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

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The nuclear interactions of cosmic-ray particles in lead and aluminum have been studied in two cloud-chamber experiments. The results of the first experiment, which yields an unbiased sample of interactions of protons, are used to discuss the relative and absolute cross sections in the two materials and the absolute intensity and energy spectrum of the incident protons. The second experiment was designed to select interactions of neutrons in which at least one penetrating ionizing particle was produced.

The types of interactions observed are in this case intimately related to the probability of triggering the cloud chamber. This problem is discussed in some detail, preparatory to more detailed analysis of this experiment in Part II of this paper.

I. INTRODUCTION

MANY experimenters[1–6] have used counter controlled cloud chambers to study the nuclear interactions of cosmic-ray particles. The greatest difficulty in the interpretion of data so obtained has arisen from the complicated and usually unknown effects of the method used for selecting events of interest. The present investigation was intended to minimize this difficulty by use of simple counter selection systems. The two systems used required (a) the detection of a single incident ionizing primary particle and (b) the detection of a single secondary ionizing penetrating particle.

Alternate thin lead and aluminum plates were mounted in the chamber. This particular arrangement was found useful for two reasons: (1) to compare the characteristics of nuclear interactions in two materials of widely different atomic number, and (2) to simplify the identification of particles and the definition of nuclear interactions.

The cloud chamber was operated under a wooden roof of thickness 3 g/cm^2 at Echo Lake, Colorado, elevation 10,600 ft (700 g/cm^2). The discussion of results has been divided into two papers, which we shall denote as Part I and Part II. In Secs. II and III of Part I, we are concerned with the characteristics of the primary particles. A sample of nuclear interactions of cosmic-ray protons (Sec. II) yields information as to the relative and absolute cross sections for particular interactions and as to the flux and energy distribution of these protons. We shall consider in Sec. III the nuclear interactions of neutrons in the two materials resulting in the production of penetrating particles, and discuss some consequences of our choice of triggering arrangement.

II. EXPERIMENTS A AND A′

(1) Experimental Arrangement

The cloud chamber contained seven lead plates $\frac{1}{4}$ inch thick and six aluminum plates $\frac{5}{16}$ inch thick, alternately arranged as shown in Fig. 1. The depth of the illuminated region was six inches. Stereoscopic photographs were taken with cameras whose axes were separated by 12 inches, at a distance of 55 inches from the front of the cloud chamber.

In Experiment A, the cloud chamber was expanded by a signal from a counter telescope placed above the chamber and shielded by a one-inch lead brick, as shown in Fig. 1. The volume defined by the intersection of the cone of acceptance of the telescope and the top

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[1] W. B. Fretter, Phys. Rev. **73**, 41 (1948). (Reference on previous work may be found in this article.)

[2] H. S. Bridge and W. E. Hazen, Phys. Rev. **74**, 579 (1948).

[3] C. Y. Chao, Phys. Rev. **75**, 581 (1948).

[4] W. B. Fretter, Phys. Rev. **76**, 511 (1949).

[5] Lovati, Mura, Salvini, and Tagliaferri, Phys. Rev. **77**, 284 (1950).

[6] W. W. Brown and A. S. McKay, Phys. Rev. **77**, 342 (1950).

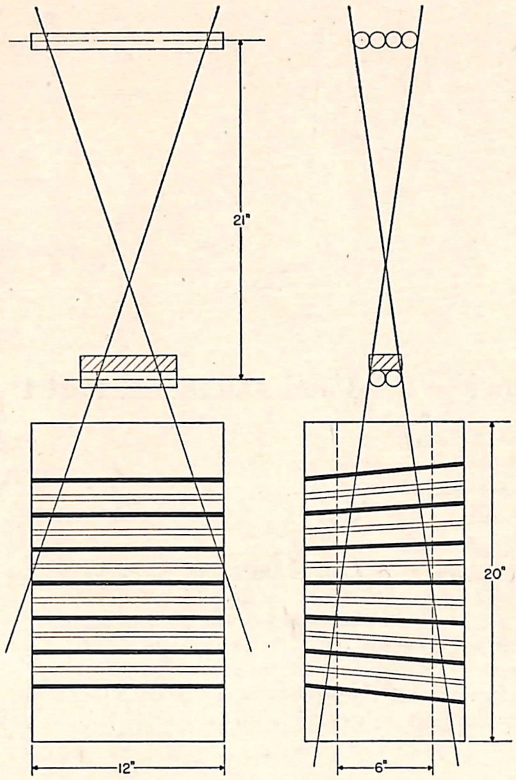

FIG. 1. Plate assembly and triggering arrangement of Experiment A.

and bottom plates in the chamber was included in the illuminated region within two percent. The primary purpose of the experiment was to obtain an unbiased sample of interactions of these particles with the material in the chamber.

In Experiment A′, a tray of eighteen counters was placed below the chamber, and the chamber was expanded whenever the telescope recorded a signal in anticoincidence with this tray, or in coincidence with the discharge of more than one counter in this tray. The resulting pictures were found to be useful only in improving the statistics on the relative numbers of protons and mesons stopping in the chamber.

(2) Triggering Events. Experiment A

One could usually identify, from the appearance of the counter age tracks in the pictures, the method by which the counter telescope had been triggered. One observed in a number of pictures only an electronic component, and considered that in this case the telescope had been triggered by an air shower. In most cases, however, a single particle entered the chamber after traversing the counter telescope. By studying the behavior of these particles, we obtain statistical information on the relative abundance of the ionizing components of cosmic radiation. For this purpose, the analysis was restricted to pictures which belonged to a series of pictures of uniformly good quality. The events observed in this set of pictures (a total number of 3827) are listed in Table I, and are discussed in detail in the following paragraphs.

(*a*) *Single Penetrating Particles*

Single particles (minimum range 104 g/cm^2 of lead) were observed to traverse the chamber without interaction in 2397 pictures of the set. The corresponding number of particles defined as belonging to the hard component (particles of range greater than 167 g/cm^2 of lead) is five percent less, or 2262. Since the flux of the hard component at the altitude in question is a well-known quantity, this number is one to which the number of all other events may be compared.

(*b*) *Particles Stopped*

The particles which stopped in the chamber were a mixture of μ-mesons, protons at the end of their range, and protons stopped by nuclear collision. The protons, whether or not at the end of their ranges, show much smaller Coulomb scattering than did the mesons, as is illustrated in Table II. One can make use of this fact to estimate the proportion of mesons and protons stopping in the chamber. One computes, from measurements on all the particles stopped, the root mean square scattering angles at the second lead plate above the plate in which the particles stopped. This value is then compared to the expected root mean square projected angle of scattering for mesons ($\alpha_\mu=12.5°$) and protons (α_p). The upper and lower limits on the number of mesons are obtained by assuming that all protons stop by nuclear collision ($\alpha_p\simeq 0$) or stop at the end of their range ($\alpha_p=4.8°$). From the combined pictures of Experiments A and A′, one finds in this way that, of 81 particles stopped in the fourth through twelfth plates, between 32 and 39 were mesons. The behavior of the protons is seen to have a small effect on the computation.

Of the 46 stopped particles observed in Experiment A, only 30 stopped in the fourth through twelfth plates. From the above, it is estimated that 13 of these were mesons, and 17 were protons. The correlation of the number of stopped mesons with the flux of slow mesons incident on the telescope is difficult because of the great loss through scattering in the lead block in the telescope. One computes, for example, a loss of 75 percent of all mesons of ranges such as to stop in the middle plate of the chamber. The corresponding loss of protons, however, is only 9 percent, so that the results

TABLE I. Frequency of occurrence of various types of events based on 3827 frames of the A-experiment.

Single particle emerging from telescope				Elcetronic showers		
Through	Stopping	Interacting	Nuclear scattering	High energy electron	Air shower	Blank pictures
2397	46	35	9	5	273	1062

concerning stopped protons are significant (see Sec. II-5 and Table III).

(c) *Nuclear Interactions*

In 44 cases, an ionizing particle emerging from the counter telescope produced a nuclear interaction in the illuminated region of the chamber. It is assumed that all such particles were protons. We shall discuss these interactions in detail in Sec. II-3. In particular, it will be shown that the corrected number of interactions occurring in the second through twelfth plates is 42.

(d) *Electronic Component*

We consider first the evidence for identification of single incident electrons. An electron of 1-Bev energy passing through the counter telescope would undergo multiplication in the one-inch lead block, and would appear in the chamber as a shower with about ten particles at the maximum.[7] Only five such showers were observed. This number corresponds to a directional intensity of high energy electrons of about 3×10^{-5} sec^{-1} ster^{-1} cm^{-2}. Hazen[8] has computed a directional intensity seven times as large for both electron- and photon-initiated showers in the same energy range and at the same altitude. We may explain the difference in the two figures by noting that most of the showers may well be photon-initiated, and that we detect only electron-initiated showers.

It is seen from Table I that over a quarter of the set of pictures of Experiment A showed either a purely electronic component, or were blank. The first type were easily identified as caused by ordinary extensive air showers. The blank pictures are attributable neither to accidental telescope coincidences nor to instrumental failures. It is most likely that, in these cases, the counter telescope responded to air showers of very low density, which were not visible in the cloud chamber.

TABLE II. Energy, scattering, and ionization of particles stopping in a lead plate. In this computation only losses by ionization are taken into account.

		Proton			Meson ($214m_e$)		
Interval	Plate	Energy (Mev)	rms scatt. ($\bar{\alpha}$)	$I/I_{\min}$	Energy (Mev)	rms scatt. ($\bar{\alpha}$)	$I/I_{\min}$
	Pb						
1		0–60		–4.8	0–24		–2.2
	Al						
2		42–76		6.6–4.0	16–30		2.8–1.9
	Pb						
3		78–103		4.0–3.3	31–42		1.6
	Al						
4		95–115		3.5–3.1	36–48		1.5
	Pb		4.3			11	
5		117–135		2.9	48–60		1.4
	Al		1.0			2.6	
6		128–145		2.8	52–62		1.3
	Pb		3.5			9	
7		148–153		2.5	62–72		
	Al					2.2	
8		157–172		2.4	65–75		
	Pb		2.9			7.7	
9		175–189		2.3	73–83		
	Al					1.8	
10		183–197		2.2	78–86		
	Pb		2.5			6.8	
11		199–213		2.2	87–95		
	Al					1.6	
12		207–220		2.1	92–100		
	Pb		2.3			5.9	
13		222–235			97–105		
Range in g/cm^2 Pb							
100		300	1.7	1.8	140	4.6	
170		400	1.3	1.5	220	3.2	
240		500	1.1	···	300	2.5	
310		600	0.9	···	385	2.0	
410		720	···		500	1.5	

(3) Description of Nuclear Interactions

Since, in this section and in Sec. II-4, we shall be concerned only with relative numbers of nuclear interactions, we shall consider a more extensive set of pictures, thus improving our statistical results. We consider in addition to the interactions of Table I others that were not of counter age, or that were observed in groups of pictures whose quality was not considered good enough for inclusion in the set of Table I. All of these interactions were produced by ionizing primaries.

(a) *Identification of Nuclear Interactions*

The various types of nuclear interactions are best illustrated by the pictures of Fig. 2. Interactions of types (1) and (2) are called "nuclear scattering." In these cases, one required that a particle of minimum ionization traverse two lead plates with no appreciable scattering (less than 1°) and then be deflected through an angle of more than 10°. When the deflection occurred

TABLE III. Absolute numbers of protons of various energies incident on the telescope. These numbers are normalized to 2262 particles of the "hard component."

	Protons stopping 4th–12th	Protons interacting (2nd–12th plates)				
		Types 1–2	Types 3–4	Types 5–6	Type 7	
Corrected number of events	17	13	11	13	2	3
Number of protons incident on telescope	23	56	47	56	8	12
Approximate energy of the protons (Bev)	0.2 to 0.3		0.3 to 1		1 to 2	>2
Intensities relative to the hard component	10^{-2}	2.5×10^{-2}	2.1×10^{-2}	2.5×10^{-2}	0.3×10^{-2}	0.5×10^{-2}

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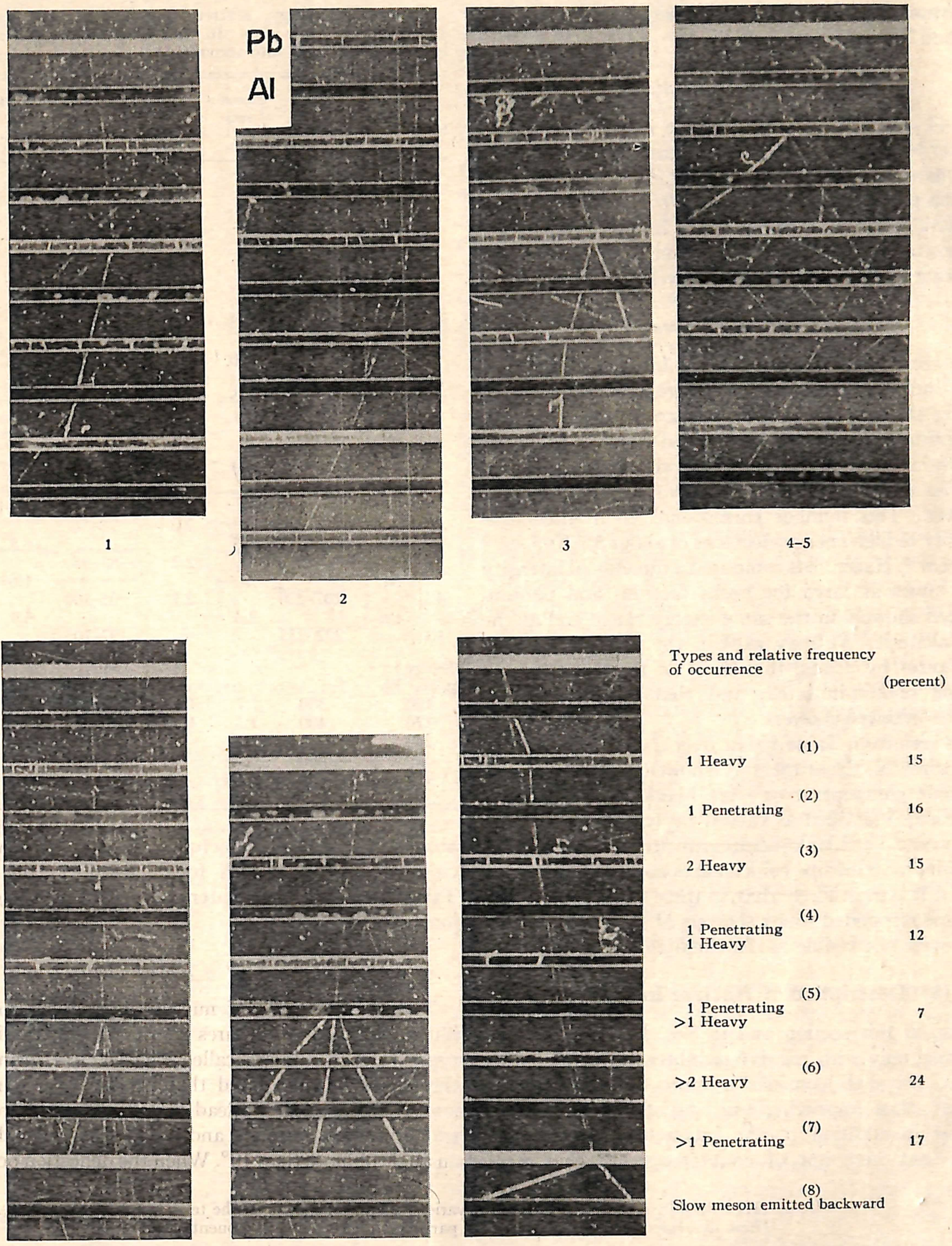
[7] I. G. Tamm and S. Belenky, J. Phys. U.S.S.R. **1**, No. 2 (1939).

[8] W. E. Hazen, Phys. Rev. **65**, 67 (1944).



Types and relative frequency of occurrence

		(percent)
(1)	1 Heavy	15
(2)	1 Penetrating	16
(3)	2 Heavy	15
(4)	1 Penetrating 1 Heavy	12
(5)	1 Penetrating >1 Heavy	7
(6)	>2 Heavy	24
(7)	>1 Penetrating	17
(8)	Slow meson emitted backward	

FIG. 2. A sample of nuclear interactions (Experiment A).

after traversal of more lead plates, scattering angles of 2° were accepted. All angles were measured in projection. The expected number of μ-mesons abnormally scattered through Coulomb interaction (and thus mistaken as protons suffering nuclear scattering) can then be calculated. We consider only the effect of multiple scattering. (For $\frac{1}{4}$-inch lead plates, the effect of single Coulomb scattering is negligible, if one assumes that the maximum angle of single scattering is equal to $\hbar/Rp$, in which R is the radius of the nucleus, and p is the momentum of the meson.) The probability of observing scatterings in the specified sequence

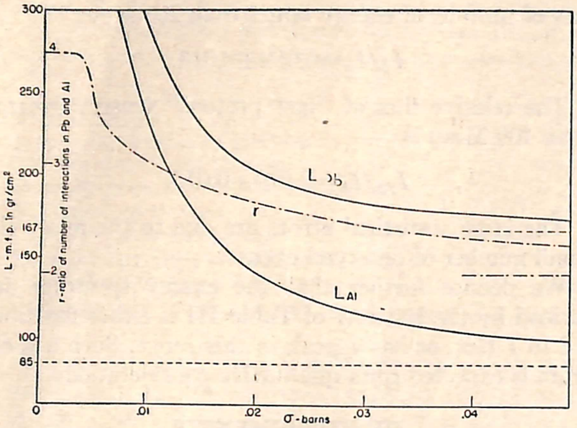


FIG. 3. Mean free path in lead and aluminum under the theory of transparency. These mean free paths are plotted as functions of the cross sections ($\bar{\sigma}$) for the interaction of the individual nucleons with the incident particle for $R=1.37A^{\frac{1}{3}}10^{-13}$ cm. The value of r is the expected ratio of the numbers of nuclear interactions occurring in 7 lead plates (49.7 g/cm²) and 6 aluminum plates (12.8 g/cm²).

is found to have an average value of 0.2 percent for mesons of range between 15 and 170 g/cm² of lead, and to be negligible for mesons of greater range. Since the intensity of "slow" mesons is 10 percent of that of the hard component, one finds that for the set of pictures of Table I, the expected number of mesons thus scattered is $0.002\times 0.10\times 2262\approx 0.4$, as compared with the 9 cases of "nuclear scattering." Moreover, these events occurred about as frequently in lead and aluminum, and the observed deflection was larger than 20° in 9/10 of the cases. These are further indications of the nuclear origin of these interactions.

The minimum requirement for identification of interactions of types (3) to (7) was the observation of one heavily ionizing particle, or of one penetrating particle emitted at an angle of more than 10° (in projection) with the direction of the incident particle. These conditions were found to be sufficient to reject all knock-on showers of mesons.

Nuclear scatterings could not be observed in the first three plates in the chamber because of the criterion used in their selection. Moreover, the identification of all interactions occurring in the top and bottom plates was not considered reliable, and the corresponding pictures were rejected. We shall therefore consider in the following discussions only interactions observed in the second through twelfth plates, and correct the number of nuclear scatterings for the loss in plates 2 and 3. The relative frequencies of occurrence of the interactions of various types (Fig. 2) are obtained from this corrected number of 70 interactions.

(b) *Estimate of the Energy of the Primary Protons*

The following observations indicate that the energy of the protons producing the great majority of the observed interactions is below 1 Bev. If we consider the group of interactions of types (1), (2), (3), and (4), we find that in no case can a secondary meson or electronic component be detected. Furthermore, the incident protons in one quarter of these cases was visibly scattered. The protons producing interactions of types (5) and (6) were of somewhat higher energy than those of the first group, since none were visibly scattered. However, the estimated energy of the ionizing secondary particles was less than 450 Mev, and in only 4 cases out of 22 did one identify a secondary meson or electronic component.

The example of type (7) is one of the small group (11 percent of the total) of interactions of high energy protons. These were characterized by the production of two or more penetrating particles. In one-half of these cases, the energy of the ionizing secondary particles was estimated to be greater than 1 Bev.

(c) *The Possibility of Single Proton-Nucleon Collision*

We have investigated the possibility that some of the interactions of types (3) and (4) were due to a single collision between the incident proton and a proton of the nucleus.[9] We determined the directions in space of the particles, and set limits to their energies. We could then compare these values with those predicted by the energy-angle relation for collisions between free nucleons, corrected for the motion of the nucleons in the nucleus. In 22 out of 26 cases we could not interpret the event as a simple proton-proton collision, even by assuming the most favorable velocity for the struck proton. One may therefore conclude that in the collision of a proton of average energy 500 Mev with a nucleus of lead or aluminum, the secondary nucleons are a result of multiple collisions within the nucleus.

(d) *Proton-Neutron Charge Exchange*

On the basis of the results obtained in Berkeley[10] with 350-Mev protons, we expected to observe a considerable proportion of events of the type "charge exchange," in which a proton would turn into a neutron of almost the same energy. A number of interactions of types (1), (3), and (6) were interpreted as possible examples of charge exchange, in which cases an average of 100 Mev was transferred to secondary protons; this corresponded to a probable total energy loss of 200 Mev. Only one case was found in which no visible secondary particle was produced. We shall derive similar conclusions in Sec. III concerning the inverse process of neutron-proton charge exchange.

(4) **Numbers of Nuclear Interactions in Lead and Aluminum. Transparency**

The choice of lead and aluminum for the plates was made for the purpose of obtaining relative cross

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[9] J. G. Wilson, Proc. Roy. Soc. (London) **A174**, 72 (1940). (This has been found to be the case in one picture.)

[10] University of California Radiation Laboratory Report UCRL 637, unpublished.

sections for the production of nuclear interactions in a light and heavy element. The results of this section and of Sec. III-4 will be compared with the expected relative number of interactions under the assumption of geometric cross sections (nuclear radius proportional to $A^{\frac{1}{3}}$). This ratio, for the seven lead plates (49.7 g/cm²), and the six aluminum plates (12.8 g/cm²), is found to be

$$r_g=2.0.$$

Of the 70 nuclear interactions considered in Sec. II-3, 41 occurred in five lead plates, and 29 in six aluminum plates. The ratio of the interactions in lead and in aluminum normalized to the total amount of material of the chamber is, therefore,

$$r_A=2.0\pm0.5.$$

The result is compatible with geometric cross sections. The ratio r can be related to the absolute cross sections in the two materials by application of the theory of transparency of the nucleus.[11, 12] The curves of Fig. 3 illustrate the variation of this ratio and of the collision mean free paths of particles in the two materials as a function of the assumed particle-nucleon cross sections. One sees from these curves that the value $r=2.5$ (still consistent with the experimental result) corresponds to mean free paths of 200 g/cm² of lead and 140 g/cm² of aluminum.

(5) Spectrum and Absolute Intensity of Protons at 10,600 Feet

In this section we shall estimate the absolute directional intensity of protons and obtain a qualitative description of their energy spectrum. For this purpose, we shall now consider only the set of pictures of Table I.

The first row of Table III gives the number of protons stopped in the fourth through twelfth plates of the chamber [as obtained in Sec. II-2(b)], and the corrected numbers of nuclear interactions observed in the chamber from the second through twelfth plates [from Sec. II-2(c)]. We list in the third row the estimated energies of the incident protons responsible for these various types of interactions.

We obtain the absolute numbers of protons entering the telescope (listed in the second row of Table II) in the following two steps: (1) We compute the numbers of protons entering the chamber by assuming that all protons of the first column stop at the end of their ranges, and that all the other protons interact in the chamber with geometric cross sections; and (2) we increase these numbers for the loss by interaction (also with assumed geometric cross section) in the material above the chamber.

We can now compare these numbers with the corresponding flux (2262 particles) of the hard component. These relative intensities are listed in the last row of Table III. The sum of the numbers yields the relative flux of protons of energy larger than 200 Mev:

$$I_p/I_h=0.089\pm0.018.$$

The relative flux of "fast protons" (energy greater than 400 Mev) is

$$I_{fp}/I_h=0.079\pm0.015.$$

The large statistical errors are due to the relatively small number of observed events.

We deduce further that the energy spectrum described by the last row of Table III is either flat from 0.2 to 1 Bev, or has a peak in this range. Such a spectrum is expected from qualitative considerations.

III. EXPERIMENT B

(1) Experimental Arrangement

In this experiment the cloud chamber was triggered by a signal from a shielded counter telescope placed below the chamber when not accompanied by a signal from a large tray of counters placed above the chamber (Fig. 4).

This arrangement favored the recording of events in which a neutral primary particle produced secondary ionizing particles. The plate assembly was identical with that used in Experiment A. We had intended to study the effect of varying the thickness of the lead shields S_1, S_2, and S_3. Thus, the thickness of S_1 was 0, 1 in., or 7 in., while the thicknesses of S_2 and S_3 were either 1 in. and 1 in., 0 and 4 in., or 1 in. and 9 in., respectively. However, the number of pictures taken in

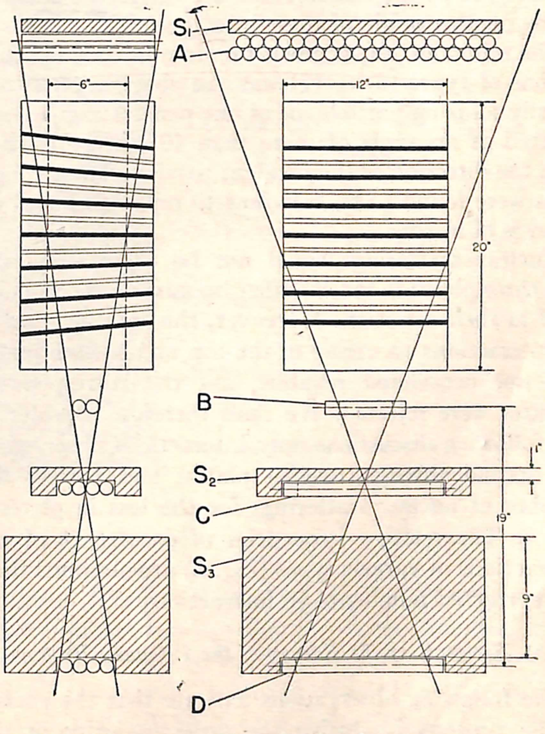

FIG. 4. Plate assembly and triggering arrangement of Experiment B.

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[11] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).
[12] R. Serber, Phys. Rev. **72**, 1114 (1947).

TABLE IV. Summary of nuclear interactions of Experiment B. The 136 nuclear interactions were due to non-ionizing primaries and occurred in the first through tenth plates. The corrected relative frequency is obtained as described in Section III-3.

	Group I				Group II				
Type of picture	(1)	(1)′	(2)	(2)′	(3)	(3)′	(4)	(4)′	(5)
Number of penetrating particles	1	1	2	2	>2	>2	>2	>2	>2
Number of electronic showers	0	⩾1	0	⩾1	0	⩾1	0	⩾1	⩾1 of high energy
Total number—showers and particles					⩽6		>6		
Number of interactions	36	5	20	7	9	25	2	12	20
Corrected relative frequency	0.69		0.22		0.06		0.01		0.02
Ratio of interactions in lead and aluminum normalized to 7 Pb and 6 Al (Fig. 3)	2.3±0.6				5.0±1.4				

each arrangement was not sufficient to allow us to draw more than qualitative conclusions on this effect. For instance, with no lead above the anticoincidence tray, we observed a few purely electronic showers which apparently were due to materialization of incident photons. This was confirmed by the fact that these events were eliminated when the thickness of S_1 was 1 in. or 7 in.

From a total of about 5000 pictures obtained in this experiment, we selected for study 322 pictures of nuclear interactions. Of these interactions 237 occurred in the illuminated region, and were clearly responsible for the triggering of the counter telescope.

(2) Effect of the Triggering Requirement

In this section we shall examine in some detail the effect of the triggering arrangement of the choice of the particular events photographed. In order to be photographed, a nuclear interaction originating within the illuminated region must produce at least one particle which penetrates the shielded counter telescope. The probability that a particular interaction will accomplish this depends primarily on the multiplicity of the penetrating particles produced, and on the location of the point of origin.

One can compute, for any point of origin, the solid angle Ω_s within which a penetrating particle must be emitted in order to traverse the telescope. The value of this angle (averaged over the surface of each plate) varies from 0.007 to 0.014 steradian from the first to the tenth plate. We shall use also the solid angle Ω_D subtended by tray D at various points within the illumination (varying from 0.03 to 0.05 steradian) and the solid angle Ω_B subtended by tray B (varying from 0.03 to 0.14 steradian). The values of these average solid angles for the middle plate of the chamber are:

$$\Omega_s=0.01,\quad \Omega_D=0.04,\quad \Omega_B=0.05.$$

Note that a particle aimed at tray D from almost any point in the illuminated region traverses tray C, and therefore that the effect of tray C can be neglected.

From the above numbers, one could, in principle, compute the absolute probability of triggering for any event of given multiplicity of penetrating particles and electronic showers, originating anywhere in the chamber. It seems useless to attempt this calculation rigorously, because of the necessity of making detailed assumptions as to the energy and angular distributions of the secondary particles and showers. We shall make instead the approximation that the penetrating particles are emitted uniformly within a cone of solid angle Ω. For the present we neglect the absorption or scattering of these particles in the lead shielding of the telescope, and take a value of Ω (0.55 steradian) which corresponds to an average angle of emission of 16° (Sec. II, Part II).

We can now calculate the probability that any interaction producing N penetrating particles triggers the telescope singly (one particle traversing trays A, B, and C):

$$P_s=1-(1-\Omega_s/\Omega)^N\simeq N\Omega_s/\Omega.$$

This probability is not very sensitive to the particular plate in which the interaction occurs, and is nearly proportional to N even for high multiplicities, because of the small values of Ω_s/Ω. P_s is of the order of 2 percent for an interaction producing one penetrating particle.

The probability P_m of multiple triggering (by separate particles traversing tray B and trays C and D) is easily shown to be much smaller than P_s for low multiplicity interactions occurring in the top plates and to increase sharply with the plate number and the multiplicity N. One may use the formula:

$$P_m=\Omega_B\Omega_D N(N-1)/\Omega^2$$

for interactions occurring in the upper plates of the cloud chamber and having a multiplicity less than five. The total probability of triggering is the sum of P_s and P_m. An important result is that multiple triggering is the dominant process for interactions occurring in the bottom half of the chamber and having multiplicity larger than three. For example, P_m is equal to P_s for $N=4$ in the seventh plate, and for $N=3$ in the ninth plate.

The probability of triggering tray B approaches one when a number of electronic showers are produced, particularly if the interaction occurs in the lower plates. In this case, the triggering process is complete if one penetrating particle is emitted in the solid angle Ω_D so as to discharge tray D. The probability of this modified single triggering is, therefore,

$$P_s'\simeq\Omega_D N/\Omega\simeq 4P_s.$$

It is evident that the triggering probability varies over a wide range, depending upon the characteristics of the nuclear interaction. For example, the value P_s' for $N=5$ is 20 times the value of P_s for $N=1$.

The considerations of the preceding paragraphs are involved in the interpretation of practically all of the data obtained in Experiment B. They will be found particularly useful in discussing the following:

(i) The true frequencies of occurrence of various interactions.

(ii) The relative cross sections for nuclear interactions in different materials (since the character of the interactions, and consequently the triggering probabilities, may depend upon the material).

(iii) The relative numbers of penetrating particles and electronic showers (Part II).

(iv) The nuclear interactions of secondary penetrating particles (Part II).

(3) Description of Interactions and Results

Results relating to 136 selected nuclear interactions are given in Table IV. These interactions were caused by a non-ionizing primary, and occurred in the illuminated region of the first ten plates in the chamber. We divided them into two groups (low and high multiplicity) and subdivided them according to the multiplicity of penetrating particles and numbers of electronic showers. The distinction of penetrating particles is often difficult in the cases of interactions of type (5), because of the production of high energy electronic showers (energy greater than 1 Bev).

The remainder of the total number (237) of interactions occurring in the illuminated region, although not included in Table IV, are considered in later discussions. These include a small number caused by ionizing primaries incident at a large inclination and a large group (76) of interactions occurring in the three lowest plates. Analysis of this last group is difficult, since one cannot identify penetrating particles or, in most cases, recognize electronic showers. These pictures will be useful only for statistical considerations for which the type of event is not of great importance. The relation frequency of occurrence of different events has been corrected for the effect of the triggering requirement according to the estimates made in the next paragraphs.

(*a*) *Corrected Frequencies of Occurrence of Various Interactions*

By applying the results of the discussion on the probability of triggering, one can estimate the true relative rates of occurrence of the events of the various types. In the four types of interactions of group I the electronic showers were nearly always of low energy, and did not contribute appreciably to the triggering process. Since a single particle was in nearly all cases responsible for the discharge of the counter telescope, the probabilities of triggering are given by the equation for P_s. These interactions were, as expected, fairly evenly distributed among the plates. The events of higher multiplicity (group II) occur most frequently in the lower plates, e.g., 13 in the first four plates, compared with 48 in plates 7 through 10. This is expected if the triggering process was predominantly of the multiple type. For the interactions of type (3), we estimate the triggering probability by taking an intermediate figure between the values of P_s and P_s' for a multiplicity $N=4$. When tray B was discharged with a probability of almost one (types (4) and (5)), the triggering probability was assumed to be given by P_s' for $N=5$. From the observed numbers of events of each type and with the knowledge of the appropriate triggering probabilities, one readily obtains the corrected relative frequencies of occurrence as listed in the fourth line of Table IV.

(*b*) *Estimate of the Energy of the Primary Neutrons*

From the amount of penetration required of the triggering particles one can estimate the minimum energy (about 400 Mev) of the neutrons producing them. The average energy of the neutrons is believed to be in the range where meson production is fairly common (i.e., about 1 Bev). For example, one observed in one-quarter of the cases of types (1) and (2) either electronic component or scattering of the penetrating particles greater than that expected for a proton.

Interactions of types (3), (4), and (5) produced ionizing secondary particles and electronic showers whose combined energy appeared to be 4 Bev, on the average. This is a crude lower limit, since one neglects the production of secondary neutrons, and arbitrarily assigns a minimum energy to each relativistic unscattered particle.

(*c*) *Neutron-Proton Charge Exchange*

The interactions of type (1) can be interpreted as examples of neutron-proton charge exchange. One assumes then that a neutron of energy greater than 400 Mev turned into a proton, and that a part of the original energy was dissipated in exciting a nucleus. The average energy delivered to slow protons was found to be on the average, about 200 Mev. Although this type of interaction is quite frequent (see Table IV), we are unable to compare its probability of occurrence with the probability of interactions which produce only low energy nucleons, since the latter event would not be recorded.

On the other hand, we may obtain the relative probability of charge exchange at the higher energies (above 4 Bev). If a neutron of this energy turns into a proton of nearly equal energy, one should observe in the chamber interactions of type (1) followed by an interaction of the resulting proton types (3), (4), or (5). This succession of events was never observed. From this fact, one computes a lower limit on the mean free path for neutron-proton charge exchange at high energies by the following arguments:

Let us consider all the interactions of high multiplicity occurring in the lower half of the chamber. The number of these due to neutrons incident at a large inclination can be assumed equal to the number produced by ionizing primaries which missed the anticoincidence tray. The neutrons producing the remaining interactions are assumed to have traversed the upper half of the chamber. The total amount of material thus traversed was 1900 g/cm^2 of lead and 600 g/cm^2 of aluminum.

One therefore concludes that the simple process of charge exchange is an extremely rare one at very high energies. If the process occurs at lower energies, the resultant excitation of the nucleus is of the order of 400 Mev (deduced from the observed energy of slow secondary protons).

(4) Ratio of Numbers of Interactions in Lead and Aluminum

As has been indicated, it is not possible in the case of Experiment B to obtain relative cross sections for interactions in the two materials simply by comparing the number of interactions observed in lead and aluminum. 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]

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[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 penepenetrating 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

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* This work was supported in part by the joint program of the ONR and AEC.

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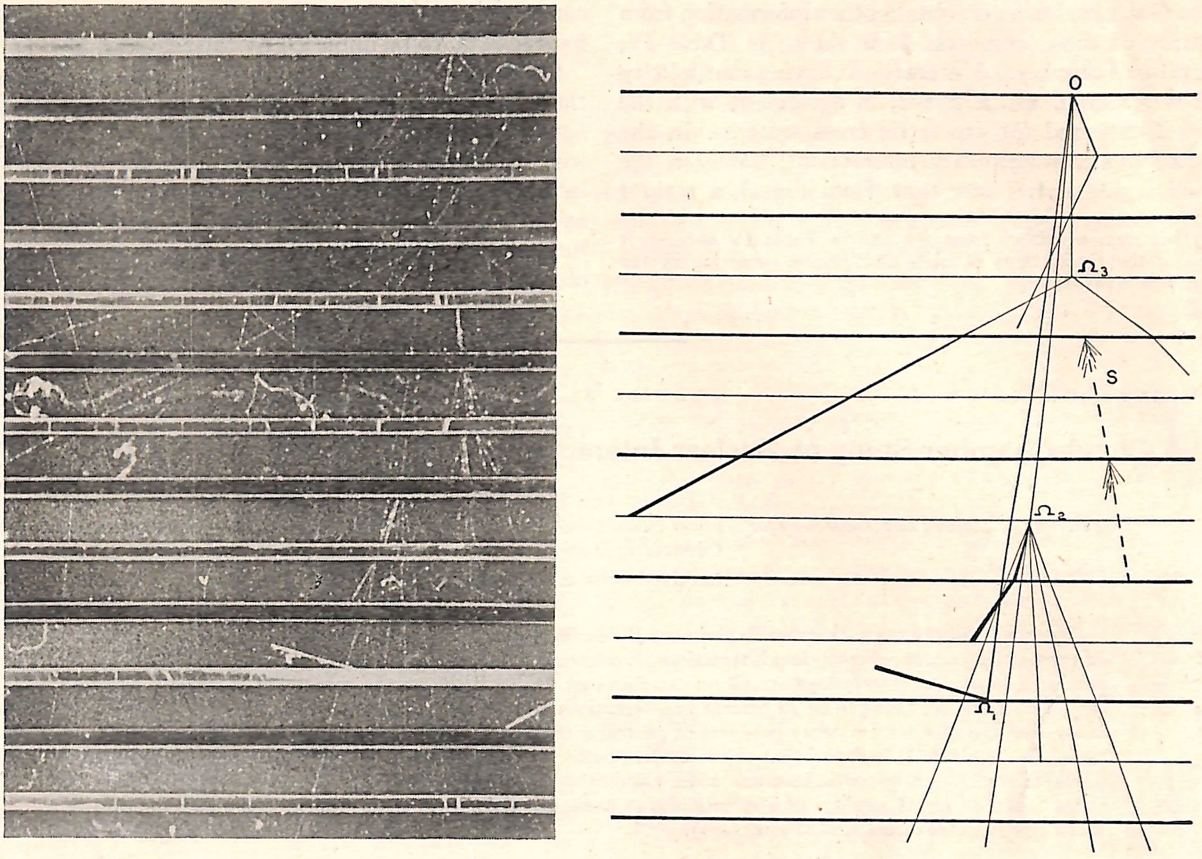
[1] Steinberger, Panofsky, and Steller, Phys. Rev. **78**, 802 (1950).

[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

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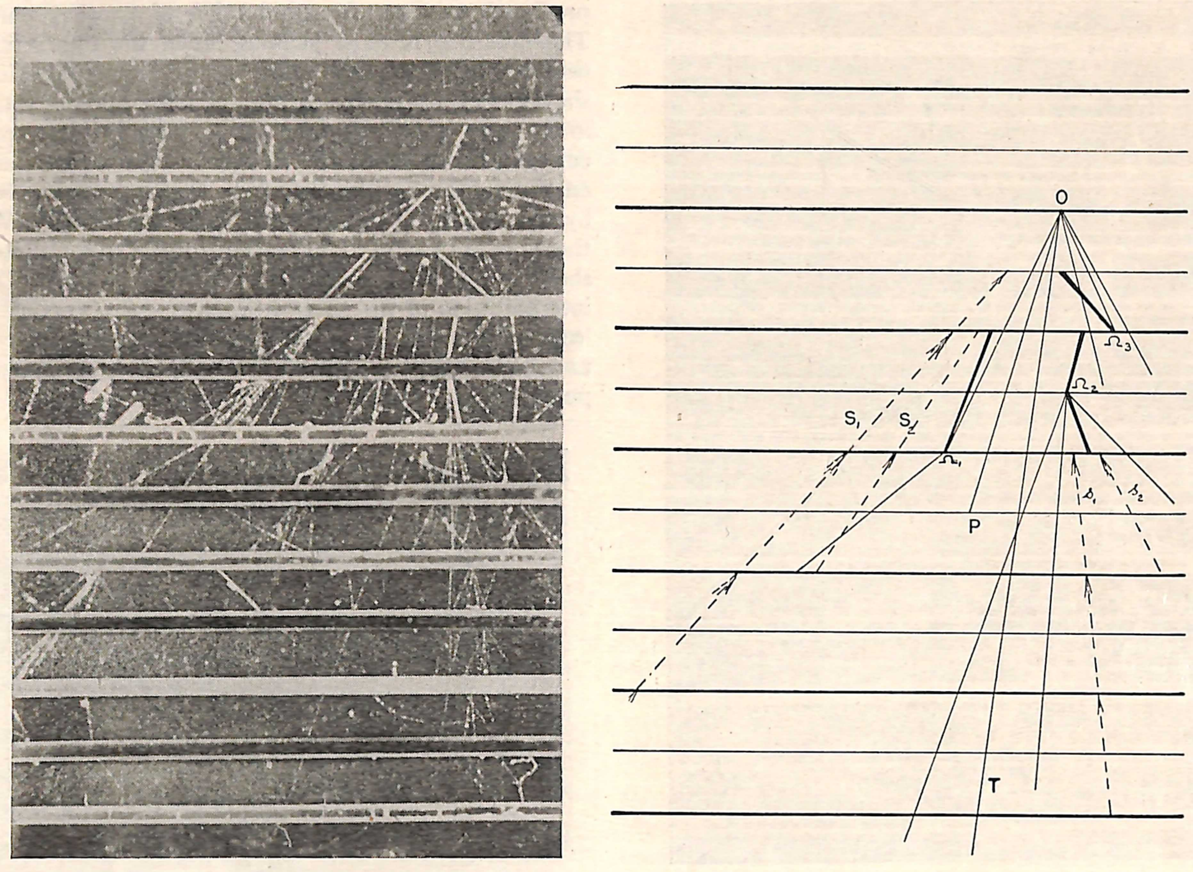
[6] I. H. Tamm and S. Belenky, J. Phys. U.S.S.R. **1**, No. 2 (1939).

[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

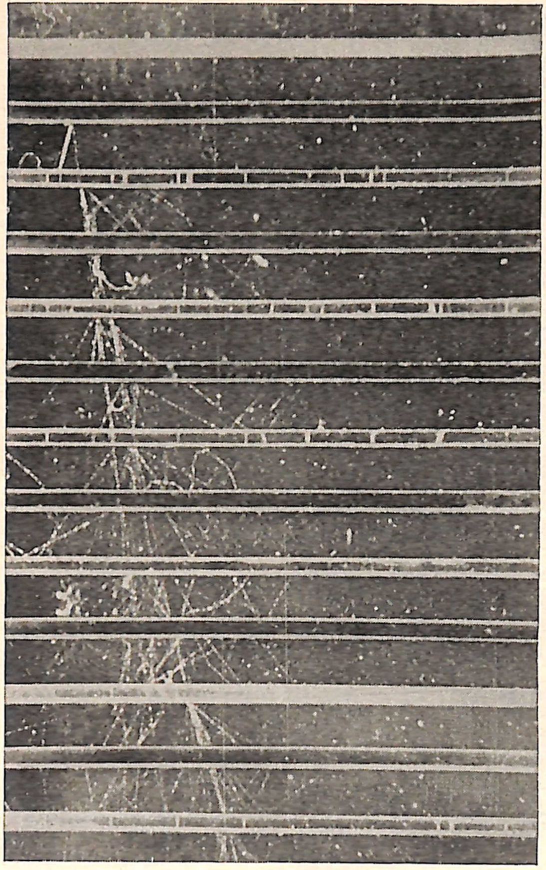


FIG. 3. This picture is representative of the large group showing low multiplicity interactions. A penetrating particle, whose track is somewhat obscured by electronic showers, penetrates five lead plates without scattering. The development of the showers is exceptionally clear. These showers are evidence 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

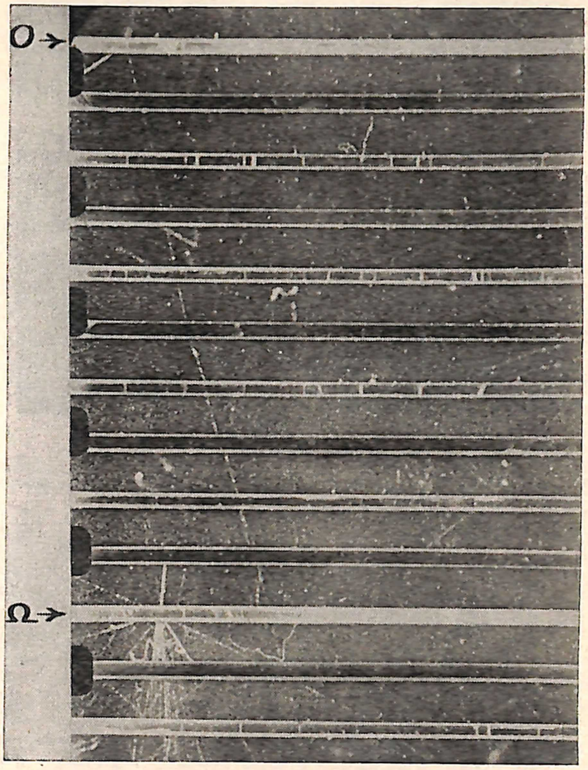


FIG. 4. In this unusual example, we observe two nuclear interactions (at 0 and Ω), the first of which is very simple, and the second very complex. The average direction of the particles produced at Ω lies along the line 0Ω, and the tracks are of the same "age." The interactions are therefore almost certainly 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.

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[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.

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.

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[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.

[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				Aluminum			
	Traversals g/cm²	Nuclear interactions (ionizing particle)	Nuclear scattering	Nuclear interactions (non-ionizing particle)	Traversals g/cm²	Nuclear interactions (ionizing particle)	Nuclear scattering	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/cm^2 Pb, 82 g/cm^2 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/cm^2 Pb and 543 g/cm^2 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/cm^2 of lead and 140 g/cm^2 of aluminum compared to a total traversal of all particles of 6015 g/cm^2 of lead and 2140 g/cm^2 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:

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

(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

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

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/cm^2 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.

(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/cm^2 and 250 g/cm^2 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/cm^2 of lead, and 140 g/cm^2 of aluminum.

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

(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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