons. If we choose this interpretation, we should have to assume either that the incident neutron had an extremely high energy (and therefore that relativistic contraction explains the small angular divergence of the particles), or that the protons resulted from a minimum of four elastic collisions within one nucleus (in which case the small divergence is very improbable). We believe, therefore, that at least one of these particles was a π-meson.



(a) (b)

Fig. 2. This picture is a fairly representative example of the high multiplicity interactions of Experiment B. Proceeding from left to right, we find:

(a) Two electron showers S_1 and S_2 beginning in the fourth (aluminum) and fifth (lead) plates. These showers presumably were produced by two photons originating in the primary interaction, 0, in the third plate. It is therefore possible to look for correlation of the photons according to the neutral meson hypothesis, as described in Sec. II. The difficulty of estimating the energies of the photons is evident. For instance, one counts the number of electrons in S_1 in the intervals below the third plate, and obtains the following sequence: 0, 2, 5, 7, 2, 2, 5, 4. Qualitatively, the shower seems about to end near the seventh plate, but begins again at the ninth plate. Similar fluctuations in the development of showers were often observed. It is seen that large errors may be made in estimating the energy of a shower when one cannot follow its development through a number of lead plates. In this case, we estimate the number of electrons at the maximum of S_1 to be 4 to 7, and the energy of the photon to be between 400 and 700 Mev. In the case of S_2, no good measure of energy could be made, since the shower left the illuminated region after traversing only four intervals. We may, however, compute the expected energy of the second photon from the knowledge of the energy of the first photon and the angle in space between the two showers ($19°\pm2°$), under the assumption that the two photons are decay products of a neutral π-meson. The energy of the second photon should then be between 230 and 550 Mev, a result which is consistent with the appearance of S_2. The neutral meson relation cannot, however, be proved in this case.

(b) Three penetrating particles produced at 0. The first interacts at Ω_1, the second leaves the illuminated region at P, and the third particle, OT (not clearly visible on the photograph), appears to have triggered the cloud chamber.

(c) A nuclear interaction at Ω_2 (presumably caused by a neutron produced at 0) which produces two penetrating particles and two photons, which materialize in the lead plate below Ω_2. As in the previous case, it is possible to define the energy of one photon (400 to 600 Mev) and the angle between the two showers ($28°\pm2°$), but not the energy of the second photon. On the neutral meson hypothesis, the expected energy of the second photon is 150 to 250 Mev.

(d) A particle which traverses one aluminum plate and then interacts (Ω_3). This particular interaction was rejected for the analysis of Sec. III, since the particle which produced it would have left the illuminated region before traversing two lead plates, and therefore would not have been recorded as a penetrating particle.

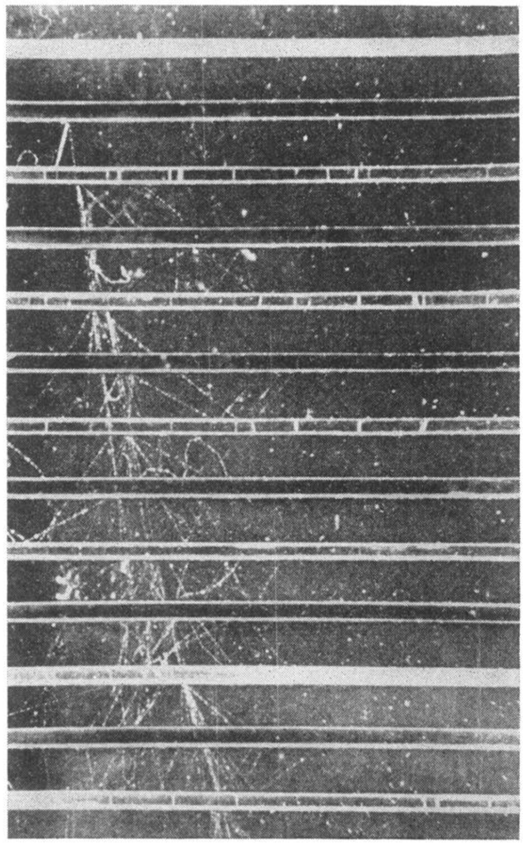


FIG. 3. This picture is representative of the large group showing low multiplicity interactions. A penetrating particle, whose track is somewhat obscured by electronic showers, penetrates five lead plates without scattering. The development of the showers is exceptionally clear. These showers are evidence of the production of two photons in the second (aluminum) plate. The energies of the photons are accurately defined (400 Mev and 900 Mev), but the angle between the showers is difficult to measure. On the neutral meson hypothesis, the angle should be 14°. The measured value is between 8° and 13°, and thus not in contradiction with the predicted value. The picture can be interpreted as showing the production by a high energy neutron of a single neutral meson of about 1300-Mev energy, and one charged meson, or possibly a recoil proton. In either case, the energy of the incident neutron must be at least 2 Bev.

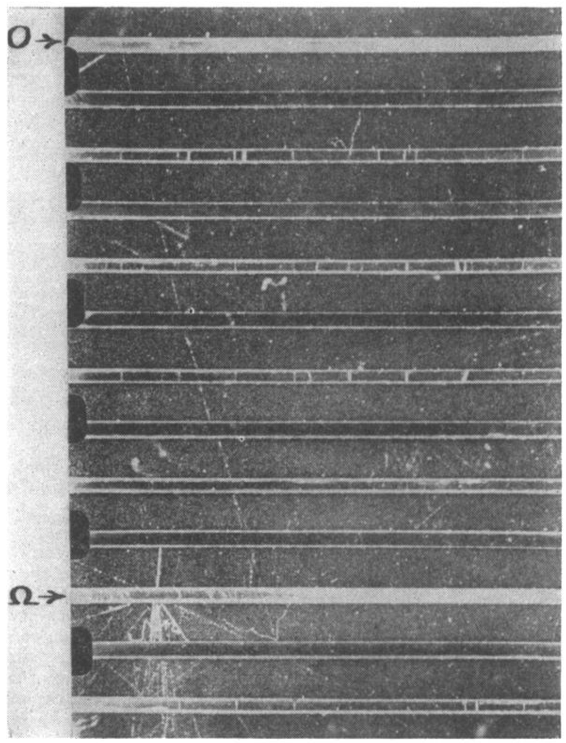


FIG. 4. In this unusual example, we observe two nuclear interactions (at 0 and Ω), the first of which is very simple, and the second very complex. The average direction of the particles produced at Ω lies along the line 0Ω, and the tracks are of the same "age." The interactions are therefore almost certainly associated. The penetrating particle produced in the interaction at 0 is emitted at an angle of 10° from the direction 0Ω. It is thus probably a meson, although it could be a knock-on proton resulting from two elastic collisions within one nucleus. The most likely interpretation of this picture is the following.

A neutron interacts in the first plate to produce one meson (energy unknown, but greater than 300 Mev), and a neutron of several Bev energy. The meson undergoes nuclear scattering in the sixth (aluminum) plate, but is not visibly scattered in five lead plates. The neutron interacts in the eleventh plate with great loss of energy. This picture is thus another example of low multiplicity meson production at very high energy.