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The Properties of Particles Producing High Energy Nuclear Collisions in Gold*

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A large multiplate counter controlled cloud chamber containing 300 g/cm^2 of gold has been used for the study of penetrating showers at an altitude of 11,500 ft. The minimum energy required to trip the counter control efficiently was about 15 Bev. Counters located inside the chamber made it possible to observe events initiated by both ionizing and non-ionizing particles. It was found that at least 83.5 percent of the particles initiating these high energy events were ionizing. From the distribution of events in the plates of the chamber, the mean free path in gold for the particles producing these penetrating showers was found to be 145±15 g/cm^2. The projected zenith angle distribution of the shower primaries could be approximately represented by $\cos^m\theta$, where m was in the range 8 to 10. Since the measurements were made at 680 g/cm^2 atmospheric depth, this corresponds to an absorption mean free path in air of 70 to 90 g/cm^2. The flux of particles capable of producing these high energy showers was found to be $(1.7\pm1)\times10^{-6}$ particles cm^{-2} sec^{-1} sterad^{-1}. This value, when compared with the flux of the primary protons at the top of the atmosphere, yielded an absorption mean free path of 71±5 g/cm^2. Application of the Gross transformation changed this value to 77±5 g/cm^2. The large mass of the gold nucleus plus the presence of two mean free paths of material inside the chamber made it very unlikely that only a small fraction of the energy of the primary particles be lost in the cloud chamber.

I. INTRODUCTION

COSMIC-RAY penetrating showers have been extensively investigated using many experimental techniques.[1] It has been found that these showers, particularly those of high energy, are very complex events involving large numbers of various particles. Counter controlled multiplate cloud chambers have been very helpful in understanding the nature of these events. This paper gives some additional results which have been obtained utilizing a large instrument of this type designed to observe very high energy nuclear interactions. The experiment was performed at Climax, Colorado (alt. 11,500 ft) in November and December of 1949.

It is very desirable to have enough material inside the chamber so that both primary and secondary nuclear events can be observed and studied in detail. About two nuclear mean free paths of absorbing material would give a high probability for the occurrence of both primary and secondary events. If a nuclear collision cross section equal to the geometric area of the nucleus is assumed, then about 300 g/cm^2 of a heavy material like lead would be necessary for this purpose. It did not seem quite feasible to build a chamber containing this much lead, but it was apparent that the use of a more dense material such as tungsten or gold would make it possible to construct a chamber of reasonable size containing this amount of absorbing material. Through a very special effort, the Office of Naval Research secured, at the request of Professor Marcel Schein, a number of machined gold plates, which made it possible to include over 300 g/cm^2 of gold inside the chamber. The use of this high density material plus the use of counters inside the chamber enabled the observation of events initiated by both ionizing and non-ionizing particles in the region above the counters and, in addition, yielded another region below the counters where the geometry was simple enough to make possible a direct determination of the mean free path of the primary particles.

II. APPARATUS

The cloud chamber and counter control arrangement are shown in Fig. 1. The inside dimensions of the chamber were as follows: 24 in. high, 16 in. wide, and 7 in. deep. Sixteen frames, mounted inside the chamber and inclined toward the camera, held the sixteen $14\frac{1}{2}$ in.$\times5\frac{3}{4}$ in.$\times$0.4 in. gold plates. The seventeenth

* Assisted by the joint program of the ONR and AEC.

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[1] For bibliography, see T. G. Walsh and O. Piccioni, Phys. Rev. 80, 619 (1950).

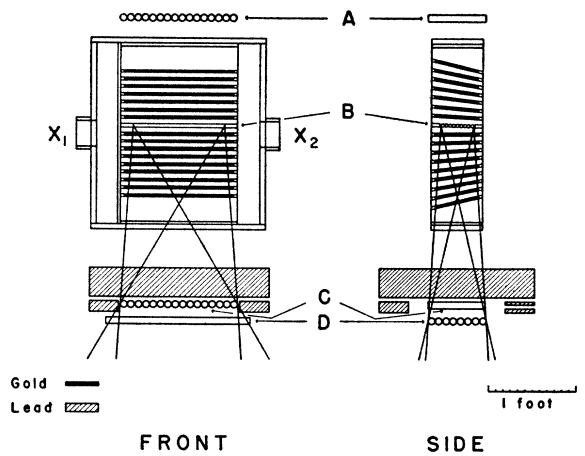

FIG. 1. Schematic view of the cloud chamber and counter banks.

frame, at position B, was replaced by a bank of nine $\frac{1}{2}$-in. diameter counters.

In order to photograph the full depth of the chamber, it was necessary to use small lens apertures. This, in turn, required more light. It was, therefore, decided to utilize rear illumination through the transparent back wall. This method is more efficient than side illumination owing to the smaller light scattering angle involved.

The front and rear walls of the chamber were tempered plate glass, $\frac{3}{4}$ in. in thickness. The expansion took place at X_1 and X_2 (Fig. 1) by means of a valve on each side. The valves were actuated simultaneously by two solenoids connected in series. The chamber was filled with argon at a total pressure of 86 cm Hg and used an excess of water-alcohol mixture.

The lights consisted of two Amglo xenon filled flash tubes, each 46 in. long and 0.35 in. in diameter, mounted in silvered semicircular cylindrical reflectors. Condenser banks of 200-μf capacity were discharged at 2000 volts through each flash tube. The lights were triggered simultaneously by two Tesla coils connected in series. The illuminated region is shown by the shaded portion

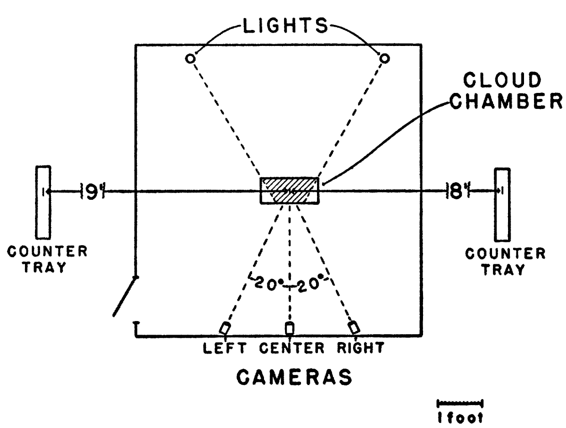

FIG. 2. Schematic plan view of the disposition of components of the apparatus.

of the chamber in Fig. 2, which also shows the disposition of lights and cameras.

The chamber was photographed by three cameras from positions shown in Fig. 2. The cameras utilized Kodak Ektar f:3.5, 50-mm lenses which were operated at apertures of f:8 to f:10 and used 35-mm Linagraph Ortho film. During part of the experiment, a camera utilizing 70-mm film was used at the center position.

The plates inside were insulated from the chamber wall by means of polystyrene bars. Thus, the clearing field of about 3 v/cm could be applied between alternate

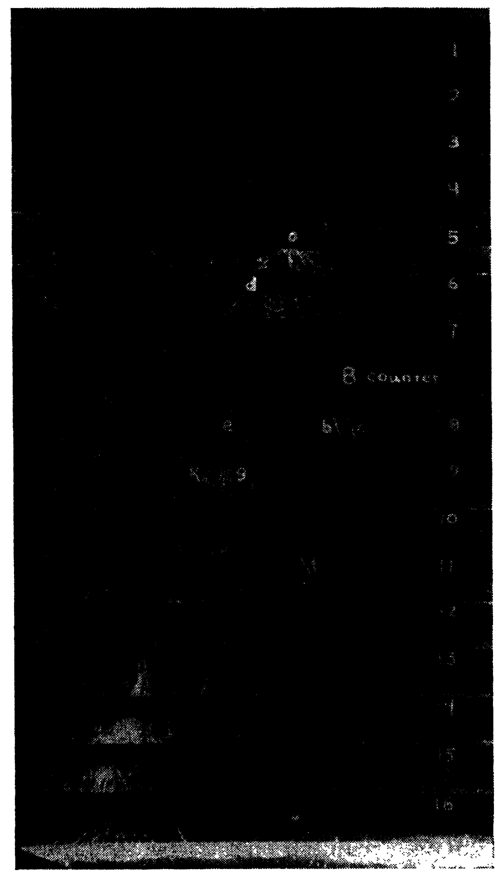

FIG. 3.

plates. The clearing field was reduced to zero for a period of about 0.2 sec starting at the time of the coincidence pulse which triggered the chamber.

The apparatus was operated continuously, day and night. The expansion ratio was checked visually about four times a day and the control circuits once a day.

The entire apparatus, except circuits, was situated inside a cubical enclosure $6\frac{1}{2}$ ft on an edge, made of $\frac{3}{8}$-in. plywood, so that the temperature could be controlled to about $\frac{1}{2}$°C.

The counter control system contained three banks of counters: B, C, and D, as shown in Fig. 1. The bank B consisted of nine counters each $12\frac{1}{2}$ in. long and $\frac{1}{2}$ in.

in diameter, the bank C of sixteen counters each 8 in. long and 1 in. in diameter, and the bank D of eight counters each 20 in. long and 1 in. in diameter. A layer of 4 in. of lead was placed above and at the sides of the counters C and proved to be very effective in reducing the number of soft showers registered by the counter control system. A fivefold coincidence BC_3D (the C_3 refers to any three of the sixteen C counters) was required for the master pulse which caused an expansion of the chamber. An additional bank of counters at position A (Fig. 1), consisting of sixteen counters, each 8 in. long and 1 in. in diameter, was not used for control of the chamber expansion but was very useful for the purpose of gaining information on the number of ionizing particles incident on the chamber.

Coincidences between the master pulse (BC_3D) and any of the individual counters at A, C, or D resulted in the flashing of a neon light (one neon light was used for each individual counter) mounted on a panel located directly above the chamber in such a position as to be photographed by the cloud chamber cameras. Two banks of counters, each consisting of four counters 20 in. long and 1 in. in diameter, were placed at distances of 8 ft and 9 ft from the chamber and were used during part of the experiment to measure coincidences between extensive atmospheric showers and nuclear events occurring in the chamber.

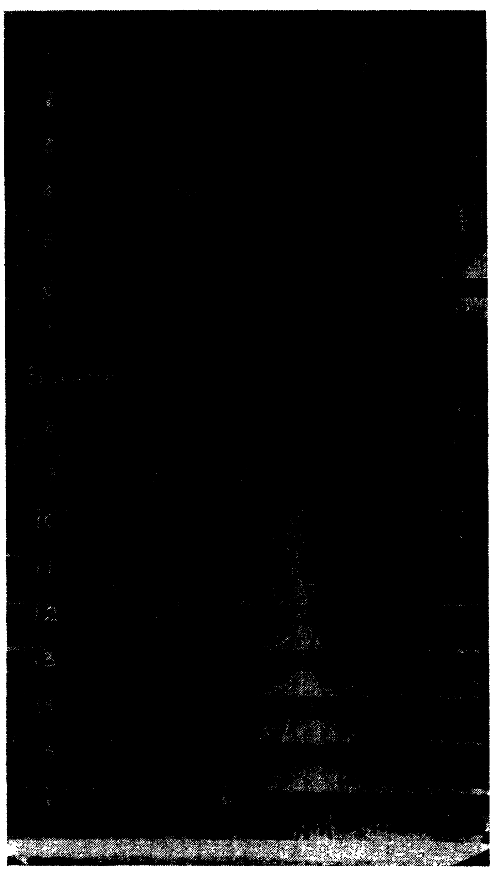

Fig. 4.

III. TYPICAL EVENTS

Since a considerable variety of cosmic-ray events were photographed in the course of this experiment, it seemed desirable to include a number of photographs demonstrating the nature of these events. In these photographs, the horizontal gold plates are numbered consecutively from top to bottom. Between the 7th and 8th plates is the counter tray B of Fig. 1.

Figure 3 shows a penetrating shower which was initiated at position *a* in plate 5, with the following features:

(1) There were three regressive particles,[2] one of which may have been scattered in plate 5, since it does not trace back to the same point as the others. One of these particles passed out of the left side of the chamber, the other two stopped in plate 4.

(2) There are at least three clearly visible tracks of heavily ionizing particles which emerged from the bottom of plate 5 at *a*.

(3) Most of the tracks visible below plate 5 were certainly those of electrons, which were part of a cascade shower which continued through plate 6 and almost completely died out after traversing plate 7.

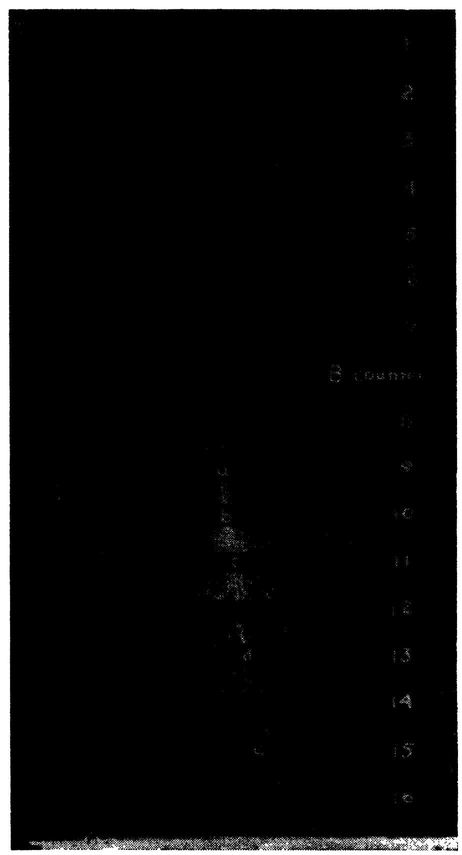

Fig. 5.

[2] There seems to be no commonly accepted designation for those particles which are observed to move in a sense opposite to that of the initiating particle. We adopt the word *regressive* as meaning *moving backwards*.

(4) Wide angle penetrating particles, for example, those indicated by the reference marks at *b* and *c*, were produced in the event *a*.

(5) There are tracks of a number of minimum ionization penetrating particles close to the axis of this event. It is difficult in this case to count these tracks because of the presence of a number of electron tracks, but there were at least five particles within a 5° cone.

(6) A low energy secondary nuclear event was produced at *d*. It is not possible to know whether this event was produced by an ionizing or non-ionizing particle because of the large number of tracks in the region.

(7) A large secondary event occurred at *e* in which heavily ionizing particles, electron cascades and penetrating particles (see *f*, for example) were produced. Two electron cascades, *g* and *k*, apparently were produced by the event *e*. The cascade *g* was at an angle of 14° to the axis of the penetrating shower.

(8) A large electron cascade originated at *h*. The direction of the axis of this event was very close to that of the initiating particle and to the core of the event produced at *a*.

In those cases in which successive production of electron cascades occurred, the electron shower produced in the original event was, in the large majority of cases, of higher energy. Hence, this event is somewhat atypical in this respect. Analysis of the secondary events in this picture is rendered somewhat difficult by the presence of at least four cascade showers. This frequent occurrence of electron showers is strong evidence against the hypothesis that these electron cores may have originated from electromagnetic interactions like bremsstrahlung or knock-on processes. On the contrary, the only explanation feasible seems to be that they originated from the decay of neutral mesons. These neutral mesons, as demonstrated at Berkeley, are known to decay into two gamma-rays, thus starting electron cascade showers.

Figure 4 shows a penetrating shower initiated by an ionizing particle in plate 10 at *c* accompanied by at least two penetrating particles *a* and *b* and probably *d*. Particles *a* and *b* together traversed fourteen plates without undergoing a nuclear collision. There was also an accompanying event at *g* probably initiated by a neutron. The tracks of penetrating particles were quite straight. There was, however, a displacement which occurred near the counter owing to the fact that the counter tray was not mounted quite level. The right edge was visibly lower than the left. As a result, tracks were displaced toward the left below the counter, and toward the right above the counter. Secondary nuclear events occurred at *e*, *f*, and *h*, and probably also at *k* and *i*. The accompanied penetrating showers were usually the same in appearance as the nonaccompanied showers.

Figure 5 shows an event at *a* in plate 9 which, at first glance, would seem to have been initiated by a non-ionizing particle. Stereoscopic measurements show, however, that this event originated very near the back glass and that the incident particle entered the chamber through the back glass at the height of plate 8. Therefore, it would have been visible only in the one space between plates 8 and 9. The large number of regressive particles made it difficult to decide whether the incident particle was ionizing or not. Of the nine or ten regressive particles, only one was sufficiently energetic to penetrate plate 8 (and thus to trip counter B). In addition to the initial event *a*, other nuclear events occurred at *b*, *c*, *d*, and *e*. The electron shower had an

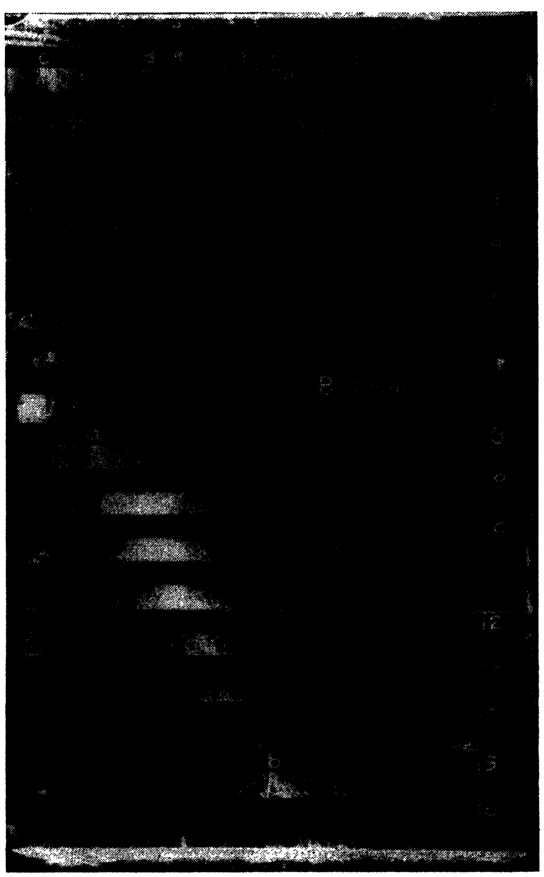

FIG. 6.

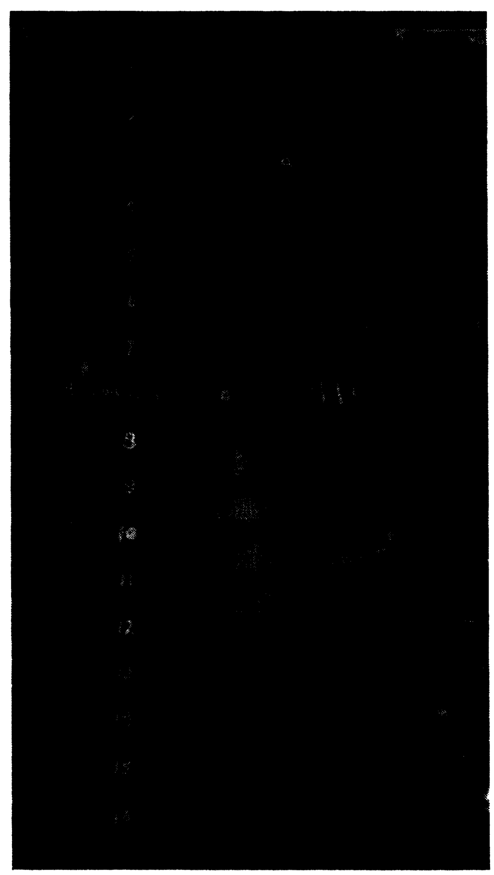

FIG. 7.

energy of about 5×10^9 ev. About eight minimum ionization particles passed out of the bottom of the chamber.

Figure 6 shows a photograph of a large air shower accompanied by a high energy nuclear event which started at *a*. One of the secondary particles in the core of the penetrating shower produced a large secondary event at *b*. Numerous electron cascades (*c* to *j*) can be seen at the top of the chamber. All of these cascades were of the order of a few times 10^8 ev in energy. The axes of all the events were quite parallel.

Figure 7, on the other hand, shows two separate locally produced penetrating showers which started at *a* and *b* accompanied by an air shower of very low density. An additional small event appeared at *c*. The event at *a* was initiated by an ionizing particle which entered through the top of the chamber. Many of the particles produced in this event passed out of the back of the chamber, but a few tracks (*d* and *e*, for example) are visible for some distance. The event at *b* actually originated in the front glass. A number of tracks starting midway in the space below *b* show where the shower particles emerged from the glass. At *f* an old α-ray track, split by the clearing field, may be seen. Few events of this type were observed.

Figure 8 shows what was probably the core of an extensive air shower. Electron showers up to an energy of a few times 10^9 ev appear. The nuclear events at *b*, *c*, and *e* seem to be part of one cascading penetrating shower of very high energy, while those at *d* and *f* were probably part of another penetrating shower parallel to the first one. Still another nuclear event of lower energy occurred at *a* in plate 1. Electron cascades are apparent in all parts of the photograph. Many particles entered the chamber above the first plate, and all the counters were tripped above the chamber.

Figure 9 shows what was probably the highest energy event observed in this experiment. The chamber was completely filled with tracks including the full depth (as can be seen at the bottom corners of the picture). Even the region of the chamber considered to be nonilluminated shows the presence of droplets. The print from which this photograph is reproduced was exposed about three times as much as the other photographs. When the exposure was increased by another factor of three, it was possible to resolve hundreds of parallel tracks in the space above the first plate at an angle of about 15° to the vertical. The particles producing these tracks apparently multiplied in passing through the first plate, for below that it is impossible to resolve individual tracks. Every counter in the control system was discharged. The use of several methods of estimating the minimum energy density incident on the chamber gave about the same figure, 5×10^9 ev/cm^2. Assuming a total extension of this air shower of about 100 m leads to a figure for the minimum total energy of this event of $\sim5\times10^{17}$ ev.

IV. RATIO OF IONIZING TO NON-IONIZING INITIATING PARTICLES

Since the counter control did not require that counters above the chamber be tripped, any nuclear event which started in plates 1 to 7 and was of high enough energy, could be photographed, regardless of whether the initiating particle was of the ionizing or non-ionizing type. Owing to the fact that counters B were part of the control system, events which occurred in plates 8 to 16 below B could be initiated only by

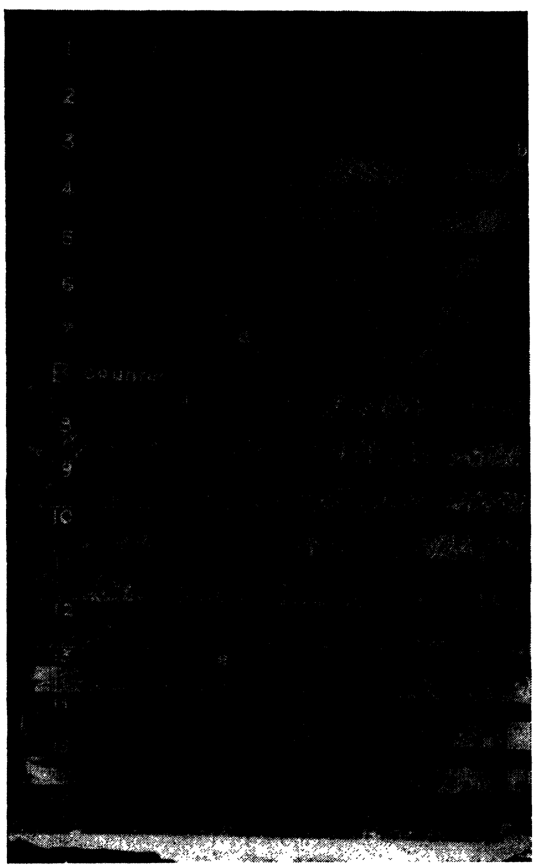

FIG. 8.

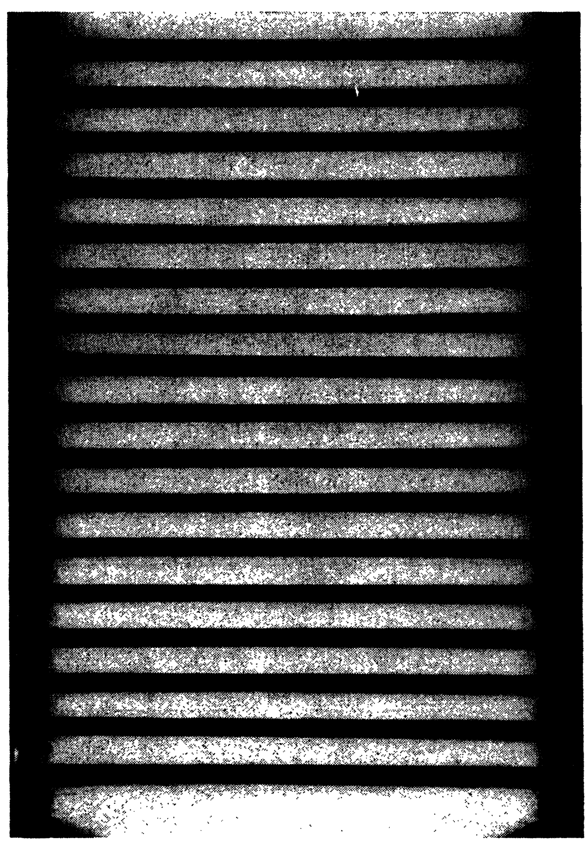

FIG. 9.

ionizing particles (neglecting the effect of regressive particles). This made it possible to analyze all events occurring in the plates above B (Fig. 1) in order to determine whether or not the incident particles were ionizing. Only incident particles were included in the data which satisfied the following criteria:

(1) It was required that the track of an incident particle, if ionizing, be visible in at least two spaces between gold plates. (Since most of the regressive particles had a range less than 1 cm of gold, confusion of the incident track with those of the regressive particles could thus be minimized. Because of this criterion, nuclear events initiated in the first plate were not counted.)

(2) All incoming particles were examined in two cameras to assure their exact positions in space relative to the axis of the nuclear event. (It was found that in all cases of ionizing incident particles, the direction of the incident particle was the same as that of the axis of the penetrating shower.)

(3) Events accompanied by other penetrating showers or electron showers were excluded.

(4) It was required that the proper one of the counters in bank A was fired whenever an ionizing incident particle visible in the chamber was within the solid angle of the counters ABCD.

(5) In the case of non-ionizing incident particles, stereoscopic measurements were made in order to make sure that the penetrating shower started at such a point and exhibited such a direction in the chamber that the incident particle would have been clearly visible if it had been ionizing.

(6) The criterion (5) was applied to all events in order to avoid systematic error.

The results shown in Table I essentially agree with the preliminary data given in a previous publication.[3]

The questionable cases are mainly (1) cases in which it was very difficult to decide whether or not the incident track would be visible owing to its very unfavorable position in the chamber, and (2) cases in which the picture quality was below average.

It follows then that the minimum fraction of ionizing incident particles is given by adding all of the questionable cases to the non-ionizing category, thus resulting in a figure of 83.5 percent ionizing particles initiating high energy penetrating showers.

The results given here show a much larger fraction of ionizing incident particles than do previous measurements. Fretter[4] showed that some penetrating showers are produced by non-ionizing particles but did not determine the relative numbers. The determination of this ratio using coincidence arrays has generally yielded a figure of about 50 percent for the ionizing incident particles producing penetrating showers. The nuclear emulsion work of the Bristol group[5] has also indicated a much smaller fraction of ionizing incident particles, but the number of cases of comparable multiplicity in their data is small. This marked difference seems to indicate strongly that the average energy of the penetrating showers observed in this experiment was higher than that of the other observers, in agreement with Hartzler's[6] determination of minimum energy as $E>15$ Bev.

TABLE I. Character of the initating particle.

Initiating particle	Number of cases	Percent of total
Ionizing	139	83.5
Non-ionizing	7	4.0
Questionable	21	12.5
Total	167	100.0

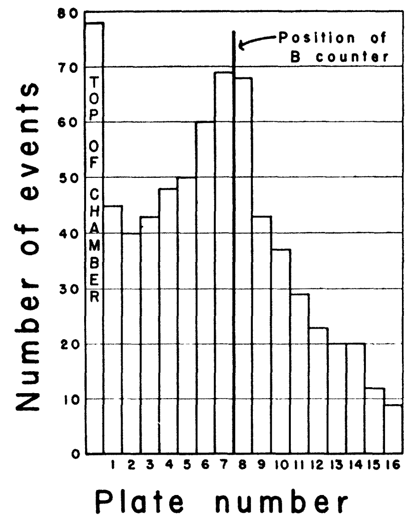

FIG. 10. Histogram showing the number of nuclear events which were initiated in each plate.

From these results it appears that at high energies penetrating showers are initiated mainly by protons or possibly π-mesons which originate from nuclear collisions occurring between primary protons and air nuclei in the first mean free path above the apparatus. The contribution due to μ-mesons must be negligible because of their very small nuclear interactions.

However, at least 4 percent, and possibly as many as 16 percent, of the penetrating showers were initiated by non-ionizing particles. It is possible to account for this effect without introducing elastic collisions of protons and neutrons, for these non-ionizing particles could be the product of the break-up of α-particles and heavy nuclei at the top of the atmosphere. Because of the short mean free paths of these multiply charged particles, none of them would reach low altitudes, but they would certainly be expected to contribute to the nucleonic

[3] Gottlieb, Hartzler, and Schein, Phys. Rev. **79**, 741 (1950).

[4] W. B. Fretter, Phys. Rev. **73**, 41 (1948).

[5] Brown, Camerini, Fowler, Heiller, King, and Powell, Phil. Mag. **40**, 862 (1949).

[6] A. J. Hartzler, Phys. Rev. **82**, 359 (1951).

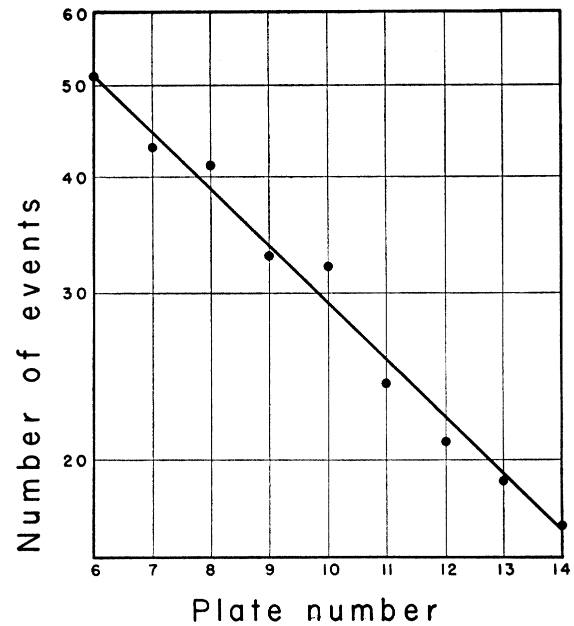

FIG. 11. The number of events which were initiated in plates 6 to 14 by particles within the same area and solid angle limits. The least squares slope corresponds to a collision mean free path of 145 g/cm².

component. The energy of the heavy nuclei would, of course, have to be at least 15 Bev/nucleon.

V. MEAN FREE PATH

The depth in the chamber at which nuclear events occurred was, of course, a function of the mean free path of the initiating particles and of the geometry of the apparatus. The distribution of occurrence of high energy nuclear events in the sixteen gold plates of the chamber is shown in Fig. 10. All events capable of tripping the control counters BC_3D were included in these data. If the sensitive area and solid angle were constant for events occurring at any depth in the chamber, an exponential distribution would have been expected. However, the product of area times solid angle dropped off rapidly above plate 6 (as can be seen in Fig. 1), as a result of which the curve actually shows a peak in the region of plates 7 and 8, next to the B counters. The large number of events initiated in the top of the chamber was due to the fact that the average amount of material in the top wall was about 25 g/cm^2 of iron, which, assuming a cross section proportional to $A^{\frac{2}{3}}$, is equivalent to about 60 g/cm^2 of gold—or three of the plates inside the chamber. It was sometimes difficult to decide whether an event started in plate 1 or in the top of the chamber, so it is quite likely that the number of events which originated in plate 1 was actually smaller than the number shown in Fig. 10. Thus, it is clear that the data for the top part of the chamber are not well suited, because of the large geometrical factors involved, to a determination of the mean free paths of the initiating particles. On the other hand, in the part of the chamber from plate 6 to the bottom, the product of area times solid angle was constant (for single particles traversing the chamber), as can be seen in Fig. 1. The only correction to be applied to the data in this part of the chamber arose from the fact that the counters B did not entirely fill the cross section of the chamber. This affected the data in the following manner.

(1) An ionizing particle which produced a nuclear event in the region of the chamber below the counters B tripped the counter control only if it passed through counters B. However, this control could be discharged by regressive particles or by accompanying particles even though the shower initiating particle missed B. This correction applied chiefly to events originating in plate 8. Figure 5 shows a photograph of such a case. In this case, the initial nuclear event occurred in plate 9, but the initiating particle entered the chamber at the 8th plate from the back. It could not be determined whether the initiating particle was ionizing, due to the large number of regressive particles. One of the three regressive particles had sufficient energy to pass through plate 8 and thus to trip the counters B.

(2) An event which occurred in plates 6 or 7 above the counter could result in a firing of counter B by a secondary particle even though the axis of the shower missed B. This correction, as would be expected, was larger for plate 7 than for plate 6. The correction amounted to 15 percent in plate 6 and 24 percent in plate 7.

By a measurement of the position of the point at which the axis of the penetrating shower passed through the chamber at the plane defined by the counter tray, it was possible to eliminate each event whose axis did not pass through the B counter. For obvious reasons one can overlook events occurring near the bottom of the chamber. Hence, the events corresponding to plates 15 and 16 were not considered in the determination of the mean free path. This does not affect the accuracy of this determination in any way.

The distribution of nuclear events, corrected as previously described, is shown on a semilogarithmic plot in Fig. 11. Each point represents the corrected number of events which occurred in the designated plate. A least squares determination of the slope of the line drawn through the points gave for the mean free path a figure of 7.20 plates. The small deviations of the points from the straight line seem to indicate that no large systematic error was involved. Each plate was 19.6 g/cm^2 thick. Since most of the particles traversed the plates at an angle θ to the vertical, the path length was greater than the thickness of the plates by a factor of $1/\cos\theta$. By measuring the angles of all events, it was found that this correction amounted to 2 percent. Thus, the mean free path was found to be

$$\lambda = 145 \pm 15 \text{ g/cm}^2.$$

The error figure (which is much larger than the statistical error) takes into account a possible nonrandom distribution of the zenith angles of incident particles. This mean free path yields a cross section for nuclear interactions of high energy cosmic-ray particles in gold of

$$\Phi_{\text{exp}} = 2.3 \times 10^{-24} \text{ cm}^2.$$

This may be compared with the approximate value of the geometric area of the gold nucleus (derived from the expression $r=1.5\times10^{-13}A^{\frac{1}{3}}$):

$$\Phi_{\text{theor}}=2.4\times10^{-24}\ \text{cm}^2.$$

VI. ZENITH ANGLE DISTRIBUTION

In order to determine the zenith angle distribution of the particles producing penetrating showers, measurements were made of the zenith angle of each penetrating shower as projected on the surface viewed by the center camera. Owing to the fact that the expansion of the chamber was toward the sides, a displacement of the gas in the chamber occurred, resulting in a track zenith angle slightly larger than that of the original particle. If a cosmic-ray particle passed through the chamber at a projected angle θ_p to the vertical, then the resultant track after expansion made a projected angle θ_T to the vertical, where θ_p and θ_T were related by the equation $\tan\theta_T=1.08\tan\theta_p$. The factor 1.08 arises from the fact that this figure represented the expansion ratio at which the cloud chamber was operated.

The histogram of Fig. 12 shows the projected zenith angle distribution of all of the penetrating showers observed. The abscissa is the projected track angle, θ_T, while the ordinate in each case is the number of penetrating showers in each 4° interval of θ_T.

In order to evaluate this distribution it was necessary, in addition, to know the angular divergence of secondary particles with respect to the direction of the axis of the shower. This was necessary because of the discrimination of the counter control against large angle events. From the geometry of the counter control system it can be shown that there was no discrimination for single particles up to an angle of 4°, except that the effective area varied as $\cos\theta_p$. The average angular divergence of individual events was about 12°. Therefore, up to an angle of about 16° it can be assumed that discrimination of the apparatus was negligible.

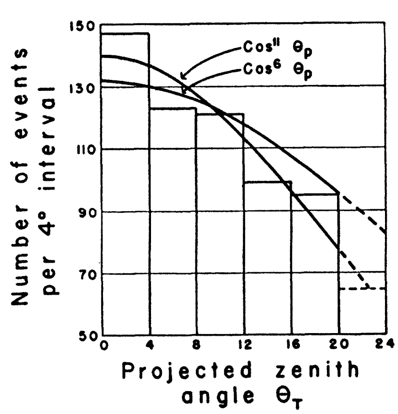

FIG. 12. Histogram showing the number of events originated within each 4° interval of projected zenith angle. The curves for $\cos^{11}\theta_p$ and $\cos^6\theta_p$ are normalized over the interval from $\theta_T=0°$ to $\theta_T=20°$.

Also plotted in Fig. 12 are the curves $N=K\cos^m\theta_p$ transformed into the corresponding function of θ_T for $m=6$ and $m=11$, where K in each case is the normalization constant chosen so that the integral of each curve from $\theta_T=0°$ to $\theta_T=20°$ is equal to the area of the histogram in the same interval of angle.

An absorption mean free path of X g/cm² corresponds for small angles, at an atmospheric depth of 680 g/cm², to a projected zenith angle distribution of the form $\cos^n\theta$, where n is then $680/X$. Since the sensitive area varies as $\cos\theta$, the projected zenith angle distribution as measured with this apparatus would then be of the form $\cos^{n+1}\theta$. Thus, the curves in Fig. 12 for $\cos^m\theta_T$, with $m=11$ and $m=6$, correspond to mean free paths of about 70 and 140 g/cm², respectively. An accurate determination of the absorption mean free path is not possible on the basis of these data, but the value for m would seem to be in the range 8 to 10, corresponding to a mean free path in the range of 70 to 90 g/cm². The figure of 140 g/cm² definitely is not in accord with the sharp drop in the histogram observable at $\theta=4°$ and $\theta=12°$.

This zenith angle distribution is in agreement with that of Green,[7] who reported a zenith angle distribution of the form $\cos^m\theta$, where the value of m was in the range 7 to 9. Since these measurements were made at an atmospheric depth of 655 g/cm², they, too, would correspond to a mean free path in the range 70 to 90 g/cm².

VII. FLUX OF PENETRATING SHOWER PRODUCING PARTICLES

Out of a total of 7324 counter controlled expansions, there were 1514 which showed at least one penetrating shower. Single unaccompanied penetrating showers tripped the chamber at the rate of 1.32 per hour of chamber running time. (The chamber running time is the actually elapsed time from which is subtracted the product of the number of expansions in that time interval times the cloud-chamber recycling time of $2\frac{2}{3}$ minutes.)

From the above rate, the vertical flux of shower producing particles can be calculated by taking into account the following factors:

(1) The counters B did not completely fill the whole horizontal cross-sectional area inside the chamber. Owing to the spread of the shower particles, the effective area for events starting above the counters B was larger than that for events starting below B. The actual cross-sectional area of the counters at B was 400 cm². The effective cross-sectional area of the counters, as obtained from the weighted number of showers occurring above and below B, was found to be 600 cm².

(2) Only events at a projected zenith angle θ_x (projected on the surface viewed by the center camera) less than 15° were counted. It was also necessary to measure the component of the zenith angle θ_y in a vertical plane normal to the surface viewed by the center camera, in order that the solid angle for observation of penetrating showers could be calculated. For θ_y less than 4°, the

[7] J. R. Green, Phys. Rev. 80, 832 (1950).

whole counter area was useful for single ionizing particles traversing the chamber. On the basis of measurements carried out on a number of penetrating showers, it was found that the spread of ionizing particles with respect to the direction of the axis of an event was about 12°. The maximum value of θ_y averaged over the B counter area was about 20°. These values of θ_x and θ_y resulted in a solid angle of 0.4 steradian.

(3) On the average, an incident particle traversing the chamber had to pass through about 200 g/cm² of gold. It has been shown that the collision mean free path of these particles was about 145 g/cm². Then, the fraction of the incident particles capable of producing penetrating showers which pass through the chamber without taking part in a nuclear encounter is $N/N_0=e^{-200/145}$, or about $\frac{1}{4}$.

Taking all of these factors into account, one gets a flux of high energy penetrating shower producing particles at 51°N geometric at Climax of

$$I=(1.7\pm1)\times10^{-6} \text{ particles cm}^{-2}\text{ sec}^{-1}\text{ sterad}^{-1}.$$

The minimum energy of a nuclear event required to trip the counter control system has been estimated by Hartzler[6] as 15 Bev. It is considered unlikely that the minimum energy could be as high as 25 Bev. The flux, as calculated from the counting rate of Fretter,[8] is about three times the value given here, while the flux measured by Hazen, Randall, and Tiffany[9] is about six times the value given here.

More absorbing material was used in this apparatus than in those of the previously mentioned workers, so that the flux measurement in this experiment would be expected to give a somewhat lower figure. The three measurements, therefore, certainly agree within an order of magnitude.

It is of particular interest to compare this measured flux with that of primary protons capable of initiating these showers. From the data of Winckler, Stix, Dwight, and Sabin[10] the vertical flux of primary protons of energy greater than 15 Bev is $I_0=0.026$ particles cm^{-2} sec^{-1} sterad^{-1}.

Assuming a simple exponential law of absorption,

$$I=I_0e^{-d/\lambda},$$

where d is the atmospheric depth (680 g/cm² at Climax), one gets for λ, the absorption mean free path of primary protons of energy above 15 Bev,

$$\lambda=71\pm5 \text{ g/cm}^2.$$

When the Gross transformation is applied over the solid angle of the apparatus, this figure becomes

$$\lambda=77\pm5 \text{ g/cm}^2.$$

An upper limit of a mean free path compatible with the observed flux can be estimated by assuming that the actual flux was twice the measured value and that the minimum energy of the events observed was 25 Bev. An application of the Gross transformation to these data gives as an upper limit for the absorption mean free path a figure $\lambda=90$ g/cm². This is quite different from the absorption mean free path which has been determined by utilizing counter arrays. Tinlot[11] reported a figure of 120 g/cm², while Walsh and Piccioni,[1] by correcting for events coming in at large angles, found an absorption mean free path of 140 g/cm. These experiments undoubtedly included lower energy events than those described in the present experiment, however. On the basis of an absorption of 140 g/cm², the flux would be about 60 times the observed value.

On the other hand, if it is argued that fractional energy encounters made the energy of the incoming particle much higher than that transferred in a nuclear event, then it is necessary to assume that the minimum energy of the penetrating shower producing particles in this experiment was well over 100 Bev in order to get a mean free path of 140 g/cm². However, there are a number of factors which make this explanation unlikely.

(1) A particle passing through a gold nucleus will, on the average, encounter more than 5 nucleons. Thus, even if two encounters with air nuclei are necessary for a proton to be absorbed, then, in the case of the gold nucleus, these two encounters would be quite likely to occur in the same gold nucleus.

(2) The chamber contained an amount of material corresponding to two mean free paths, so that most of the energy would be expected in any case to be lost to secondary particles inside the chamber.

(3) Successive nuclear events produced in the chamber definitely showed an appreciable degradation of energy.

Thus, the flux measurements indicate an average absorption mean free path in the atmosphere above mountain altitudes to be about 80 g/cm², in agreement with other cloud-chamber measurements. However, Fretter found an absorption mean free path of 120 g/cm² between 3027 m and sea level. It will be checked whether the present apparatus shows a similar effect.

It is quite likely, of course, that the mean free path varies with altitude due to the contribution of π-mesons to the production of very high energy penetrating showers. For π-mesons of mean life at rest τ_0 and mean free path λ, the number of mesons which interact or decay is given by

$$dN=-N[(dt/\tau_0)+(dX/\lambda)],$$

where X is path length measured in g/cm². For particles of relativistic energy, the mean life in the laboratory system becomes $\gamma\tau_0$, and the equation can be written as

$$dN=-N[(dX/\gamma\tau_0\rho c)+(dX/\lambda)],$$

where ρ is the density of air and c the velocity of light. The ratio of the number of particles which decay, N_d, to the number which produce nuclear interactions, N_n, is then

$$N_n/N_d=\gamma\tau_0\rho c/\lambda.$$

[8] W. B. Fretter, Phys. Rev. **76**, 511 (1949).
[9] Hazen, Randall, and Tiffany, Phys. Rev. **75**, 694 (1949).
[10] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).
[11] J. Tinlot, Phys. Rev. **73**, 1476 (1948); **74**, 1197 (1948).

Inserting values for c and τ_0 and assuming $\lambda_{\text{air}}=67$ g/cm^2, and replacing ρ by $0.001P$, where P is the atmospheric pressure in atmospheres,

$$N_n/N_d=P\gamma\times 10^{-2}.$$

For mesons of 10-Mev energy ($\gamma=70$),

$$N_n/N_d=0.7P.$$

Thus, at one atmosphere, about 40 percent of the π-mesons of energy $\sim$10 Bev produce nuclear interactions, while at $\frac{1}{2}$-atmosphere this number is down to 20 percent. These π-mesons which interact thus result in an increase in the measured absorption length of the shower producing radiation.

Thus, it is possible, at least qualitatively, to reconcile a 70 to 90 g/cm^2 absorption mean free path for primary particles above mountain altitudes with the observed 120 g/cm^2 absorption free path of shower producing particles between mountain altitudes and sea level.

VIII. CONCLUSION

It has been shown that at least 83.5 percent of the high energy ($E>15$ Bev) penetrating showers are initiated by ionizing particles. These ionizing particles are probably largely primary protons. It is quite possible, of course, that some of these events are initiated by π-mesons produced in the nuclear mean free path of air immediately above the chamber. The measured collision cross section for gold was found to be 2.26×10^{-24} cm^2, which is very close to the usually accepted value of the area of the gold nucleus.

A determination of the vertical flux of shower producing particles ($E>15$ Bev) at Climax yields a value which, compared with the value of Winckler, Stix, Dwight, and Sabin[10] at the top of the atmosphere of 0.026 particles cm^{-2} sec^{-1} ster^{-1}, results in a mean free path of 77 ± 5 g/cm^2, which is quite close to the value corresponding to the geometric cross section (assuming an exponential absorption of the penetrating shower producing particles). This is in agreement with the figure derived from the zenith angle distribution and barometric effect of very large bursts.[12]

Other measurements of the absorption mean free path of penetrating showers have yielded a figure of 120 to 140 g/cm^2. There are two possibilities for explaining this discrepancy. It might be assumed that the energies of the incident particles in this experiment have been grossly underestimated if only fractional energy losses were to take place in the chamber. In order to yield an absorption mean free path of 140 g/cm^2, it would be necessary to assume a minimum primary energy of about 100 Bev which, in turn, would mean that only about $\frac{1}{6}$ of the energy was lost in all of the successive events visible in the chamber. However, there was more than 300 g/cm^2 of material in the chamber, which is equivalent in mass to about $\frac{1}{3}$ of the atmosphere. Thus, the loss of such a small fraction of the energy in this large amount of material would seem to be quite inexplicable.

Alternatively, the discrepancy might arise from the fact that other experiments have dealt with somewhat lower energies—as is shown by the latitude effect which was observed by Walsh and Piccioni. In addition, owing to the fact that the ratio of the ionizing to the non-ionizing particles was not known in other experiments, it is possible that a larger number of events produced by neutrons resulting from elastic collisions were included.

A mean free path in air close to that corresponding to the geometric cross section is also indicated by the measurements of the zenith angle distribution of the particles producing these high energy penetrating showers. It was found that the measured projected zenith angle distribution could be represented to a first approximation by an equation of the form $\cos^m\theta$, where m had a value from 8 to 10 which corresponds to an absorption mean free path in the range 70 to 90 g/cm^2.

These measurements all indicate that the particles producing high energy interactions lose a large fraction of their energy in the first encounter to π-mesons. This would agree with the observations of high energy stars in emulsions which show that most of the high energy secondary particles are π-mesons.

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[12] T. G. Stinchcomb, Phys. Rev. **80**, 479 (1950).

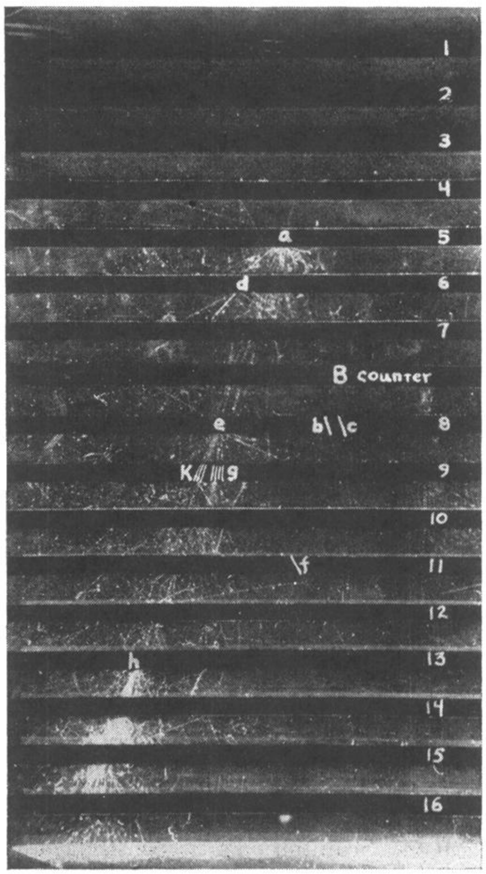

FIG. 3.

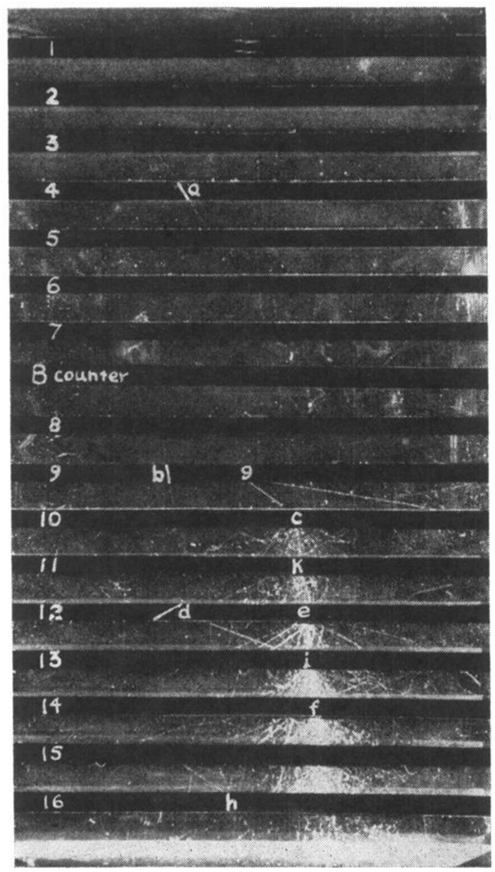

Fig. 4.

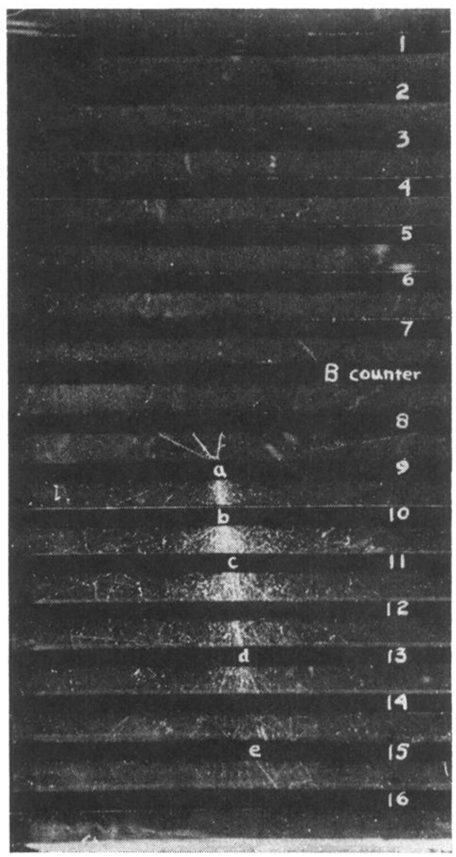

Fig. 5.

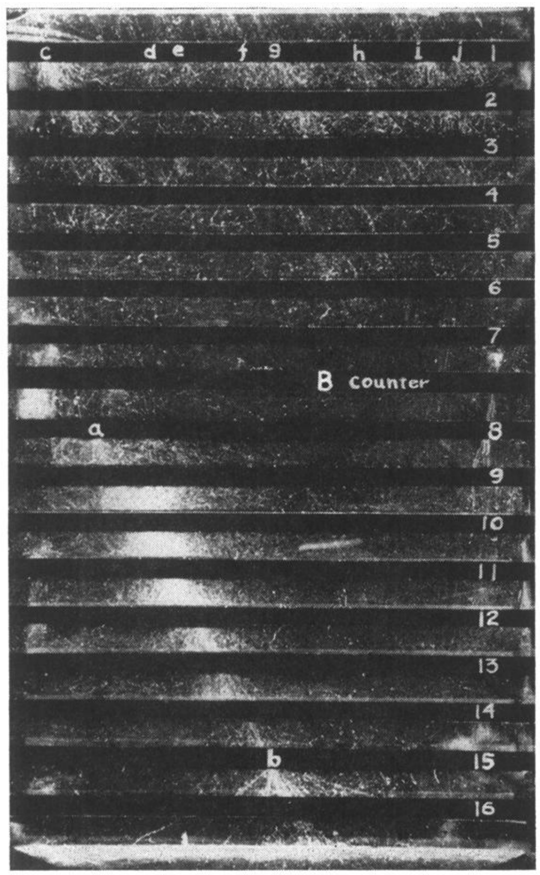

FIG. 6.

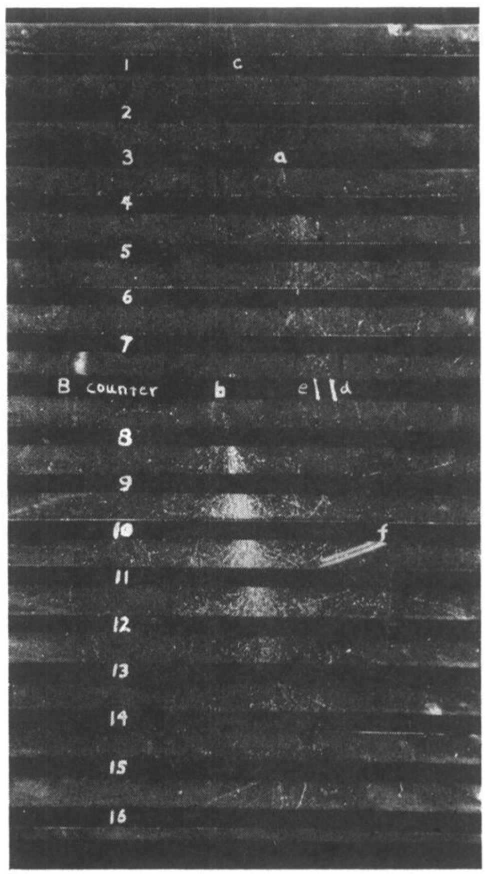

FIG. 7.

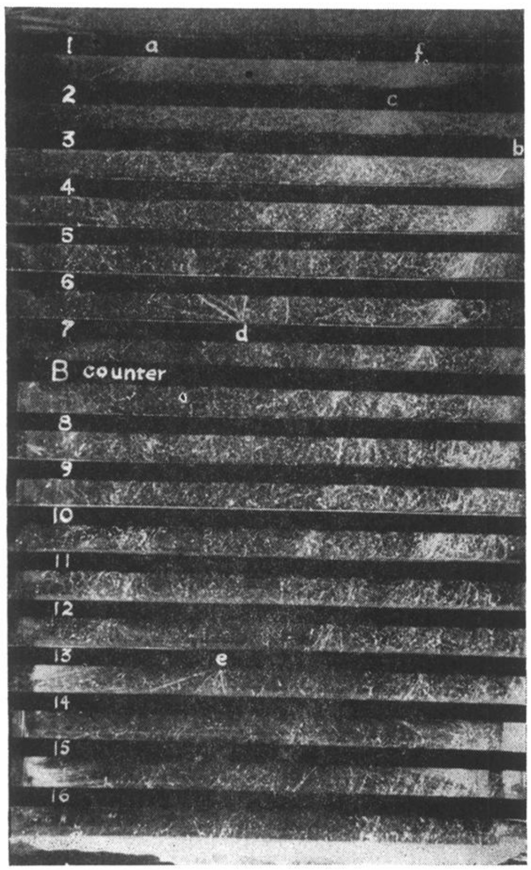

Fig. 8.

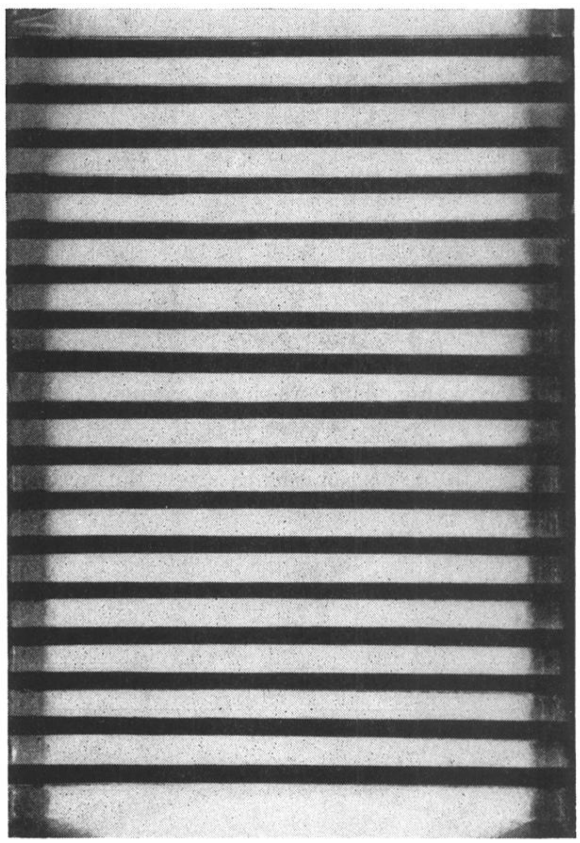

Fig. 9.