PHYSICAL REVIEW VOLUME 77, NUMBER 3 FEBRUARY 1, 1950

A Cloud-Chamber Study of Cosmic-Ray Nuclear Interactions at 3260 Meters Elevation

W. W. BROWN* AND A. S. MCKAY†
Cornell University, Ithaca, New York
(Received September 14, 1949)

In 4949 photographs of cosmic-ray phenomena, not associated with dense air showers, occurring in a counter controlled cloud chamber surrounded by lead, the numbers of nuclear interactions in which secondaries were produced and observed to occur in and above the chamber were 182 and 223, respectively. The mean free path for nuclear interaction of the penetrating particles produced in these nuclear interactions is 316 ± 70 g/cm^2 of lead, while for nuclear scattering (large angle scattering without the production of secondaries) it is at least 4 or 5 times this value. The projected zenith angular distributions of the secondaries from these interactions are given. The lightly ionizing secondaries going in the forward direction have an angular distribution $\sim\cos^3\theta$, while those in the backward direction from nuclear interactions occurring in the chamber have a uniform distribution.

1. INTRODUCTION

DURING the summer of 1948 a series of cloud-chamber pictures of cosmic-ray phenomena were taken at Echo Lake, Colorado (elevation 3260 meters). The various types of Geiger counter coincidences employed in the selection of these phenomena provided a means of dividing them into two main classes: (*a*) those associated with extensive air showers, and (*b*) those not associated with extensive air showers. The former class has been described in an earlier paper[1] and the latter class is the subject of the present analysis.

2. EXPERIMENTAL

The geometrical disposition of Geiger counters and absorber about the cloud chamber‡ are shown to scale in the two perpendicular sections of Fig. 1. The roof and wall thicknesses are 6 inches and 3 inches of lead respectively. The counters at X, Y, and Z, some of which are connected in pairs as indicated, have effective dimensions $\frac{1}{2}$ inch$\times$10 inches, 1 inch$\times$2.75 inches, and 1 inch$\times$16 inches, respectively. Four neon bulbs situated at S, P, C, and A indicate the type of counter coincidence causing each particular expansion and were photographed simultaneously with the cloud chamber. The photographs were non-stereoscopic.

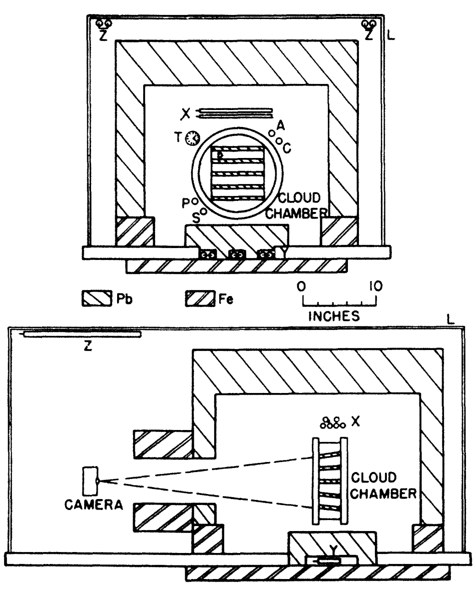

FIG. 1. Two perpendicular sections showing the disposition of absorber and counters about the cloud chamber. The chamber is triggered by various coincidences in the counters at X, Y, and Z.

The expansion of the chamber was triggered whenever a master pulse was generated by one of the following events:

(*a*) A sixfold coincidence of the counters at X, indicated by the lighting of neon bulb S, and referred to hereafter as an S-event.

(*b*) A threefold coincidence of any one of the counters at X with any two of the pairs at Y, indicated by neon bulb P and referred to hereafter as a P-event.

The simultaneous lighting of neon bulb A with either of the above coincidences indicated the presence of an accompanying extensive air shower of sufficient density to cause coincident pulses in the trays at Z, and simultaneous lighting of C indicated that an accompanying air shower had caused coincidences in some more distant counters. All events of this kind have been discussed in detail in reference 1. In the present analysis of the events (*a*) and (*b*), not associated with dense air showers, it is only important to note the absence of

Table I. The number of times counter coincidences not associated with extensive air showers triggered the cloud chamber in 871 hours under the lead shield (Fig. 1) and the number of nuclear interactions observed which satisfy the criteria of the present analysis.

		Number of pictures in which nuclear interactions were observed			
			Origin within chamber		
Type of triggering coincidence	Number of triggering coincidences	Origin above chamber	By charged particles	By uncharged particles	By particles of undetermined nature
S	3551	135	40	32	14
SP	153	29	12	5	12
P	1245	59	39	19	9

* Now at Duke University, Durham, North Carolina.
† Now with the Texas Company, Bellaire, Texas.
[1] W. W. Brown and A. S. McKay, Phys. Rev. 76, 1034 (1949).
‡ Operational details are given in reference 1.

coincidences in the air shower counters. The numbers of S-, P-, and coincident SP-events recorded in the 871 hours of operation are given in Table I.

The efficiency of the Z counters for detecting air showers of density Δ-particles per unit area is $(1-e^{-A\Delta})^2$ where $A=200$ cm² is the Z-counter area. The median angle of ejection of the lightly ionizing secondaries (mostly mesons) with reference to the primary is in agreement with that predicted by the symmetric pseudoscalar meson theory. For the nuclear interactions occurring in the chamber, the ratio of the forward moving to backward moving heavily ionizing secondaries is 3.7, while the ratio for lightly ionizing ones is between 5 and 11, a result which shows the increase in the asymmetry of the angular distribution with the energy of the secondaries. The relative number of charged to neutral penetrating secondaries from the nuclear interactions occurring above the chamber is 1.5±0.4—a result deduced from the relative number of nuclear interactions these secondaries had in the chamber and assuming the charged and neutral particles to have equal mean free paths. Cascades of 5 or more particles at their maximum development were generated at the origins of 12 percent of the nuclear interactions which occurred in the chamber. The heavily ionizing secondaries from nuclear interactions occurring in the chamber show an exponential absorption in the lead plates in which they are produced with absorption coefficients 0.20±0.02 and 0.24±0.04 per g/cm² of lead for the forward and backward ejected particles, respectively. In these same interactions a ratio of number of protons to mesons of about 0.3 is observed for particles in the ionization region 2–4 times minimum—while among particles of ionization less than twice minimum, 12 were identified as mesons and 5 as protons. Five huge cascades, of energy greater than 10 Bev, and not associated with large air showers were recorded. This efficiency rapidly approaches 1 for $\Delta>50$ particles per square meter, but is small for showers of lower density. As described in reference 1, the air shower signals "C" also indicated, in general, showers of rather high particle density. The exclusion, in the present paper, of events associated with A or C signals essentially excludes, therefore, only those events occurring in air showers of more than about 50 particles per square meter. The S, SP, and P coincidences occurring simultaneously with A or C signals were only 136 as compared with 4949 not associated with such dense air showers.

TABLE II. The mean free path for nuclear interaction of the ionizing penetrating secondaries of nuclear interactions.

Triggering coincidence	g/cm² Pb traversed in chamber by penetrating secondaries of nuclear interactions		Number of nuclear interactions of the ionizing penetrating secondaries of nuclear interactions		m.f.p. for nuclear interaction g/cm² Pb
	Observed	Corrected	Observed	Corrected	
S, SP	19700	21500	39	68	316±70
P	8800	9620	26	46	209±50

The various phenomena observed in these 4949 pictures included many like the examples of cascades, penetrating showers, mixed showers, and nuclear disintegrations shown in the accompanying photographs.

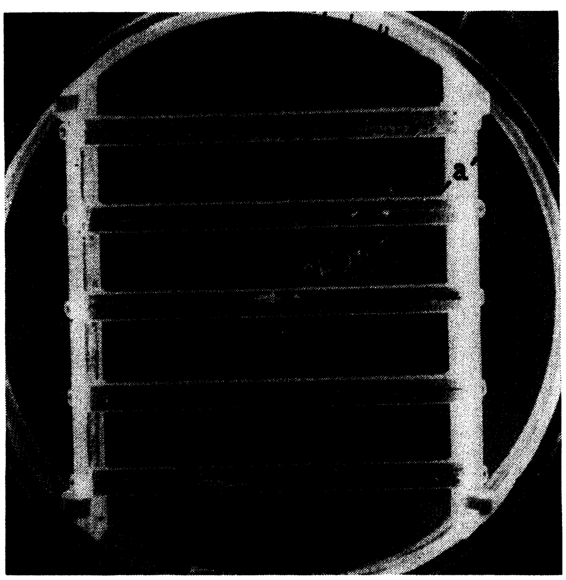

FIG. 2(A). A four-particle penetrating shower seen with a P trigger, originating two inches above the bottom of the lead roof. One of the shower particles undergoes a secondary nuclear interaction in which it produces five secondaries in the upper third of the third plate. One of the backward ejected secondaries, (a) penetrates the second plate and appears in the compartment to the right of the Lucite wall.

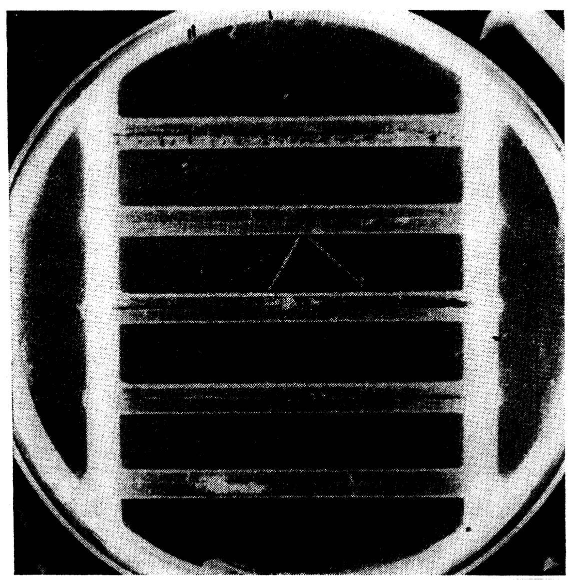

FIG. 2(B). A three-particle penetrating shower seen with an S trigger, originating about one inch above the bottom of of the lead roof. One of the shower particles undergoes a secondary nuclear interaction in which it produces three lightly ionizing and two heavily ionizing secondaries in the lower third of the second plate.

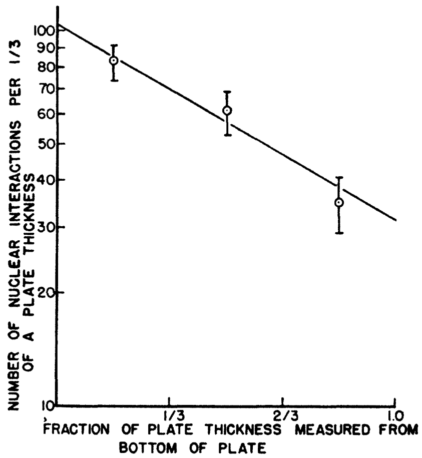

FIG. 3. The frequency of nuclear interactions occurring in the lead plates of the chamber *vs.* the point of origin of the interactions measured from the bottom of the plate in units of the plate thickness.

Similar events have been observed by others over the past few years.[2–7] In the present analysis some of the properties of these events and their secondaries are determined. For this purpose the following criteria, though not necessarily of fundamental significance, were useful for the classification of particles and nuclear interactions:

(1) Lightly ionizing particle—one which has a straight visible path and has less than 2 times minimum ionization.

(2) Heavily ionizing particle—one which has a straight visible path and has $\geqq 2$ times minimum ionization.

(3) Penetrating particle—a lightly ionizing particle which penetrates at least one lead plate without multiplication or a heavily ionizing particle which penetrates at least one plate.

(4) Penetrating shower—at least two penetrating particles which come from a common origin either above or in the chamber.

(5) Mixed shower—one or more penetrating particles and one or more cascades with common origins but different directions.

(6) Nuclear disintegration—minimum requirements are: either one penetrating particle plus one heavily ionizing particle, or one heavily plus one lightly ionizing particle, or two heavily ionizing particles which come from a common origin.

In the present article the general term "nuclear interaction" is used in referring to events which belong to any one of classes (4), (5), or (6). The term "nuclear disintegration" is employed in (6) rather than "star" since, in the present experiment, the average energy of events belonging to this group is considerably greater than that of the "stars" observed in photographic emulsions (see Section 9).

The numbers of nuclear interactions in *S*-, *SP*-, and *P*-events observed to occur above and in the chamber are given in Table I. Those occurring in the chamber are further subdivided in the table with regard to the nature of the initiating particle (charged, uncharged, or undetermined). Those made above the chamber con-

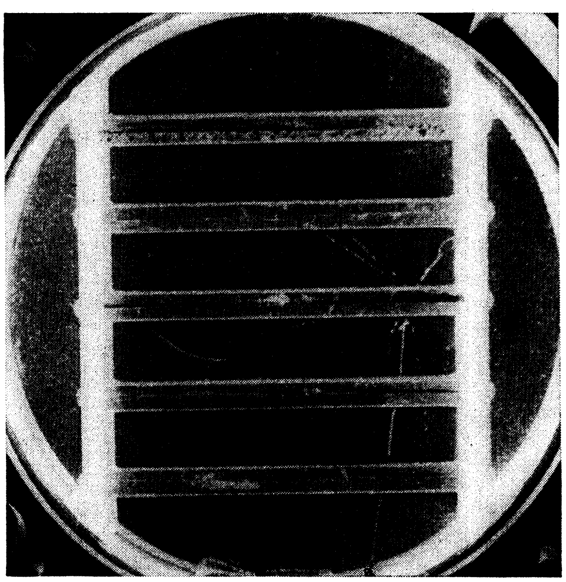

FIG. 4(A). A nuclear event seen with a *P* trigger. It appears to be made by a neutral particle. One particle (a) crosses two plates with greater than four times minimum ionization, but with no noticeable increase of ionization, and therefore must have had a mass greater than that of a proton.

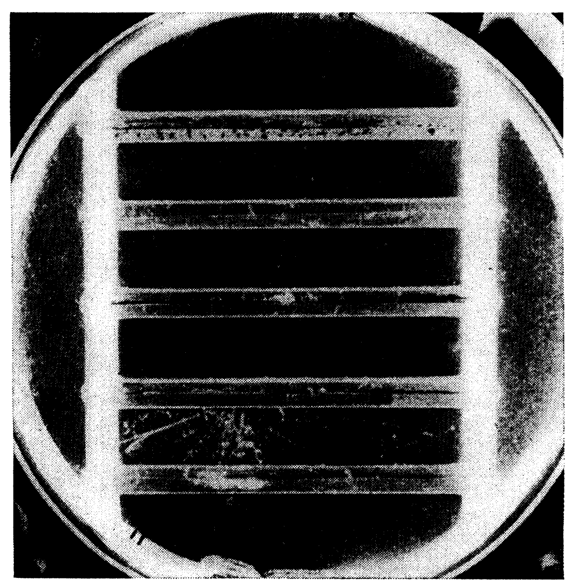

FIG. 4(B). A mixed shower seen with a *P* trigger and produced in the fourth plate probably by an ionizing particle which itself is part of a narrow penetrating shower, the origin of which is above the chamber.

[2] W. M. Powell, Phys. Rev. **69**, 385 (1946).
[3] W. B. Fretter, Phys. Rev. **73**, 41 (1948).
[4] H. Bridge and W. Hazen, Phys. Rev. **74**, 579 (1948).
[5] C. Y. Chao, Phys. Rev. **75**, 581 (1949).
[6] W. B. Fretter, Phys. Rev. **76**, 511 (1949).
[7] Lovati, Mura, Salvini, and Tagliaferri, Nature **163**, 1004 (1949).

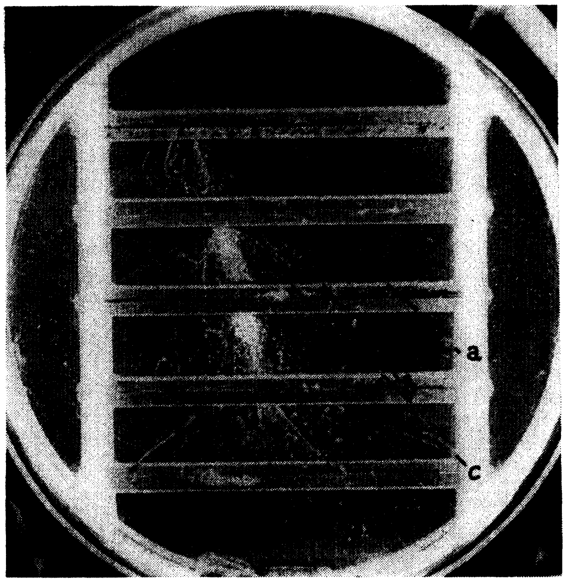

FIG. 5(A). A mixed shower seen with a P trigger. Nuclear interactions occur in plates 1, 2, and 4. There are three minimum ionizing penetrating particles at (a), (b), and (c). There are three heavily ionizing secondaries emerging from plate 4.

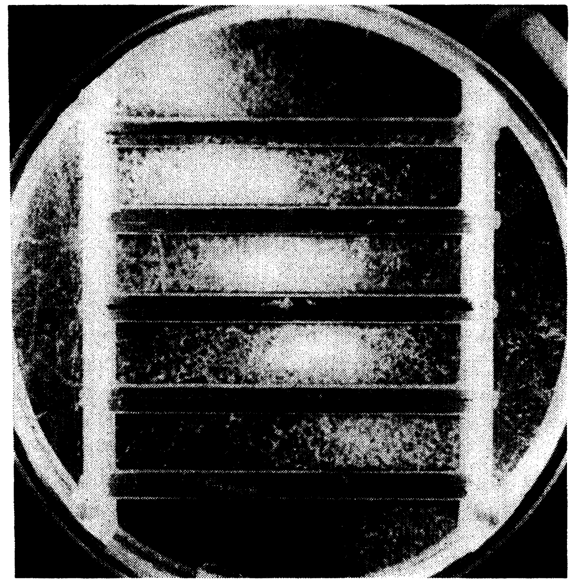

FIG. 5(B). A huge cascade with an S trigger. Altogether we saw five cascades of comparable size, none of which were accompanied by dense air showers or contained discernible penetrating particles.

sisted only of penetrating and mixed showers, while those in the chamber included nuclear disintegrations as well.

3. MEAN FREE PATH OF THE PENETRATING PARTICLES

The penetrating particles from nuclear interactions originating either above or in the chamber were observed to traverse a total projected path length of 28,500 g/cm^2 of lead in the chamber and there were 65 nuclear interactions produced by those ionizing particles (see for example Fig. 2). The distribution of total projected path length and number of nuclear interactions in S- and SP-events combined, and in P-events alone is given in Table II.

The observed path length is the projection of the true path length on a plane perpendicular to the line of sight of the camera. If $f(\theta)$ is the projected angular distribution of the penetrating particles from nuclear interactions, the ratio of the true path length to the projected path length is

$$\int_0^{\pi/2} f(\theta)\,\sec\theta d\theta \bigg/ \int_0^{\pi/2} f(\theta)d\theta.$$

It is shown below in Sections 4a and 4b that the projected zenith angular distribution of the penetrating particles from nuclear interactions originating in and above the chamber respectively are both approximately of the form $\cos^3\theta$ for angles up to 60°. For $f(\theta)$ of this form the above ratio is 1.09. The corrected values of the path lengths are given in column 3 of Table II.

The points of origin of all nuclear interactions in the chamber, irrespective of the nature of the interacting particle, could, in all but three cases, be determined by

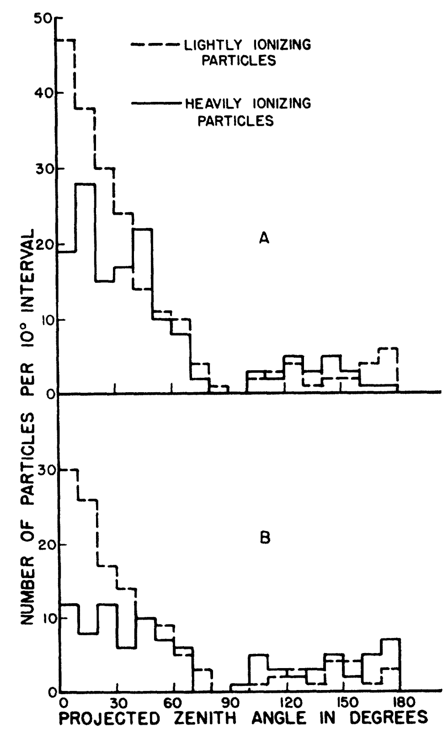

FIG. 6. The projected zenith angular distributions of the lightly and heavily ionizing secondaries of nuclear interactions occurring in the chamber. (A) Nuclear interactions of ionizing particles, (B) Nuclear interactions of neutral particles.

backward tracing of the paths of their ionizing secondaries. The frequency distribution of the points of origin, measured in each case with reference to the bottom surface of the plate, is shown in Fig. 3 plotted in intervals of $\frac{1}{3}$ of a plate. The predominance of nuclear interactions observed in the lower $\frac{2}{3}$ is a result of the asymmetry of ejection of the particles (more in the forward direction) and the strong absorption of the more heavily ionizing ones. These effects are discussed in more detail in Section 9. For the present purpose the distribution may be used to estimate the ratio of the actual number of nuclear interactions occurring in the lead to the number observed. Assuming the absorption to be of the form $n=n_0e^{-\mu t}$, application of the method of least squares gives $\mu=1.2\pm0.3$ per plate thickness (or 0.087 ± 0.022 per g/cm² of lead) and $n_0=104\pm14$ as the number per $\frac{1}{3}$ plate. Hence the desired ratio is

$$\frac{3n_0}{\text{observed number}}=\frac{312\pm42}{179\pm13}=1.75\pm0.27.$$

Since the nuclear interactions of ionizing particles are similar to those of neutral particles (see Sections 4a and 5a), it is reasonable to assume that the distributions of their points of origin in the lead plates are also similar. Hence a 75 percent correction must be added to the number of observed nuclear interactions of ionizing particles. The corrected numbers are given in column 5 of Table II and the resulting mean free paths for nuclear interaction in column 6.

It should be noted that a P coincidence is caused by two or more penetrating particles beneath the chamber and hence is more likely to occur when a shower has undergone further multiplication in the chamber than when it has not. Hence in P-selected events the probability for an interaction to be seen in the chamber is increased by the counter selection, and this is evident in the rather low mean free path given in Table II. On the other hand, an S coincidence demands multiplicity of particles only above the chamber. Since very few penetrating secondaries of nuclear interactions are ejected upward (see Section 9 and Table IV), the probability of an S coincidence is not appreciably influenced by whether or not an interaction has occurred in the chamber. Therefore the interaction mean free path deduced from the S- and SP-triggered pictures, 316 ± 70 g/cm² of lead, has not been significantly affected by the counter selection and may be considered as representing the mean free path for nuclear interaction of the penetrating particles from nuclear interactions. This is in agreement with the mean free path estimated by Lovati *et al.*,[7] but disagrees with Fretter's value of 750 g/cm².¶ Fretter made no correction for the "invisible" interactions occurring in the lead plates. Piccioni¶ also reports measurements which indicate a long range for the secondaries of penetrating showers (after filtering through large thickness of lead). He interprets this as indicating long mean free path for nuclear interaction. However, he would detect such interactions only if the primary and all its progeny were absorbed; not if an ionizing penetrating particle continued after the interaction. In the present experiment many nuclear interactions, in which there were penetrating secondaries, were observed (see for example Figs. 4B and 5A).

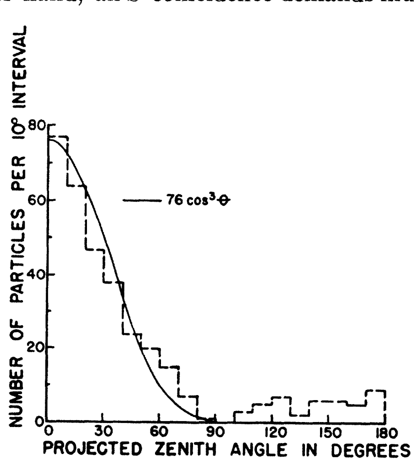

FIG. 7. The projected zenith angular distribution of all the lightly ionizing secondaries of nuclear interactions occurring in the chamber.

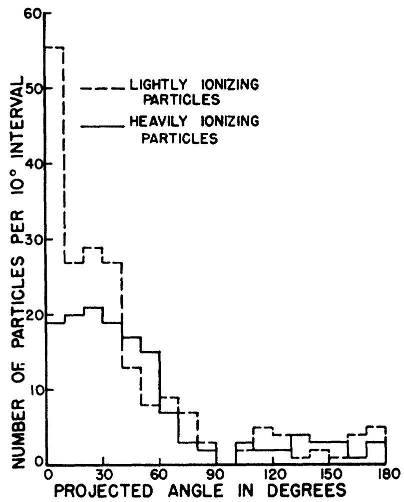

FIG. 8. The projected angular distributions of the lightly and heavily ionizing secondaries of the nuclear interactions of ionizing particles occurring in the chamber. The measured angles are those between the directions of the secondaries and that of the primary in each case.

4. ANGULAR DISTRIBUTIONS OF THE SECONDARIES

a. Nuclear Interactions in the Chamber

For nuclear interactions occurring in the cloud-chamber plates, the projected zenith angles of the

¶ Result given at Cosmic Ray Conference, Idaho Springs, Colorado, June 1949.

secondary particles that emerged from the plates could be measured in the full 0° to 180° interval, except in the region around 90° which was obscured by the plates. The zenith angular distributions of lightly ionizing (broken line histograms) and heavily ionizing secondaries (full line histograms) are given in Figs. 6A and 6B for the nuclear interactions of ionizing and neutral particles, respectively. The sum of the distributions of the lightly ionizing secondaries is given in Fig. 7. Up to 80° it may be represented by an empirical law of the

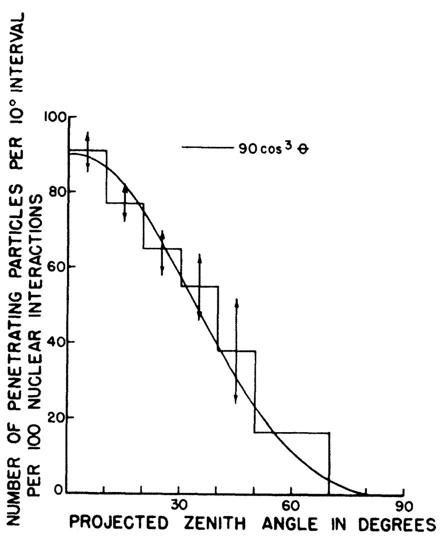

FIG. 9. The projected zenith angular distribution of the ionizing penetrating secondaries of nuclear interactions occurring above the chamber.

form $\cos^3\theta$, which has been used in Section 3 in connection with the mean free path.

For a nuclear interaction of an ionizing particle, the angles between the directions of the secondaries and the direction of the primary can be measured. The angular distribution of heavily and lightly ionizing particles about the primaries is given in Fig. 8. The median projected angle between a lightly ionizing secondary and its primary is 27°, corresponding to a median angle of 36°.

In the above angular distributions all nuclear interactions were counted irrespective of the method of counter selection since plotting of the distributions in $S+SP$- and P-events separately revealed no significant bias of secondaries in the P-events toward the vertical, either for the lightly or heavily ionizing particles. However, the ratios of the total number of lightly ionizing to heavily ionizing particles from the nuclear interactions in $S+SP$-, and P-events were 1.23 ± 0.18 and 1.70 ± 0.30, respectively. The P-event selection may thus exert some bias in favor of lightly ionizing particles without influencing the angular distribution very strongly. A bias of P-events in favor of lightly ionizing secondaries is understandable because a P coincidence requires at least two penetrating particles

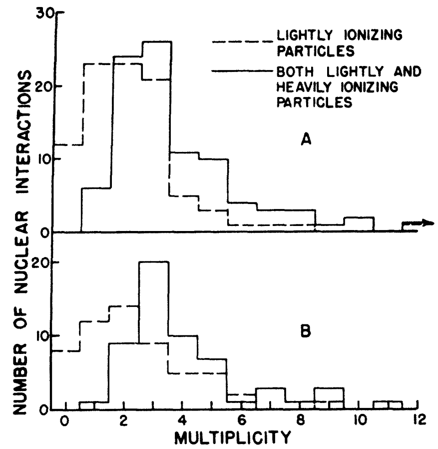

FIG. 10. The distributions of the total multiplicities and the multiplicities of the lightly ionizing secondaries of nuclear interactions occurring in the chamber (A) for the nuclear interactions of ionizing particles (B) for those of neutral particles. The occurrence of interactions of zero multiplicity of lightly ionizing secondaries merely means that these interactions were detected by the presence of the heavily ionizing secondaries only.

capable of traversing $3\frac{1}{2}$ inches of lead beneath the chamber. S coincidences, on the contrary, are not influenced by the nature of the secondaries created in the lead plates of the cloud chamber.

The projected zenith angular distributions of the secondaries of nuclear interactions of ionizing and netural particles (Figs. 6A and 6B) are similar, and the ratios of the numbers of lightly ionizing to heavily ionizing particles are 1.42 and 1.41, respectively. These two facts indicate that the neutral and ionizing particles experiencing these nuclear interactions are of about the same average energy.

b. Nuclear Interactions outside the Chamber

In all of these interactions the initiating particle is not observed and most of the heavily ionizing particles have been removed by absorbing layers between the point of origin and the cloud chamber; hence only the zenith angles of the penetrating particles were measured. For the angular distribution of these particles to have meaning some account had to be taken of the variations of the solid angle available for the detection of penetrating particles. To achieve this, the projection of the solid angle seen by the camera was divided into 10° intervals for each nuclear interaction. The number of cases where a given angular interval was visible and the number of penetrating particles in each of the intervals were recorded. Each interval and each penetrating particle was further weighted by the first power of the distance from the origin of the interaction to the nearest point in the sensitive volume of the chamber at which the particle could show its penetrating properties. Finally the ratio of the weighted numbers of penetrating particles to the weighted number of intervals was calculated and plotted as a function of zenith angle. The resulting histogram of Fig. 9 represents the prob-

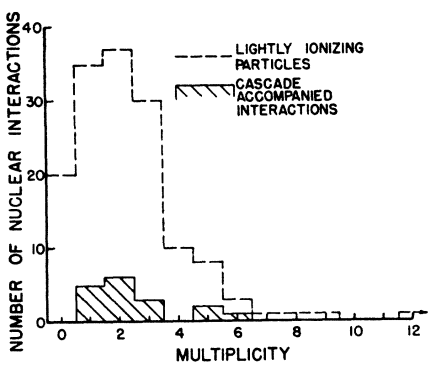

FIG. 11. The multiplicity distribution of the lightly ionizing secondaries of all nuclear interactions occurring in the chamber. The shaded portion gives the number of these interactions in which electrons or photons were generated with enough energy to make cascades in succeeding lead plates with 5 or more particles at their maximum development.

ability of a penetrating secondary particle lying in a given 10° projected zenith angular interval. The distribution follows an empirical law $\sim\cos^3\theta$, similar to that for the lightly ionizing particles ejected in the forward direction from the nuclear interactions occurring in the chamber.

5. MULTIPLICITY OF SECONDARIES AND CASCADE PRODUCTION

a. Nuclear Interactions in the Chamber

The multiplicities of the secondaries (not including those which were obviously electrons by virtue of their cascade production in Pb plates or scattering in the gas) from the nuclear interactions of ionizing and neutral particles in the lead plates of the chamber are given in the frequency histograms of Figs. 10A and 10B, respectively. Again all interactions irrespective of counter selection were counted. Broken lines represent the multiplicity of the lightly ionizing secondaries and the full lines the multiplicity of both lightly and heavily ionizing particles together. It is seen that the multiplicities of secondaries in interactions of neutral and charged particles have about the same distribution. The occurrence of nuclear interactions in which there were no lightly ionizing particles merely means that in these cases a nuclear interaction was detected by the presence of two or more heavily ionizing particles. The few cases in which there was a total of one particle were instances in which a nuclear interaction was detected by the presence of one heavy particle together with a cascade. The appearance of the distribution at these low multiplicities is thus a result of the selection criteria listed in Section 2.

The average multiplicity of lightly ionizing secondaries from the nuclear interactions of charged particles is 2.2, and for interactions of neutral particles is 2.4. Further division of these groups into $S+SP$-, and P-events still showed no significant difference in the average multiplicities, though the statistical uncertainties in these smaller groups are large. The results for the whole group ($S+SP+P$-events) are further

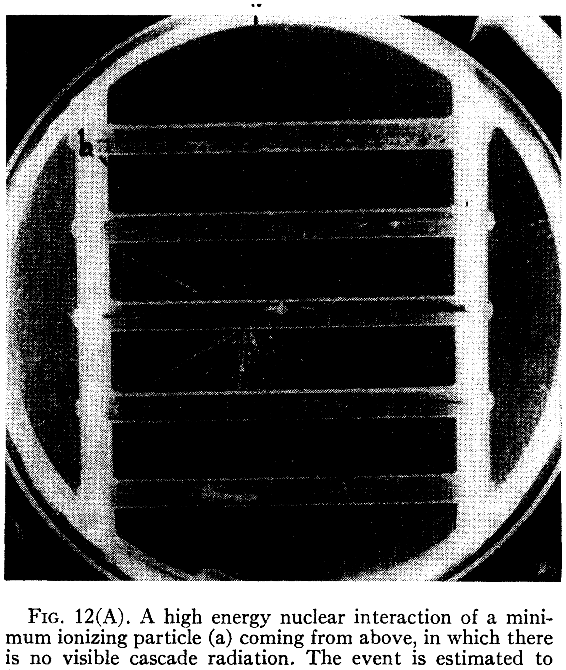

FIG. 12(A). A high energy nuclear interaction of a minimum ionizing particle (a) coming from above, in which there is no visible cascade radiation. The event is estimated to have had an energy of at least 8000 Mev. There are at least 26 secondaries coming from the common origin. One minimum ionizing particle (b) going in the backward direction penetrates the second plate. The chamber was triggered by a P coincidence, which indicates that at least two particles penetrated an additional 3.5 inches of lead.

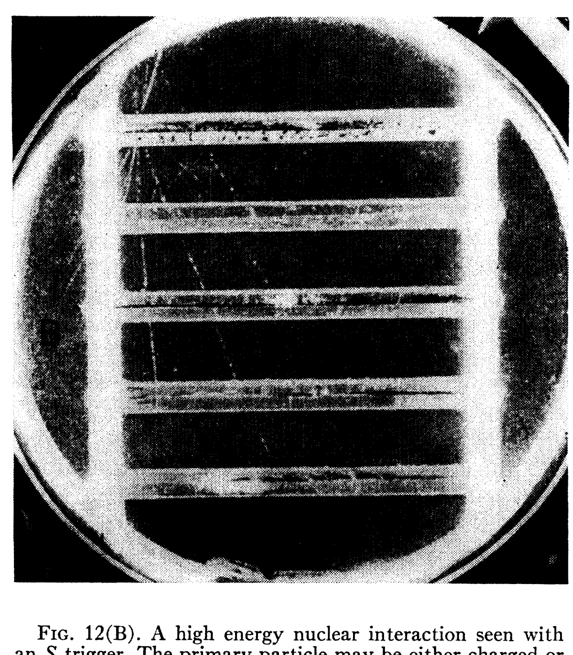

FIG. 12(B). A high energy nuclear interaction seen with an S trigger. The primary particle may be either charged or neutral and is estimated to have had an energy of at least 2500 Mev.

evidence that the interactions of neutral and charged particles involve energies of the same order of magnitude and hence that the initiating neutral and ionizing particles, most of which are secondaries from nuclear interactions occurring in the lead roof, have about the same average energies.

The multiplicity of lightly ionizing particles in all nuclear interactions occurring in the chamber, irrespective of whether their primaries are charged, neutral, or undetermined, is given in Fig. 11. The shaded portion of the histogram gives the frequency of nuclear interactions in which electrons or photons were generated with sufficient energy to make cascades of 5 or more particles at their maximum development. The frequency of cascade-accompanied nuclear interactions, compared with the total number of nuclear interactions, is only 17 percent of the frequency observed by Fretter.[6] Some of the disagreement may be accounted for by differences in the lower limit of cascade shower selected, and in the experimental arrangement. Fretter triggered on coincidences involving two counters below the chamber. Such coincidences are on the average more probable for showers including cascades than for penetrating showers with no cascade.

Since in the present experiment 72 percent of the nuclear interactions occurring in the lead plates in the chamber are made by secondaries from the interactions in the lead above, and there is little or no counter bias affecting the lower energy region of the size distribution of these secondary interactions, we are no doubt looking at phenomena of lower average energy than Fretter. Our selection of lightly ionizing particles from nuclear interactions is different from Fretter's selection of particles that penetrate at least one $\frac{1}{2}$-inch lead plate. That the majority of the lightly ionizing particles counted are not electrons is shown in Section 8.

The absence of cascade production at zero multiplicities is understandable since the primary energies involved in the production of the heavily ionizing particles by which these nuclear interactions were detected is relatively low. The absence of cascades amongst the high multiplicity events, though of questionable statistical significance, would indicate that the probability for the production of cascades in nuclear interactions does not increase with energy or multiplicity as rapidly as expected according to current theories.[8,9] This point requires further experimental test since penetrating particles in the cores of the cascades escape observation, and thus there is an observational bias against recording a high multiplicity event with an accompanying cascade. That this bias is not large is indicated by the fact that when high multiplicity nuclear interactions did occur, the angular spread of the penetrating particles was large (see for example Figs. 12 and 13) and hence in cascade-accompanied nuclear interactions (Figs. 4B and 5A) one would expect to see some of the penetrating particles.

There were many cases in which cascades occurred

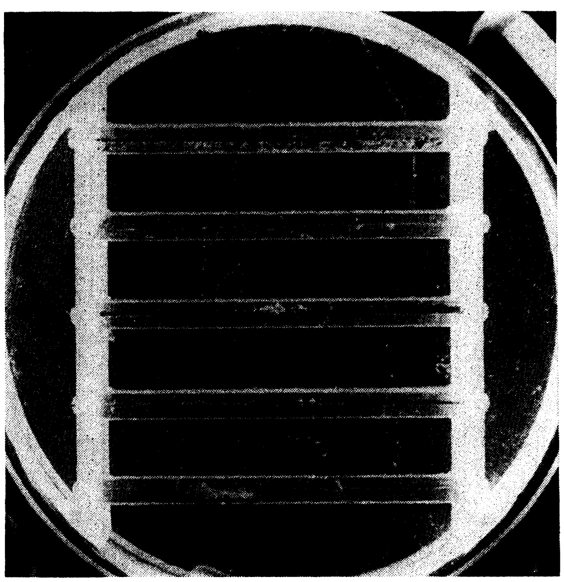

FIG. 13(A). A penetrating shower of at least nine particles, with no cascade radiation, seen with an *SP* trigger. There is very little scattering of most of the particles, and the minimum energy is estimated to be 20 Bev. The origin is at the bottom of the lead roof and we should be able to see cascade if it existed.

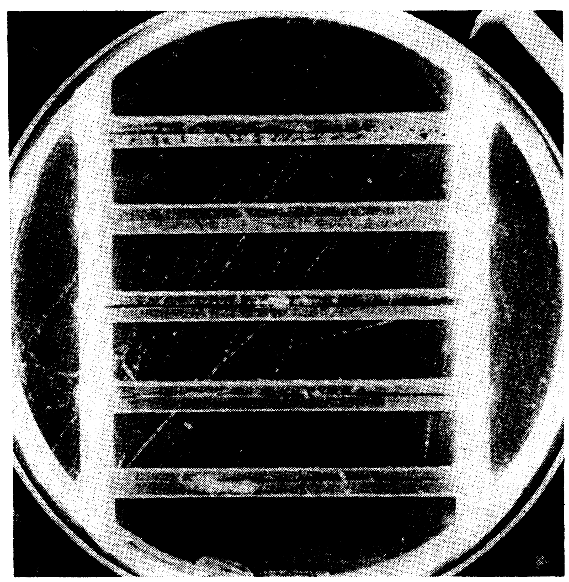

FIG. 13(B). A penetrating shower of at least eight particles seen with an *S* trigger, originating one inch above the bottom of the lead roof but exhibiting no cascade radiation. The particle showing the scattering and increased ionization is identified as a proton. The energy of this event is estimated to be greater than 8 Bev.

[8] L. I. Schiff, Phys. Rev. **76**, 89 (1949).
[9] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1949).

TABLE III. The observed scattering angles suffered by 9 penetrating particles each of which traversed at least three ½-inch lead plates and had at least one scattering greater than 8°.

Penetrating particle number	Observed scattering angles in degrees 1	2	3	4
1	5.5	0.5	16.5	
2	1.0	19.0	9.0	
3	1.5	0.5	20.0	
4	4.5	10.0	1.0	
5	4.0	2.0	24.0	
6	0.5	13.0	0.0	
7	3.0	0.5	1.5	27.0
8	10.0	4.0	8.0	5.0
9	13.0	3.5	4.5	

unaccompanied by either penetrating particles discernable in the chamber of air showers outside the chamber (e.g., Fig. 5B). These are believed to be the products of other types of interaction, such as bremsstrahlung and knock-on processes of mesons and nucleons, or the decay of energetic unstable particles.

b. Nuclear Interactions above the Chamber

The distribution of the multiplicities of the visible penetrating particles from nuclear interactions originating above the chamber, i.e., either in the lead roof or in other material between the roof and the sensitive volume of the chamber, is given in Fig. 14 for two different methods of counter selection. The combined results are given in Fig. 15 where the shaded portion of the histogram represents the number of these nuclear interactions accompanied by cascades of 5 or more particles. No cascades were observed in the 8 nuclear interactions with multiplicity $\geqq 6$. Four of these occurred so high up in the lead roof that any existing cascade component could have been absorbed, while cascade radiation from the remaining four would have had a good chance of being detected if present. Interactions for which a multiplicity of one is recorded represent the few cases in which a nuclear interaction was detected by the presence of one penetrating particle together with a cascade, with a well-defined core, going in a different direction. The peak in the distribution curve is thus not to be considered as real, since no other interactions of multiplicity one were counted because they were indistinguishable from non-interacting single penetrating particles. The frequent triggering of the six counters at X (Fig. 1) by showers with low multiplities of penetrating particles is in many cases due to the simultaneous occurrence of a relatively high multiplicity of electrons emerging from the lead roof, and to the fact that the penetrating particles of such a shower do not necessarily all pass through the chamber.

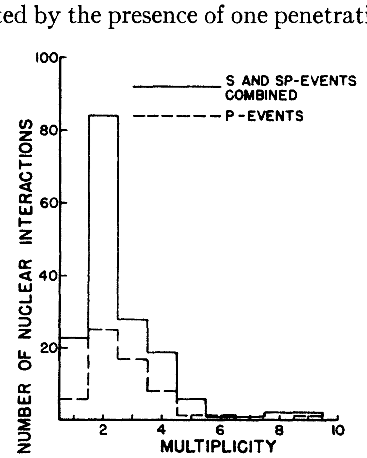

FIG. 14. The multiplicity distribution of the penetrating particles from nuclear interactions occurring above the chamber and selected by two different types of triggering coincidences.

6. SCATTERING OF THE PENETRATING PARTICLES IN THE LEAD PLATES

The projected angles through which each lightly ionizing penetrating particle from a nuclear interaction occurring in or above the chamber was scattered, on passing through a lead plate, were measured to the nearest 0.5 degree. In 9 out of 202 cases in which 3 or more scattering angles of a single penetrating particle from a nuclear interaction occurring above the chamber could be measured, the particle suffered a scattering $>8°$. The measured scattering angles for each of these 9 cases are given in Table III. In seven of these cases the largest scattering angle is four or more times the root mean square average of the other scattering angles recorded for the particular particle. These 7 scatterings are regarded as very probably different from the more usual Coulomb scatterings observed. The 202 penetrating particles traversed a total of 10,800 g/cm² of lead, which indicates a mean free path of $10{,}800/7 = 1550$ g/cm² for this type of interaction. It must be pointed out that the above criterion of selection, though necessary to distinguish this type of interaction from the Coulomb scattering, may limit us to the observation of less than

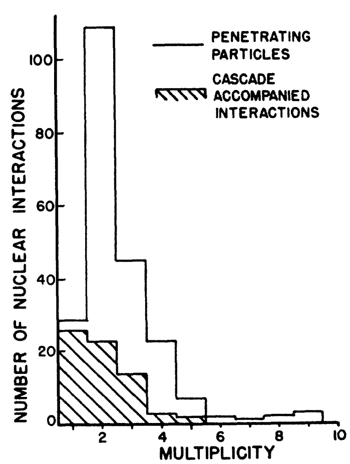

FIG. 15. The multiplicity distribution of the penetrating particles from all nuclear interactions observed to occur above the chamber. The shaded portion gives the number of these interactions in which electrons or photons were generated with enough energy to make cascades of 5 or more particles at their maximum development.

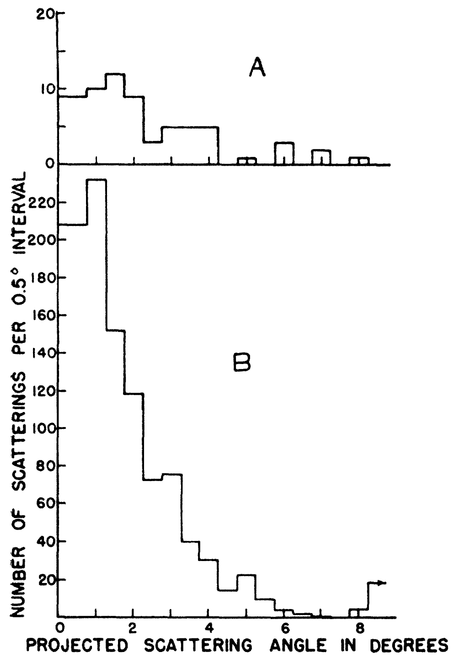

FIG. 16. The scattering angle distribution of the penetrating secondaries of nuclear interactions occurring (A) in the chamber and (B) above the chamber. Each scattering angle measured was that resulting upon passage of a particle through a $\frac{1}{2}$-inch lead plate.

the actual number of such interactions taking place. However, nuclear scattering is expected to be, on the average, at rather large angles, so that it is not likely to miss a large fraction of them. It is more likely that a few of the large-angle scatterings observed are unusual cases of Coulomb scattering, so that the mean free path for nuclear scattering is longer than 1550 g/cm^2, which must be regarded as an approximate lower limit on the mean free path. The results thus indicate that the mean free path for nuclear interaction without the production of secondaries is at least 4 or 5 times that for nuclear interaction with the production of secondaries. This is in agreement with Fretter's measurements.||

The distribution of the scattering angles is given in Figs. 16A and 16B for the penetrating particles from nuclear interactions occurring in and above the chamber respectively. The root mean square scattering angles are 3.0° and 2.3° respectively, neglecting angles $>8°$, a large fraction of which are likely non-Coulomb scatterings. According to the formula for the distribution of scattering angles of cosmic-ray particles given by Rossi and Greisen,[10] single particles with values of $p\beta=430$ Mev and 570 Mev respectively would have root mean square projected scattering angles in traversing $\frac{1}{2}$-inch lead plates equal to the above averages. These can be considered as low estimates for the average values of $p\beta$ for these distributions for two reasons: (1) Averaging of the scattering angles essentially averages the reciprocal of $p\beta$, which gives undue weight to the particles of low momentum; (2) small scattering angles are most frequent and errors in measurement would tend to shift the distribution a little to larger angles.

The average multiplicity of the lightly ionizing secondaries of nuclear interactions occurring in the chamber has been given in Section 5 as 2.2. Using the above value of $p\beta=430$ Mev as representing the average energy of these secondaries, and assuming the relative numbers of ionizing and neutral secondaries to be 1.5 (the same as that estimated below in Section 7 for the penetrating secondaries of nuclear interactions occurring above the chamber), the average energy of the interacting particles is estimated to be $2.2\times 0.43 \times(1.5+1)/1.5=1.6$ Bev. If the lower energy neutral and ionizing heavy secondaries, as well as the cascade producing electron secondaries were also considered, it would be conservative to estimate the average energy as lying in the range 2 to 3 Bev. If the secondaries are emitted symmetrically in the center of mass system, in accordance with the symmetric pseudoscalar theory of meson production,[9] the median angle of emission with respect to the primary in the laboratory system, corresponding to this energy interval, ranges from 39° to 48° irrespective of whether the primary is a π-meson or a proton. The scalar theory[9] on the other hand would indicate a median angle $\mu/p\approx 146/430=0.34$ radians or 19°, which may be considered as an upper limit since 430 Mev is a low estimate. Our measured value of the median angle, 36°, given in Section 4, is in rough agreement with the symmetric theory. This is in contradiction to Walker's results** which were obtained from counter data and favored the scalar theory.

7. RELATIVE NUMBER OF NEUTRAL AND CHARGED PENETRATING PARTICLES

It has already been mentioned that the average multiplicities of the nuclear interactions of ionizing and non-ionizing penetrating particles are nearly equal, and also that the lightly and heavily ionizing secondaries occur in the same relative numbers and with about the same angular distributions in showers generated by neutral and by ionizing particles. These similarities indicate

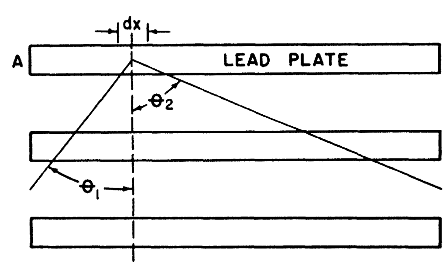

FIG. 17. Diagram showing the limiting values of the projected zenith angles, θ_1 and θ_2, between which a penetrating secondary from a nuclear interaction occurring in the interval dx of plate A must lie in order to show penetration.

|| Given at Cosmic Ray Conference, Idaho Springs, Colorado (June, 1949).

[10] B. Rossi and K. I. Greisen, Rev. Mod. Phys. 13, 240 (1941).

** W. D. Walker, Ph.D. thesis, Cornell University (1949).

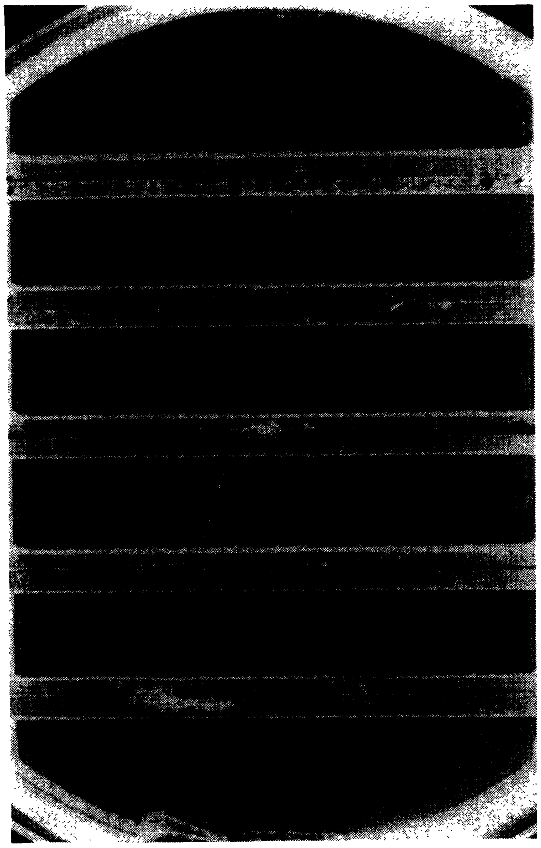

FIG. 18. A penetrating particle, which, by virtue of its scattering, ionization, and range is identified as a proton. From the theoretical relationships between these properties, the ionization relative to minimum ionization, in each of the compartments of the chamber starting from the top lies in the intervals 1.9–2.2; 2.2–2.5; 2.5–3; 3–4; and 4.5, respectively. This track was used for comparison in the estimation of the ionization of other tracks in the range 2–4 times minimum.

that the neutral and ionizing penetrating particles have about the same average energy, since all of the above properties are probably related to the energy of the primary. Of the three properties the multiplicities probably represent the best measure of the energies.

If the neutral and ionizing particles have the same mean free path for nuclear interaction, the relative numbers of the nuclear interactions of neutral and ionizing particles would be a fair measure of the relative numbers of the neutral and ionizing particles themselves. Since the six counters above the chamber respond to events of fairly large multiplicity of ionizing particles (both electrons and penetrating particles), the bias against the recording of nuclear interactions by neutral particles in the chamber is small. In the S-events there were 39 and 26 nuclear interactions in the chamber made by ionizing and neutral particles respectively, that had been generated in nuclear interactions which had occurred above the chamber. Hence the ratio of ionizing to neutral penetrating particles from nuclear interactions is 1.5 ± 0.4. Interacting particles unaccompanied by another penetrating particle were not counted as it was not clear in such cases whether the interacting particle (neutral or ionizing) was a member of a nuclear interaction occurring above the chamber.

8. THE NATURE OF THE SECONDARIES

From the 149 nuclear interactions of neutral and charged particles occurring in the lead plates of the chamber there was a total of 293 lightly ionizing secondaries (not including those which were obviously electrons) ejected in the forward direction. Of these, 119 (or a fraction 0.41) penetrated at least one lead plate. From the angular distribution of secondaries given in Fig. 7 and the assumption that they are all penetrating, the number expected to impinge on a lead plate and be visible in the following compartment can be calculated as follows: a minimum ionizing particle emerging from plate A in the region dx (Fig. 17) would be capable of exhibiting penetration in one or more succeeding plates if its direction lies in the projected zenith angular interval (as seen by the camera) determined by the limiting zenith angles θ_1 and θ_2. The fractional number of particles lying in this interval can be calculated from the projected zenith angular differential distribution $f(\theta)$ of Fig. 7 and is given by

$$\int_{\theta_1}^{\theta_2} f(\theta)d\theta \Big/ \int_{-\pi/2}^{\pi/2} f(\theta)d\theta.$$

To account also for those particles which escape by passing out of the field of view through the front or back of the chamber without penetrating a lead plate, a similar calculation must be made for the projection perpendicular to that seen by the camera and given by

$$\int_{\phi_1}^{\phi_2} f(\phi)d\phi \Big/ \int_{-\pi/2}^{\pi/2} f(\phi)d\phi,$$

where $f(\phi)$ is the same function as $f(\theta)$.

The fractional number of lightly ionizing particles capable of showing penetration is the product of these two integrals averaged over the length and width of the lead plate. Using the measured angular distribution of Fig. 7 and values of θ_1, θ_2, ϕ_1, ϕ_2 as functions of position, obtained from geometrical considerations, numerical integration yields 0.48 as the fraction. Since particles from plate 5 could show no penetration, only those coming from nuclear interactions in the first 4 plates can be counted. Since 0.93 of the nuclear interactions happened in the first four plates the fraction of particles which can show penetration is $0.93\times0.48=0.44$ This differs by only 0.03 from the observed fraction; thus probably less than 10 percent of the lightly ionizing tracks in the forward direction are electrons and this is assumed to be a negligible percentage.

A similar calculation may be carried out for the lightly ionizing particles traveling in the backward direction. A uniform angular distribution is used (see

Fig. 7), and a numerical integration, this time discounting the nuclear interactions occurring in the top plate, indicates that we should see 14 percent of the lightly ionizing particles penetrate one or more lead plates if they are all penetrating particles. We observed that 5 out of 63, or 8 percent, of the lightly ionizing particles crossed a lead plate. This indicates that at most 50 percent of the lightly ionizing particles in the backward direction could be electrons since there is little chance of an electron crossing a lead plate with small scattering. In making these estimates of the percentages of electrons we have neglected the small probability that a π-meson and the somewhat larger probability that a μ-meson may be a little less than twice minimum ionization and still not have enough energy to penetrate a plate. As a result these estimates are an upper limit for the fraction of electrons.

We now consider all tracks from nuclear interactions that are in the forward direction and have an ionization density between two and four times minimum as determined visually, by comparison with the proton track (see Fig. 18) that shows successive increases in ionization in crossing plates and finally stops. Calculations based on the range-momentum and ionization-momentum curves of Rossi and Greisen[10] show that π-mesons having 1.7 times minimum ionization and protons having 4.5 times minimum ionization are just able to penetrate a lead plate. Therefore, all tracks in the interval 2–4 times minimum ionization that then penetrate a plate must belong to particles of rest mass greater than that of a π-meson, while those that are unable to penetrate are very likely mesons; and, as has been shown by the experiment of Piccioni,[11] are π-mesons rather than μ-mesons.

We observe in all of the nuclear interactions occurring in the lead plates, 95 particles in the forward direction, in the range 2–4 times minimum ionization, of which 9 penetrate a plate, while 86 do not appear to penetrate. Using the zenith angular distributions of heavily ionizing particles as given in Fig. 6A and 6B we calculate, in a manner similar to that used for lightly ionizing particles, that 44 percent of these particles should be observed to penetrate if all were able to penetrate. There are thus $9/0.44=20$ heavily ionizing penetrating particles (protons) and $95-20=75$ non-penetrating heavily ionizing particles. While the statistics are not good, the result indicates that secondaries in this ionization interval are more likely to be mesons than protons in spite of the fact that a fixed ionization interval represents a larger energy interval (by a factor $\sim 1840/320 \approx 6$) for protons than for π-mesons.

In one instance (Fig. 4A) a heavily ionizing secondary particle from a nuclear interaction (probably of a neutral particle) penetrates two lead plates after showing an ionization in the gas of more than four times the minimum. That there is little change in ionization and direction in crossing the fourth lead plate indicates that the particle is heavier than a proton. The apparent decrease in ionization just above and below the fifth plate could result from non-uniform illumination.

Out of all the penetrating tracks from nuclear interactions in the chamber which were <2 times minimum ionization, twelve could be identified as mesons because they had a greater increase in their ionization on crossing a plate than would be expected for a proton, while five tracks were identified as protons.

9. THE ABSORPTION OF THE SECONDARIES

The projected location of the point of origin of a nuclear interaction occurring in a lead plate in the chamber could, in most cases, be determined to the nearest 0.1 inch by backward extension of the visible portions of the paths of the secondaries. The distribution of the origins of nuclear interactions in the top, middle, and bottom thirds of the lead plates has already been given in Fig. 3. This absorption effect is due mainly to the fact that 85 percent of the nuclear interactions had their origins determined by the directions of emergence of heavily ionizing particles and that more of these particles are ejected downward than upward. In Table IV the interactions have been further subdivided into groups in accordance with their primaries being charged, neutral, or undetermined, and this time the number of particles is given instead of just the number of interactions. The total number of particles from each group and each $\frac{1}{3}$ of a lead plate thickness is divided into those moving upward and those moving

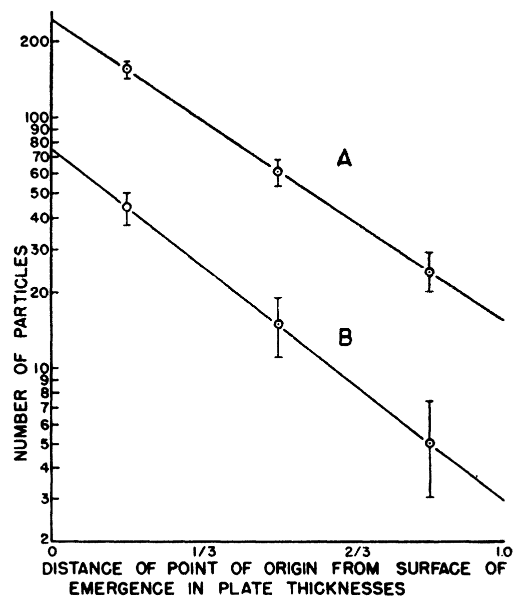

FIG. 19. Showing the absorption of the heavily ionizing particles, (A) in the forward direction and (B) in the backward direction, by the varying vertical thickness of lead between the points of origin of the particles in a plate and the sensitive part of the chamber. The ordinates are in numbers of particles per $\frac{1}{3}$ of a plate thickness.

[11] O. Piccioni, Phys. Rev. 75, 1281 (1949).

TABLE IV. The frequency of occurrence of the lightly and heavily ionizing secondaries of nuclear interactions occurring in the lead plates of the chamber. The secondaries are grouped according to their point of origin in a lead plate, their direction of motion relative to that of the primary (forward or backward), and the nature of their primaries (charged, neutral, or undetermined).

Depth of point of origin in Pb plate in units of one-plate thickness (one plate =14.0 g/cm²)	Nuclear interactions of charged particles				Nuclear interactions of neutral particles				Nuclear interactions of particles of undetermined nature				Total			
	Heavily ionizing secondaries		Lightly ionizing secondaries		Heavily ionizing secondaries		Lightly ionizing secondaries		Heavily ionizing secondaries		Lightly ionizing secondaries		Heavily ionizing secondaries		Lightly ionizing secondaries	
	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward
0 to 0.33	9	16	18	5	10	23	31	8	5	5	6	9	24	44	55	22
0.33 to 0.67	32	5	68	8	16	8	42	7	13	2	11	4	61	15	121	19
0.67 to 1.0	80	1	93	11	35	2	41	4	39	2	38	7	154	5	172	22

downward, and each of these classes into lightly ionizing and heavily ionizing particles.

The effective absorption of the heavily ionizing particles both in the forward and backward directions is shown by curves A and B respectively in Fig. 19. The two semilogarithmic curves are seen to be straight and almost parallel and indicate an effective exponential absorption with absorption coefficients of 2.8 ± 0.3 and 3.3 ± 0.6 per plate thickness (or 0.20 ± 0.02 and 0.24 ± 0.04 per g/cm^2 of lead) for the forward and backward particles, respectively. Most of these particles are more energetic at their origin than the heavily ionizing ones observed in stars in photographic emulsions.[12]

From the data of Table IV, it seems that the lightly ionizing secondaries in the forward direction also show as strong an absorption as the heavily ionizing secondaries. This however is only apparent and results from the fact that 85 percent of the nuclear interactions occurring in the chamber were detected by virtue of the presence of the heavily ionizing secondaries.

The ratio of heavily ionizing particles moving forward to those in the backward direction is seen from Table IV to be $237/64=3.7$. If we assume that at most 50 percent of the lightly ionizing tracks in the backward direction are electrons, as suggested by the estimate made in Section 8, and that all of the lightly ionizing tracks in the forward direction are heavier than electrons, we find $348/31=11$ for the maximum relative numbers of forward and backward traveling lightly ionizing mesons and protons. If on the other hand we assume that none of the particles (that do not generate cascades and are not visibly scattered in the gas) are electrons, we find $348/62=5.5$ for the minimum relative numbers of forward and backward traveling, lightly ionizing mesons and protons. Even this minimum ratio is higher than the ratio 3.7 for heavily ionizing particles.

10. KNOCK-ON ELECTRONS OF PENETRATING PARTICLES

The projected angles θ were measured between knock-on electrons of energy greater than 1 Mev after emerging from a lead plate and the knock-on producing penetrating particles arising from nuclear interactions above or in the chamber. A $\cos^2\theta$ distribution provides satisfactory agreement with the observed numbers of these knock-ons in the forward direction—a less steep distribution than the $\cos^{2.5}\theta$ previously observed by the authors and E. D. Palmatier[13] when the penetrating particles were μ-mesons and were more nearly vertical.

In the present experiment there were 131 knock-ons in 1711 emergences of penetrating particles from a lead plate or 0.077 ± 0.007 knock-on per penetrating particle, a result not significantly different from that previously obtained for μ-meson produced knock-ons by Hazen[14] and by the authors.[13] The ratio of the number of the back-scattered knock-on electrons to the number of forward ones is 0.38 ± 0.06 whereas a value 0.25 ± 0.04 for this ratio was previously observed.[13]

The authors wish to thank Professors K. Greisen and G. Cocconi for suggesting this experiment and for their generous help both in solving experimental problems and in discussions of the results. They are grateful to the Research Corporation for a grant which covered the expense of performing this experiment. The cost of constructing the apparatus was provided through an ONR contract. The facilities of the Inter-University High Altitude Laboratories were of great help in performing the experiment.

[12] D. H. Perkins, Nature **160**, 299 (1947).

[13] Brown, McKay, and Palmatier, Phys. Rev. **76**, 506 (1949).

[14] W. E. Hazen, Phys. Rev. **64**, 7 (1943).

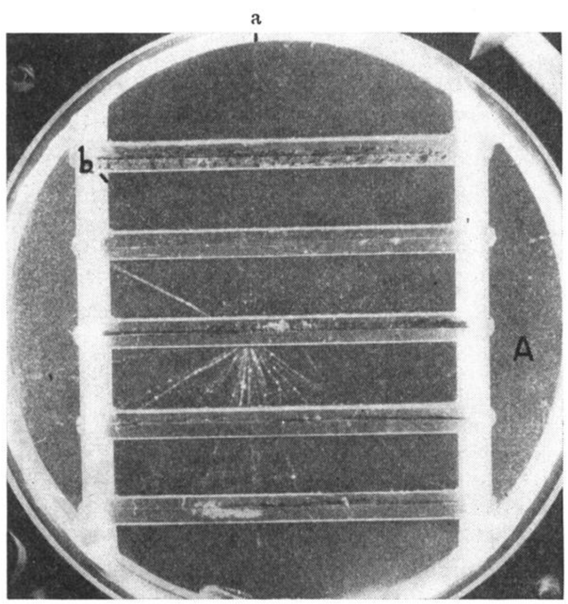

FIG. 12(A). A high energy nuclear interaction of a minimum ionizing particle (a) coming from above, in which there is no visible cascade radiation. The event is estimated to have had an energy of at least 8000 Mev. There are at least 26 secondaries coming from the common origin. One minimum ionizing particle (b) going in the backward direction penetrates the second plate. The chamber was triggered by a P coincidence, which indicates that at least two particles penetrated an additional 3.5 inches of lead.

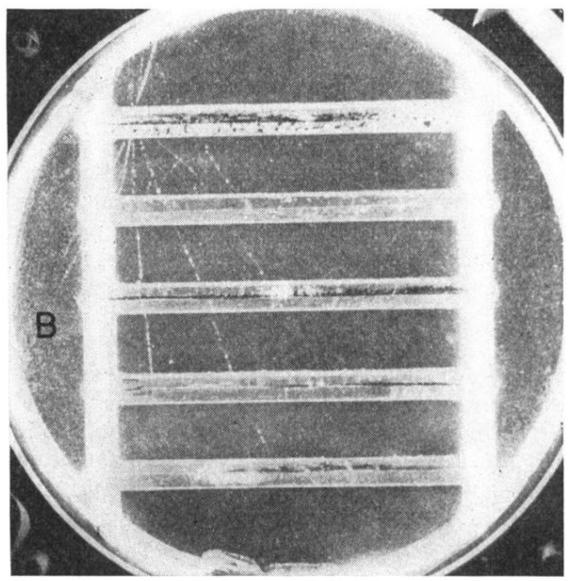

FIG. 12(B). A high energy nuclear interaction seen with an S trigger. The primary particle may be either charged or neutral and is estimated to have had an energy of at least 2500 Mev.

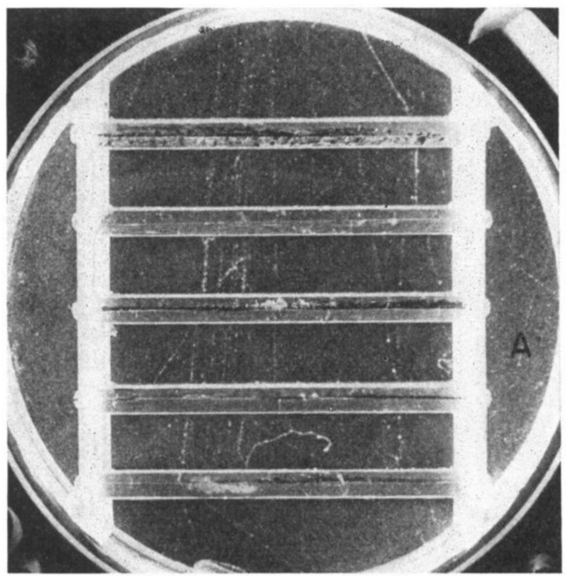

FIG. 13(A). A penetrating shower of at least nine particles, with no cascade radiation, seen with an *SP* trigger. There is very little scattering of most of the particles, and the minimum energy is estimated to be 20 Bev. The origin is at the bottom of the lead roof and we should be able to see cascade if it existed.

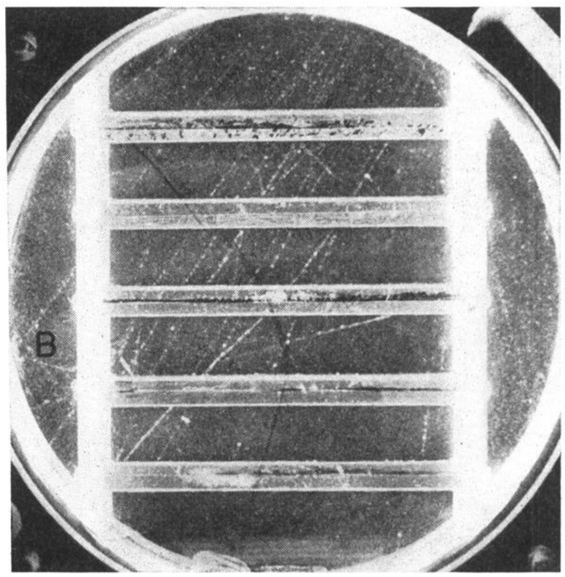

FIG. 13(B). A penetrating shower of at least eight particles seen with an S trigger, originating one inch above the bottom of the lead roof but exhibiting no cascade radiation. The particle showing the scattering and increased ionization is identified as a proton. The energy of this event is estimated to be greater than 8 Bev.

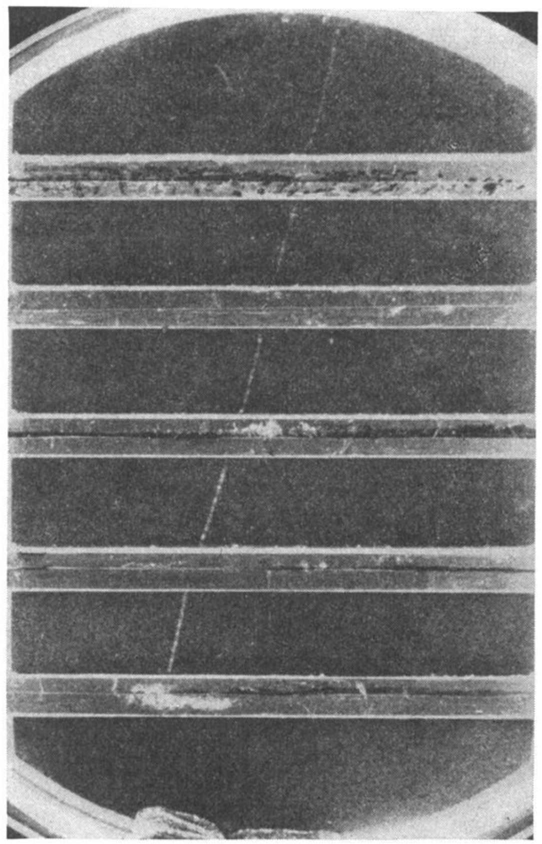

FIG. 18. A penetrating particle, which, by virtue of its scattering, ionization, and range is identified as a proton. From the theoretical relationships between these properties, the ionization relative to minimum ionization, in each of the compartments of the chamber starting from the top lies in the intervals 1.9–2.2; 2.2–2.5; 2.5–3; 3–4; and 4.5, respectively. This track was used for comparison in the estimation of the ionization of other tracks in the range 2–4 times minimum.

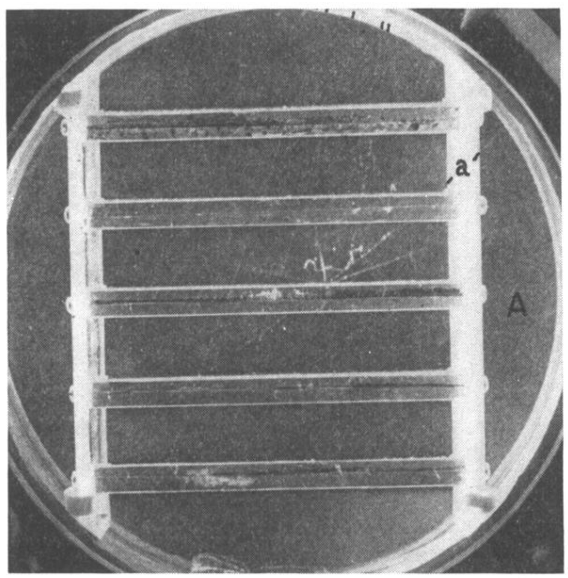

FIG. 2(A). A four-particle penetrating shower seen with a P trigger, originating two inches above the bottom of the lead roof. One of the shower particles undergoes a secondary nuclear interaction in which it produces five secondaries in the upper third of the third plate. One of the backward ejected secondaries, (a) penetrates the second plate and appears in the compartment to the right of the Lucite wall.

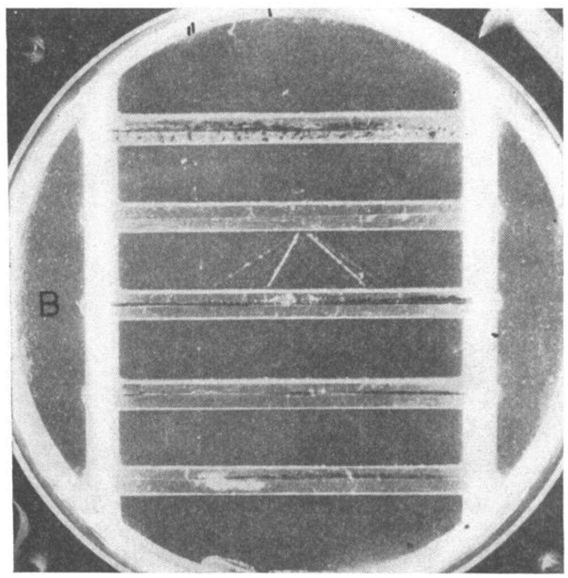

FIG. 2(B). A three-particle penetrating shower seen with an S trigger, originating about one inch above the bottom of of the lead roof. One of the shower particles undergoes a secondary nuclear interaction in which it produces three lightly ionizing and two heavily ionizing secondaries in the lower third of the second plate.

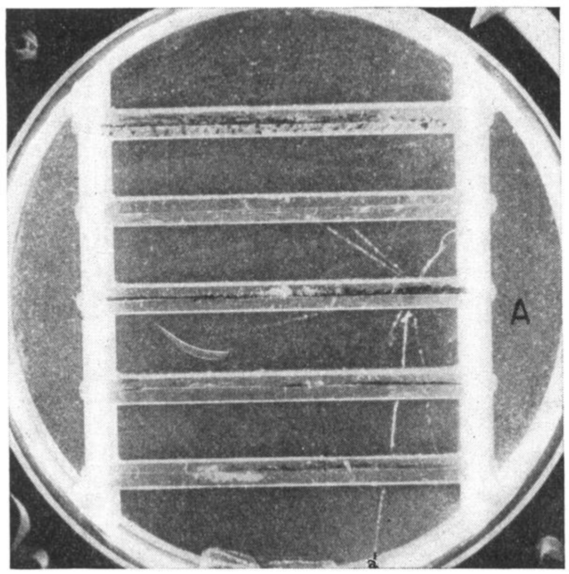

FIG. 4(A). A nuclear event seen with a P trigger. It appears to be made by a neutral particle. One particle (a) crosses two plates with greater than four times minimum ionization, but with no noticeable increase of ionization, and therefore must have had a mass greater than that of a proton.

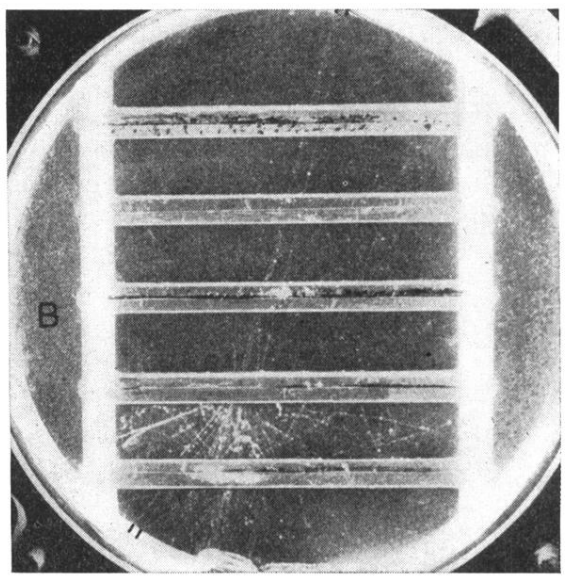

FIG. 4(B). A mixed shower seen with a P trigger and produced in the fourth plate probably by an ionizing particle which itself is part of a narrow penetrating shower, the origin of which is above the chamber.

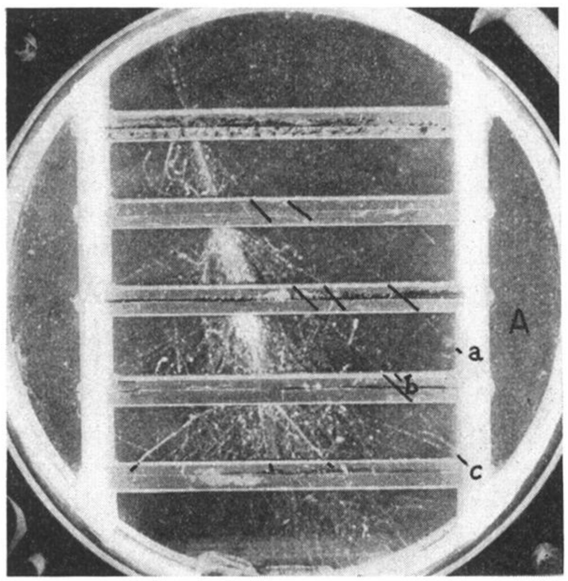

FIG. 5(A). A mixed shower seen with a *P* trigger. Nuclear interactions occur in plates 1, 2, and 4. There are three minimum ionizing penetrating particles at (a), (b), and (c). There are three heavily ionizing secondaries emerging from plate 4.

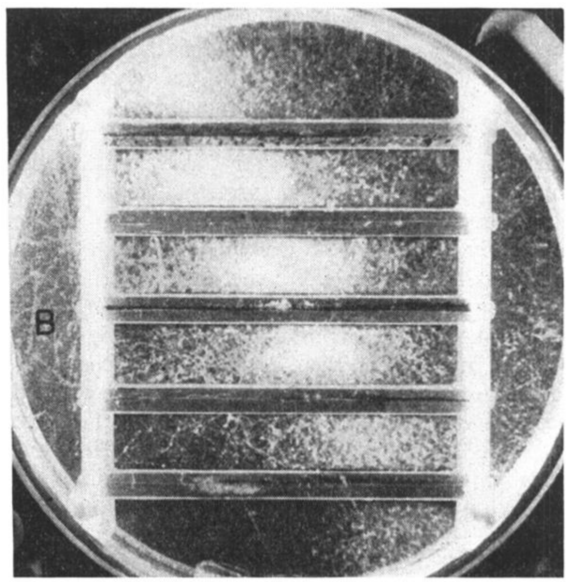

FIG. 5(B). A huge cascade with an *S* trigger. Altogether we saw five cascades of comparable size, none of which were accompanied by dense air showers or contained discernible penetrating particles.