questionable how important their contribution is. On the one hand, the fact that the proton forbidden zone has as its limits the Dirac lines strongly supports the use of a quenching mechanism to explain the deviations from the Schmidt lines,[7] but the occurrence of a forbidden zone for the neutrons raises the question whether this coincidence is not accidental.

It was once suggested that the direction of deviation of the magnetic moments be explained by a mixture of an $l\pm\frac{1}{2}$ state with an $l'\mp\frac{1}{2}$ one. This interpretation has been rejected because of the difference in parity of these two states. The present note somewhat revives these ideas, the parity difficulty being overcome by involving pairs in the admixture. In this respect it is similar to the somewhat less explicit work of Davidson.[8] Although some arguments were given in favor of our rule for the formation of the many-particle configuration stated above, this rule should still be considered as somewhat arbitrary.

The case of nuclei with nuclear spin $\frac{1}{2}$ deserves special mention. Only such a state of the core can affect its magnetic moment which has a total angular momentum 1. States of that angular momentum are rather rare among the known spectra of even-even nuclei and probably need a comparatively higher energy to be excited. There is, however, no indication of a better agreement with the Schmidt limits for spin $\frac{1}{2}$ nuclei. The question is thus left open.

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A Search for Penetrating Showers from Hydrogen at Sea Level Using a Cloud Chamber*

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The extent to which multiple production of π-mesons takes place in local sea-level penetrating showers was studied with a counter controlled cloud chamber in a magnetic field. The rates at which penetrating showers occur under carbon, aluminum, and lead were determined and a search was made for them under liquid hydrogen. In a total operating time of 626 hours with an average thickness of 2.28 g/cm^2 of liquid hydrogen above the chamber, no penetrating showers were found which could have originated in the hydrogen. On the basis of the rates at which such showers occur in heavier materials and the number of them formed in the material of the Dewar while operating with hydrogen, one would have expected to detect a minimum of 6 showers from the hydrogen if the cross section for the production of penetrating showers were the geometric area of the nucleus (taken as 6×10^{-26} cm^2 for hydrogen). It can then be concluded that the majority of sea-level local penetrating showers detected below heavy materials by an apparatus of this kind can be attributed mainly to plural production. From momentum measurements in the magnetic field, the minimum value which can be assigned to the momentum of the incident nucleons which causes the average penetrating shower detected with this apparatus was estimated at 6 Bev/c. It follows that the multiple production of charged mesons in a single nucleon-proton collision at about 6 Bev probably does not occur in more than 15 percent of the cases.

The ratios of the rates at which penetrating showers were detected under C, Al, and Pb were proportional to the geometric area of the nuclei within statistical limits.

An event found in the hydrogen which is very similar in appearance to the μ-meson interaction first observed by Braddick and Hensby is discussed. A photograph of a nuclear collision in lead is described in which very little energy is transferred to the lead nucleus although the incident particle has a momentum estimated to be 40 Bev/c.

I. INTRODUCTION

ONE of the more direct ways to study high energy nuclear interactions of fundamental particles is by means of cloud-chamber observations on local penetrating showers. There have been many cloud-chamber studies of these events at various altitudes and issuing from a wide variety of materials.[1–11] At sea level, practically all such showers are believed to be caused by the collision of very high energy nucleons with atomic nuclei.[12] The resulting penetrating showers have a complex character in general which Janossy suggested is due to successive collisions in the same nucleus (so-called plural production of mesons).[13] A large positive excess among the penetrating particles in local sea-level penetrating showers has been established[8,14] which is interpreted to indicate the presence

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[1] Watase, Miyake, and Suga (private communication to Marcel Schein).

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of a large proportion of protons among the secondaries. This seems to show that at the energies involved in the majority of these showers, most of them are due to plural processes.

Heisenberg has suggested that more than one meson can be created in a single nucleon-nucleon interaction,[15] and considerable evidence for the existence of multiple production has been obtained at extremely high energies in photographic emulsions.[16] Recently, a penetrating shower with four secondaries has been found in hydrogen in a high pressure cloud chamber,[1] and penetrating showers have been observed from lithium[2] and beryllium[3] in multiple plate cloud chambers. It is not clear, however, that these showers occurred at the same energies and with the same frequency as do the majority of sea-level penetrating showers in heavier elements.

It seems important, then, to study the cross section for penetrating showers in nucleon-nucleon collisions by using a hydrogen target. If multiple production is probable at the energies at which the main fraction of sea-level penetrating showers occur, it would be expected that penetrating showers would also occur in hydrogen with comparable frequency. On the other hand, if such penetrating showers in heavy elements are due to the ejection of high energy nucleons and the plural production of mesons, the cross section for showers in hydrogen should be extremely small. If both plural and multiple production play a role at these energies, showers should occur in hydrogen but their frequency and character should be radically different than in heavier elements since in hydrogen plural production of mesons could not occur and since at most two protons could be emitted.

For this purpose an experiment was carried out in which a Dewar containing liquid hydrogen was mounted above a counter controlled cloud chamber. To make a comparison, lead, aluminum, and carbon were also used as targets for the production of penetrating showers.

Any particle which could traverse a two-centimeter lead plate mounted in the center of the cloud chamber without multiplication or scattering through an angle greater than 5° was classed as a penetrating particle. If the momentum of the particle could be determined to be over 1 Bev/*c*, the requirement that the scattering be under 5° was dropped. A penetrating shower was defined as at least two penetrating particles accompanied either by one or more heavily ionizing particles or by a cascade component or both. This is the criterion used by Butler, Rosser, and Barker with a somewhat similar cloud chamber operated under a lead target.[14]

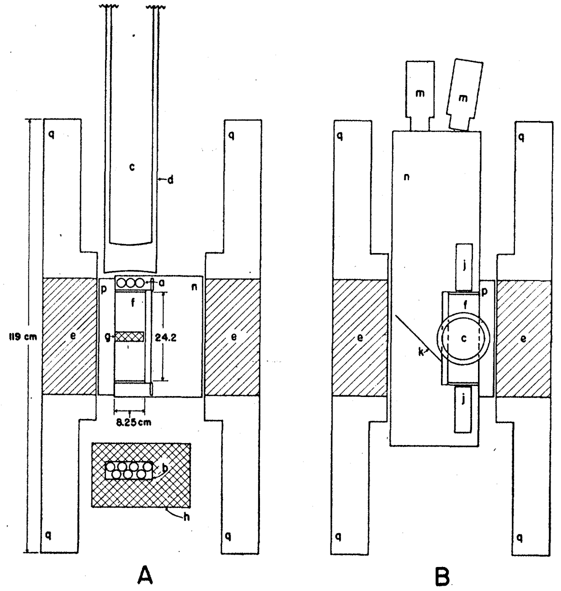

FIG. 1. Side view (*A*) and top view (*B*) of the apparatus with the hydrogen Dewar in place and using control 2. *a*, upper counter tray; *b*, lower tray; *c*, hydrogen; *d*, hydrogen Dewar; *e*, magnet pole-pieces; *f*, cloud chamber; *g*, lead plate; *h*, lead shield; *j*, flash lamp housings; *k*, mirror; *m*, cameras; *n*, light-tight aluminum box; *p*, back chamber of the cloud chamber; *q*, magnet coil housings.

Any event which could be recognized as part of an extensive shower was not considered. It should be added that the counter control imposed another condition on the showers which were studied—that at least one particle issuing from the target block was able to penetrate 56 g/cm^2 of lead (*h*, Fig. 1). This required a minimum momentum of 620 Mev/*c* for a proton and 150 Mev/*c* for a meson.

The cloud chamber was placed in a large electromagnet, but since the heat exchanger was shared with a small cyclotron, the magnet could not be operated part of the time and a number of pictures were obtained without a magnetic field.

II. THE APPARATUS

The arrangement of the apparatus used in this work is shown schematically in Fig. 1.

The electromagnet had pole faces (*e* in Fig. 1) 30.5 cm in diameter and was operated with an air gap of 28 cm during part of the experiment and of 33 cm during the remainder. It was oil cooled and was capable of producing a field of 9270 oersteds with the smaller gap and of 8500 with the larger, without a temperature rise sufficient to disturb the operation of the cloud chamber. At a distance of 5 cm from the axis of the cloud chamber, the field was 1.8 percent lower. By examining the negatives of cloud-chamber pictures under a low power microscope, track curvatures could be determined up to about 16 meters on most tracks, which corresponded to a momentum of about 4 Bev/*c*. On very

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[15] W. Heisenberg, Z. Physik **101**, 533 (1936).

[16] Lord, Fainberg, and Schein, Phys. Rev. **81**, 313 (1951), **80**, 970 (1950); Kaplon, Peters, and Ritson, Phys. Rev. **85**, 900 (1952); Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950); E. Pickup and L. Voyvodic, Phys. Rev. **82**, 265 (1951); M. Teucher, Naturwiss. **37**, 260 (1950); Hopper, Biswas, and Derby, Phys. Rev. **84**, 457 (1951); L. S. Osborne, Phys. Rev. **81**, 239 (1951); W. Heisenberg, Naturwiss. **39**, 69 (1952).

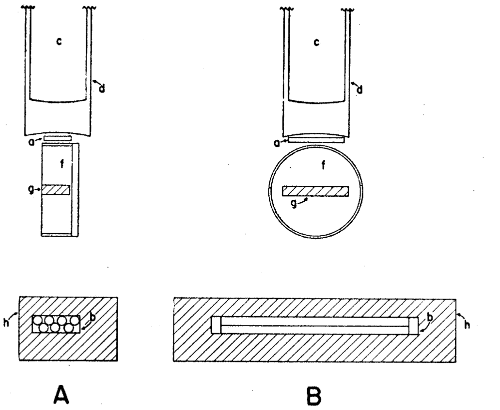

FIG. 2. Side view (*A*) and front view (*B*), of the counter control. *a*, tray *a*; *b*, tray *b*; *c*, hydrogen; *d*, Dewar; *f*, cloud chamber; *g*, lead plate; *h*, lead shield.

sharp long tracks, curvatures could be measured to about 30 meters, corresponding to about 8 Bev/*c*.

The chamber (*f* in Fig. 1) was cylindrical in shape with a diameter of 25 cm and a useful depth of 6 cm. A lead plate 2 cm thick (*g*) was mounted in the center of the chamber. A mirror (*k*) was mounted at an angle of 45° with the axis of the chamber and stereoscopic pictures were taken with the two cameras (*m*).

On the basis of the results obtained with Geiger counters[17] it was not anticipated that events in hydrogen would exhibit high multiplicities except at very high energies. For this reason, the counter control was designed to discriminate as little as possible against events in which few particles are present. Three counter arrangements were used which were approximately equally effective in the rate at which they produced pictures of penetrating showers. They will be designated as controls 1, 2, and 3, respectively.

In the arrangement of control 1, tray *a* of Fig. 2 consisted of 12 counters 1.2 cm in diameter with the axis of the counters parallel to that of the chamber. A tray of 7 counters 2.5 cm in diameter (tray *b*), shielded by lead (*h*) against electron showers, was placed below the chamber. A coincidence between a selected minimum number of counters in tray *a* and any counter in tray *b* tripped the chamber. The minimum number of counters in tray *a* required was controlled by the bias setting of a discriminator circuit so that it could be varied as desired. While using control 1, the required minimum was set at any 3, since this setting gave a higher ratio of operating time (the time during which the apparatus would respond to a coincidence) to dead time than a setting of 2. The dead time of the chamber after a count is 1 minute and the ratio of operating to dead time was 15:1. The lead shielding (*h*) around tray *b* (7.5 cm thick on the bottom, 4 cm thick on one side, and 10 cm thick elsewhere) was used to reduce the frequency of low energy air showers and local electron showers which actuated the chamber. The material in the magnet and the field of the magnet also tended to reduce the number of counts resulting from this type of activity.

Since no events emanating from the hydrogen were observed in 104 hours operating time with control 1, control 2 was adopted. In this arrangement, tray *a* (Fig. 2) consisted of 3 counters 2.5 cm in diameter, mounted with axis at right angles to the axis of the chamber. To make it possible to register only two particle events, any 2 of these in coincidence with any one counter of tray *b* was required to operate the chamber. To further reduce the control discrimination against low energy events, the amount of lead above tray *b* was changed to 5 cm. These measures reduced the ratio of operating time to dead time to about 9 to 1 and did not appreciably affect the rate at which penetrating showers were registered. The resolving time of the circuits was about 4 microseconds so that very few accidentals were expected, although only 3 counters in all were required to operate the chamber.

Control 3 was adopted to further reduce the distance

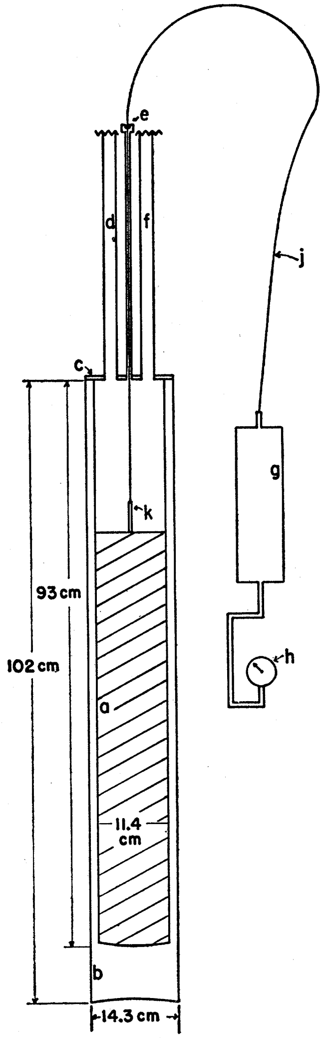

FIG. 3. Liquid hydrogen Dewar. *a*, liquid hydrogen; *b*, bottom evacuated space, containing carbon; *c*, Dewar cover; *d*, exhaust tube for the evaporating hydrogen; *f*, filling tube; *e*, gasket; *g*, hydrogen tank; *h*, pressure gauge; *j*, capillary tube; *k*, bulb.

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[17] M. Vidale and M. Schein, Phys. Rev. 84, 593 (1951).

between the Dewar and the chamber and to register more collimated events. Tray *a* in this case consisted of six 1.2-cm diameter counters mounted with axis perpendicular to the axis of the cloud chamber. Any two of them in coincidence with one in tray *b* would operate the chamber.

While operating with controls 1 and 2, the liquid hydrogen was contained in a cylindrical Dewar (Figs. 1 and 3) of 11.3-cm inside diameter and 91.4-cm inside height. While control 1 was used, this Dewar was placed inside a larger Dewar containing liquid nitrogen. When control 2 was adopted, the nitrogen Dewar was omitted in order to place the hydrogen as close as possible to the chamber. Dispensing with the liquid nitrogen considerably increased the evaporation rate of the hydrogen. The liquid hydrogen target remained over 2 g/cm^2 thick for 100 hours with the liquid nitrogen present and for only 25 hours without it. While operating with control 3, a Dewar of 15.2-cm inner diameter and 143.5-cm inner height was adopted in order to increase the solid angle subtended by the Dewar as seen from the cloud chamber.

The height of the hydrogen column was measured with a hydrogen thermometer as shown in Fig. 3. The bulb (*k*) inside the Dewar was connected by a flexible capillary tube (*j*) to a pressure gauge (*h*) and a tank (*g*) which acted as a hydrogen reservoir. The bulb could be lowered until it touched the surface of the liquid hydrogen by sliding the tube (*j*) through a Teflon gasket (*e*). At this point, the gauge registered a sharp decrease in pressure.

Because of the construction of the Dewars, the chamber, and the magnet, it was not possible to reduce the distance between the bottom of the hydrogen column and the top of the visible part of the chamber to less than 26.7 cm with control 1, 14 cm with control 2, or 11.3 cm with control 3. A large part of this distance was due to the fact that each of the Dewars was about 9 cm thick from the bottom of the inside shell to the base. This space was occupied by a copper reflector and a layer of about 2.2 g/cm^2 of carbon to adsorb residual gases in the evacuated space at low temperatures. A Dewar which largely eliminated this space was obtained but could not be used because of leaks.

When the carbon, aluminum, and lead were used as targets for generating penetrating showers, they could be placed somewhat closer to the chamber, 5 cm above using control 2 and 8.17 cm using control 1.

To determine the position of the tracks sufficiently accurately so that the point of origin of the showers above the chamber could be found, the negatives of the pictures were reprojected in the original cameras, and they were also studied with a low power microscope with a micrometer stage. The second method, while more tedious, proved to be more accurate. It was found by photographing thin wires and by measuring very energetic tracks that the distortion of the lenses was less than the uncertainty with which the center of a good track could be determined. The position of the smallest clusters of droplets along a sharp track could be measured to ±1 micron on the negative, corresponding to about ±10 microns in the position of the track in space. The distortions introduced by imperfections in the lenses were less than this. The positions of the tracks were measured relative to a centimeter scale in the front of the chamber. A wire in the back of the chamber served to check apparent distances. Corrections were made for the gas motion in the chamber by assuming that the motion of any small volume of the gas was parallel to the axis of the chamber by an amount of 8 percent (the expansion ratio) of its perpendicular distance from the front glass plate. Corrections were also made for the refraction of the front glass plate but these corrections were small.

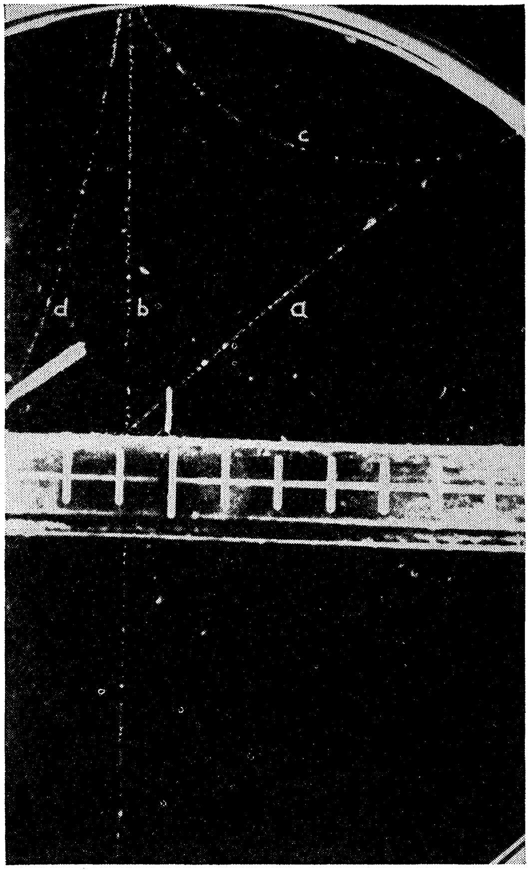

FIG. 4. Star formed in the lead plate of the chamber by a very high energy particle.

III. DISCUSSION OF EVENTS

Figure 4 is an unusual event in which a very energetic particle (track *b*) forms a star in the upper part of the lead plate but loses only a small fraction of its energy in doing so. Track *a* is about four times minimum ionization and its curvature is that of a positively charged particle of momentum 300 Mev/*c*. These facts

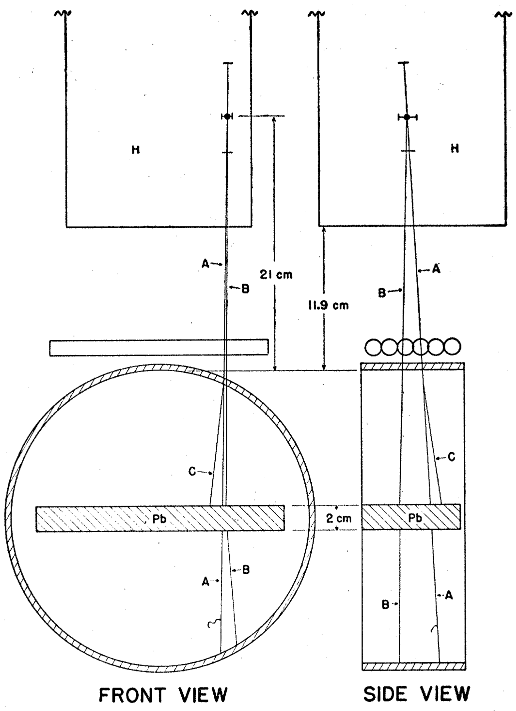

FIG. 5. Schematic drawing of an event in which two penetrating particles trace back to a point in the hydrogen. The estimated accuracy in the location of the junction point is indicated. An energetic δ-ray is visible from track *A* in the lower part of the chamber.

indicate that it is a proton. Although the star occurs in the well illuminated part of the chamber, no tracks other than *a* and *b* can be seen issuing from it. Track *b* is deviated 0.55° (in the plane of the picture) on traversing the lead. That this is the result of the star formation and is not due to small angle scattering[18] is evidenced by the fact that its radius of curvature under the lead is too large to measure which means the momentum is greater than 4 Bev/*c*. Track *c* is an electron, and the two tracks at *d* are positrons which appear to accompany track *b*. When the picture was taken, 110 g/cm^2 of lead was above the chamber and the cascade radiation was probably formed in this lead by *b* or possibly by other particles which do not appear in the picture.

If one assumes that the small energy transfer is due to the possibility that particle *b* only grazed the nucleus, imparting some momentum to a peripheral nucleon which then caused the star, the momentum of *b* can be found from the assumed energy of the star.[6] The minimum energy which could have been given to the star by track *b* is the energy of the visible proton, *a*, which is 44 Mev. The minimum momentum of *b* under this assumption is 31 Bev/*c*. A more probable momentum would be 45 Bev/*c*, corresponding to an assumed energy for the star of 90 Mev, which allows for neutral particles and fragments which do not escape from the lead.

It is very unlikely that track *b* is the result of an interaction in the 110 g/cm^2 of lead above the chamber since, if this were the case, a large penetrating shower would accompany it instead of the small amount of cascade radiation actually seen.

High energy collisions with small energy transfers have been observed in photographic emulsions[19] and in multiplate cloud chambers,[6] but they are rare.[6,7,11] The average number of penetrating tracks formed in gold by a 30-Bev primary is 7 and by a 60-Bev particle, 11.[6]

Figure 5 is a drawing of an event which took place in the hydrogen. The corresponding cloud chamber picture is shown in Fig. 6. It occurred while using control 3 and with no magnetic field. Tracks *a* and *b* trace to a point in the hydrogen $21\,{}^{+4.5}_{-3.0}$ cm above the visible part of the chamber. The three tracks are at minimum ionization. Track *a* is scattered through a projected angle of 0.3° in the 2-cm lead plate. If this deviation is due to multiple scattering, its most probable momentum is 6 Bev/*c*. Track *c* meets *a* at a point in the glass of the chamber and can be interpreted as a knock-on electron. It makes an angle of 10° with *a* which, if it were a knock-on, from conservation of momentum and energy, would correspond to a momentum of 30 Mev/*c* if *a* is a meson, or about 5 Mev/*c* if *a* is a proton of momentum 6 Bev/*c*. As would be expected for an electron in this energy range, it does not penetrate the lead plate.[20]

Track *b* makes an angle of 4.3±0.8° with *a*. It is scattered in the lead plate through a projected angle of 5.4±0.2° with its original direction. If this deviation were due to multiple scattering, the most probable momentum of *b* would be 300 Mev/*c* (or 590 Mev/*c* if *b* were the track of a proton, but in this case, the ionization rules out a proton of this low a momentum).

A number of pairs of penetrating particles which make an angle of a few degrees with each other has been seen during the course of this experiment. Most of them were apparently formed in the carbon or lead targets, but one has been found which traces back to the Dewar walls.

In cloud-chamber pictures taken underground, Braddick and Hensby and others[21] have found a number of penetrating pairs very similar to that described above. These investigators conclude that the initiating particle in the events which they have studied is a μ-meson, that the secondary is probably a μ- or π-meson

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[18] J. G. Wilson, Proc. Roy. Soc. (London) **A174**, 73 (1940).

[19] Lord, Schein, and Vidale, Phys. Rev. **76**, 321 (1949).

[20] Niels Arley, *On the Theory of Stochastic Processes and their Application to the Theory of Cosmic Radiation* (G.E.C. Gads Forlag, Copenhagen, 1943; 2nd ed. John Wiley and Sons, Inc., New York, 1949); R. R. Wilson, Phys. Rev. **86**, 261 (1952).

[21] H. J. J. Braddick and G. S. Hensby, Nature **144**, 1012 (1939); Braddick, Nash, and Wolfendale, Phil. Mag. **42**, 1277 (1951); E. P. George and P. T. Trent, Nature **164**, 838 (1949); E. P. George (private communication).

of mean energy 1 Bev, and that the cross section for the process is about 5×10^{-29} cm^2/nucleon for lead and of the same order of magnitude for sandstone.[22] A cross section of this magnitude is estimated to be consistent with the observation of such an event in hydrogen during the operating time of this experiment.

If, however, one assumes that this event is not of the same type as those found by Braddick and Hensby, several alternative interpretations should be considered.

The first is elastic scattering of a meson or a proton on a proton in the hydrogen. From conservation of momentum and energy, the equation for the angle θ, between two particles in the laboratory system of reference after one has collided with the other, is

$$\cos\theta = (E_0 - m_0c^2)(E_1 - m_0c^2)/p_0p_1c^2.$$

E_0 is the energy after collision (including rest mass) of the particle originally at rest, m_0 is its mass, and p_0 its momentum after collision. The corresponding quantities for the incident particle are given the subscript 1. It is apparent from this equation that if, as in this case, m_0 is equal to or larger than the rest mass of the incoming particle, θ cannot be as small as 4.3° unless both particles are of extremely high energy, which is certainly not the case because of their scattering in the lead. The angles and energies are also inconsistent with the hypothesis that a and b are an electron pair, as is also apparent from the fact that both particles penetrate 2 cm of lead.

If we consider the possibility that track a is a μ-meson and b a knock-on electron, the relation between the angle, θ, between a and b and the momentum of b is

$$P_b = \frac{\cos\theta}{\sin^2\theta}\ \text{Mev}/c,$$

provided $\theta \geqslant 4°$ and the momentum of the meson $\geqslant 5$ Bev/c. This equation follows from the conservation of momentum and energy. Taking into account the probable uncertainty in θ due to the multiple scattering experienced by track b in the material (0.3 radiation length) between the point where a and b meet and the interior of the cloud chamber, the momentum of b is probably between 200 and 400 Mev/c. The cross section per atom for a knock-on of energy ϵE formed by a meson of energy E and spin $\frac{1}{2}$[23] is

$$\sigma(E,\epsilon)d\epsilon = 1.6\times 10^{-32}\frac{2\pi Z}{\alpha}\frac{\mu}{m}\frac{\mu c^2}{E}\frac{d\epsilon}{\epsilon^2}\left(1-\frac{\epsilon}{\epsilon_m}+\frac{\epsilon^2}{2}\right)\ \text{cm}^2,$$

$$E \leqslant 500\ \text{Bev},$$

where Z is the charge of the atom struck, α the fine structure constant, μ the meson mass, m the electron mass, and ϵ_m the maximum fractional energy transfer possible,

$$\epsilon_m \sim E/(E+10),$$

if E is expressed in Bev. The cross section for producing an electron in the energy range w_1 to w_2 is then (if all energies are expressed in Bev):

$$\sigma(E, w_1, w_2) = 2.76\times 10^{-28} Z\left\{\left(\frac{1}{w_1}-\frac{1}{w_2}\right) - \frac{E+10}{\epsilon^2}\ln\frac{w_2}{w_1} + \frac{1}{2E^2}(w_2 - w_1)\right\}\ \text{cm}^2,$$

$$E \leqslant 500, \quad w_1 < w_2 \leqslant E^2/(E+10).$$

From this expression, the cross section for the production of a knock-on electron of more than 300-Mev energy by a 6-Bev μ-meson is 5.6×10^{-26} cm^2/hydrogen atom. Before this cross section is compared with that for the μ-meson interaction described by Braddick, however, it must be multiplied by the probability that an electron of about 300-Mev energy would traverse the lead plate without any interaction other than multiple scattering (which would account for the total scattering angle at this energy). The work of Arley

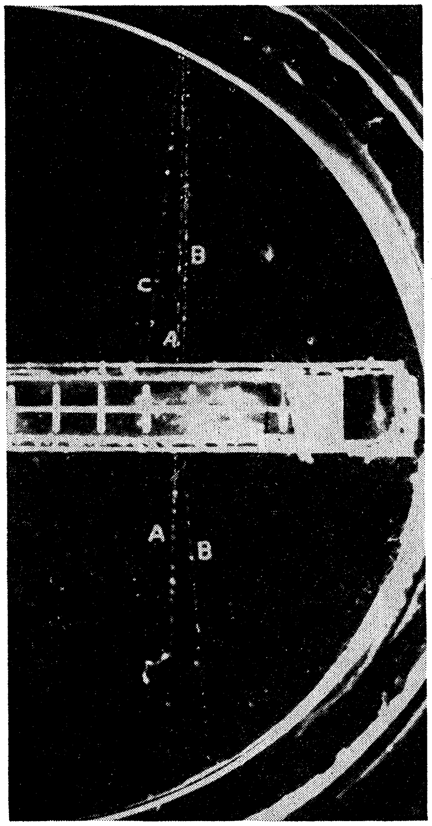

FIG. 6. Front camera view of event sketched in Fig. 5.

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[22] According to recent counter experiments of Amaldi, Castagnoli, Gigli, and Sciuti, however, the cross section for this type of event is 6×10^{-30} cm^2/nucleon (private communication to Marcel Schein).

[23] H. C. Corben and J. Schwinger, Phys. Rev. **58**, 953 (1940); R. F. Christy and S. Kusaka, Phys. Rev. **59**, 416 (1941).

and of Wilson[20] shows that the probability of an electron of 300-Mev momentum appearing below the lead as a single particle is about 15 percent. The probability of the scattering angle being small must, however, be much lower than this. Neddermeyer and Anderson[24] using a platinum plate equivalent to 1.96 cm of lead in a cloud chamber found that the energy loss in the platinum was 80 to 100 percent in 14 out of 17 cases and was as low as 50 percent in only one case for particles whose energy was under 500 Mev and which were either accompanied by other particles on entering the chamber, or which produced other particles in the platinum. In the present instance, track *b* traverses a total of 4.2 radiation lengths so that the probability that it would undergo no relatively large scale energy losses if it is an electron might be expected to be about $1\frac{1}{2}$ percent ($e^{-4.2}$). It is concluded that the cross section for a knock-on which would have the appearance of Fig. 5 is about $0.015\times 5.6\times 10^{-28}=8\times 10^{-30}$ cm^2/hydrogen atom.

It is also possible that the tracks in Fig. 5 issued from a nucleon-proton collision in which a single π-meson was produced. The probability that this is the case cannot be estimated without making some assumptions concerning the interactions. In Fermi's theory[25] the assumption is made that the probability of an allowable state is proportional to its statistical weight. An estimate was made under this assumption and the assumptions that at the energies involved here the total cross section for single meson production is geometric[26] and that the conservation of angular momentum does not greatly alter the angular distribution from that of a central collision. With these assumptions, it was found that the probability of a single meson production event in which two secondary charged particles are emitted within an angle as small as 4.3° is less than 5 percent of the probability of a μ-meson interaction of this appearance, assuming it occurred with the cross section given by Braddick. In this estimate, the nucleon spectrum was assumed to be twice the proton spectrum given by Mylroi and Wilson[27] since the number of neutron produced penetrating showers at sea level is approximately equal to the number of proton produced showers.[28] The μ-meson spectrum used was that given by Rossi.[29]

TABLE I. Rates at which penetrating showers were registered under cabon, aluminum, and lead.

Material	Thickness (g/cm^2)	Rate (showers/hour)
Carbon	57.3	0.09±0.02
Aluminum	92.5	0.07±0.03
Lead	168	0.07±0.02

The fact that no example of single meson production in the hydrogen was detected (with the possible exception of the event of Fig. 5) is consistent with considerations of the type outlined above.

IV. PENETRATING SHOWERS UNDER CARBON, ALUMINUM, AND LEAD

The rates at which penetrating showers were registered under carbon, aluminum, and lead are shown in Table I. The rates are given on the basis of the operating time, which excludes the dead time of the chamber. The statistical standard deviations are given for these rates.

Butler, Rosser, and Barker[14] employed an apparatus similar to that used in this work and defined a penetrating shower in the same way. From the data which they reported, using a lead absorber above the chamber, their counting rate was 0.09±0.01, which is consistent with the figures given above, although the geometries, counter controls, and chamber sizes were somewhat different in the two cases.

Although the observations on heavier elements were made primarily to estimate the average energy of the penetrating showers and to establish the efficiency of the apparatus in detecting penetrating showers, and the counting rate to be expected, some other inferences can be made. A comparison of the counting rates in the three materials (the thickness of each of which is approximately one geometrical nuclear mean free path for collision) shows that they are equal within the limits set by the statistics. This is in agreement with recent results.[4,30]

In the case of 23 percent of the penetrating showers found under lead, γ-rays formed at least one electron shower in the lead plate in the center of the chamber, and in the case of 11 percent, at least two. In carbon the corresponding figures are 42 percent and 31 percent. This is evidence that γ-rays are formed in these showers which are not as likely to escape from the lead block as from the carbon.

From the nucleon flux and the frequency of the showers shown in Table I, it is possible to make a rough estimate of their energy, assuming that the variation of the cross section for the production of a penetrating shower with the momentum of the incident particle can be approximated by a step function, i.e., that it is zero below a certain critical momentum, p_m, and geometric above it. In a manner similar to that which will be outlined in Sec. V, this was done. The lower limit estimated for p_m was 4 Bev/*c*.

That there can be no appreciable contribution to the

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number of penetrating showers by impinging nucleons of momentum below a few Bev/c is also indicated by the fact that the rates of penetrating showers in smaller thicknesses of material can be correctly estimated by the use of the rates given in Table I by assuming the probability of a shower is proportional to $(1-e^{-x/\lambda})$. A proton must have a momentum of about 900 Mev/c to penetrate any of the three blocks of material employed in finding these rates. Consequently, if incident nucleons of momentum not much greater than 1 Bev/c contributed appreciably to the number of penetrating showers, the rates at which these showers were detected under thinner targets should be proportionately higher than the rates one would expect on the basis of the thick target results of Table I. This is not the case. As shown in Sec. V, the number of penetrating showers formed in the bottom of the Dewar (about 0.1 geometric nuclear mean free path) agrees with the number estimated from the average rates for the thick targets.

V. RESULTS WITH LIQUID HYDROGEN

The total operating time with liquid hydrogen above the chamber was 626 hours. During this time seven penetrating showers were observed which traced back to the bottom of the Dewar or to the counters. No events which appeared to come from the hydrogen were detected except for the one described in Sec. III, which cannot be classed as a penetrating shower according to our definition.

The amount of material in the bottom of the Dewar and the counters was about 0.116 geometrical nuclear mean free path (abbreviated mfp) during control 1 and 0.067 during controls 2 and 3. The number of penetrating showers which one would expect in this material on the basis of the average rate from Table I (0.08±0.01 showers/hour) and the running time (104 hours with control 1 and 522 hours with controls 2 and 3), is 6. This agrees rather well with the 7 showers observed.

By measuring the curvatures of the individual tracks in those pictures taken with the field on (5 of the 7) it was found that the total momentum of the visible tracks averaged more than 3.6 Bev/c per event. Taking into account the facts that only a lower limit could be placed on the momentum of many of the tracks in each event, that some tracks would miss the chamber, and that neutral particles must also have been present, it is estimated that the average momentum of the initiating particles must have been at least 6 Bev/c. This estimate is consistent with that of Butler, Rosser, and Barker who concluded that the average energy of the penetrating showers they observed was at least 7 Bev. It is probable that the minimum value for p_m deduced in Sec. IV from the proton spectrum (4 Bev/c) is low by a factor of $1\frac{1}{2}$ or 2.

If the cross section for the production of penetrating showers in hydrogen were 6×10^{-26} cm^2/nucleus, i.e., geometrical, 3 g/cm^2 would be a little more than 0.1 mfp. This corresponds to about 43 cm of hydrogen and this figure was taken as the limit beyond which it is impracticable to attempt to trace tracks seen in the chamber. The number of nuclear interactions in material which is 0.1 mfp or less in thickness is directly proportional to the thickness and the time. To compare the hydrogen with other materials, therefore, the time integral of the amount of hydrogen below the 43-cm mark in the Dewar was found graphically for each separate run, and these were added. The total was 50.9 mfp hours. The corresponding total for the material in the bottom of the Dewars was about the same, 47.1 mfp hr. The geometries were not the same since the hydrogen was further from the chamber but it can be said that the angular spread of the particles in the showers observed from the Dewar bottom was such that they would have been observed and recognized as penetrating showers if they had occurred higher up in the Dewar. In addition, the fact that the number of penetrating showers in thin targets is no greater than that expected on the basis of the number found in thick targets (in the cases of carbon and aluminum, the tops of the targets were more than 35 cm above the top of the chamber) indicates that very few showers would have been missed if they had occurred in the hydrogen.

It should further be pointed out that a number of nuclear events, some of which may be as energetic as a penetrating shower, must occur in heavy elements which are not recognized as being of nuclear character, but which would be so recognized if they occurred in hydrogen. There is, for instance, a group of events consisting of one penetrating particle accompanied by 3 or more minimum ionization tracks, all of which trace back approximately to a point in the interior of the target. Some of these would be penetrating showers if more than one of the tracks happened to go toward the lead plate, rather than out of the chamber. In fact, this particular type of event appears to follow the $A^{\frac{2}{3}}$ cross section law. The frequency is about $\frac{3}{2}$ times the frequency of penetrating showers in the case of lead, carbon, aluminum, and Dewar bottom, in thick or thin targets. Although from these facts it would appear that a large percentage of these events must of nuclear character, it is probably not safe to count them as such in heavy materials since some of them at least must be μ-meson knock-on showers. In the case of hydrogen, however, events of this kind would be unambiguous since the probability of a knock-on shower in hydrogen (only 0.0005 radiation length per cm) is negligible.

It can be concluded that if multiple production played a prominent role in the majority of sea-level penetrating showers, probably produced at energies of 6 Bev or more, at least 7 should have been seen issuing from the hydrogen during the course of this experiment.

While there is not enough information available to make an accurate calculation, it is possible to utilize the nucleon spectrum at sea level to make an estimate of the minimum number of penetrating showers which should be observed if the cross section for their production is assumed to have a given dependence on the momentum of the incident particle. To make such an estimate, it will be assumed that the variation of the mfp for the production of penetrating showers with the incident momentum can be approximated by a step function.

$$\lambda(p<p_m)=\infty, \quad \lambda(p\geqslant p_m)=\text{constant}.$$

The angular distribution of the penetrating secondaries from a nucleon-nucleon collision is unknown, but it has been shown that the more energetic particles which would be likely to trip the lower counter tray (*b*, Fig. 1) are emitted in the direction of the incident nucleon.[4] If one then finds the number of nucleons which would pass in a straight line through a given layer of hydrogen, through the lead plate in the well-lighted part of the chamber, and through the lower counter tray, this might be considered a lower limit to the number of possible shower producing nucleons. To estimate the minimum number of showers expected the number which would be formed in a differential layer of hydrogen 43 cm above the top of the chamber by nucleons collimated as described above, and with the mfp given above is found and it is assumed that this same number would be formed and observed in all lower layers of equal thickness. It is apparent that this is a lower limit to the number of showers which should be observed since the solid angle over which primary protons are accepted is higher for lower layers. Assuming the proton spectrum (doubled to take neutrons into account) and zenith angle dependence given by Mylroi and Wilson can be extrapolated to somewhat higher momenta than those for which it has been verified, the minimum number of showers which should be seen is

$$n_0=7.28\times 10^{26}p_m^{-1.8}\sigma\int xdt(1-\cos^6\theta_m),$$

where $\int xdt$ is the time integral of the amount of hydrogen expressed in mfp hr, and θ_m is the half-angle of the cone which has the top layer of hydrogen (that at 43 cm up) as a base and whose apex is in the lead plate of the chamber. In this equation the detection efficiency is taken at 100 percent. The fact that a penetrating shower is defined to consist of three or more particles which enter the chamber, at least two of which are penetrating, makes it very unlikely that it would fail to actuate the counter control. Substituting the values of θ_m and the integral, $\int xdt$,

$$n_0=67.5\sigma_r p_m^{-1.8},$$

where σ_r is the cross section expressed in units of the geometrical cross section, and p_m is in Bev/*c*, as before. Since no showers were observed, n_0 is probably a fraction, but its value is unknown. From this equation one can, however, see that if the cross section were geometric ($\sigma_r=1$) at $p_m=6$ Bev/*c*, an average of at least three penetrating showers should have been seen in the operating time of this experiment. The statistical probability that none would have occurred in the period (assuming a Poisson distribution for the number of showers seen in a given interval if the average number is three) is 5 percent. It should be stressed that p_m is a lower limit here and that the cross section for penetrating showers in hydrogen may well be low at momenta very much higher than this. This result is consistent with the conclusion based on the number of penetrating showers which occurred in the bottom of the Dewar and the rates at which showers occurred in carbon, aluminum, and lead, that at least seven penetrating showers should have been observed in hydrogen if the cross section for their production were geometric. The conclusion that multiple production has a small cross section compared to geometric at nucleon momenta of about 6 Bev/*c* agrees with current theories on meson production,[25,31] and with other experiments. In a high altitude counter experiment using liquid hydrogen, Vidale and Schein[17] found evidence that multiple meson production should be expected only at energies well in excess of 10 Bev. Using nuclear emulsions, Lord and Schein[32] found indications from the latitude effect that the average multiplicity when a proton strikes a carbon nucleus at 8 Bev is less than 4. Rollosson's counter work is also in agreement with this result.[33]

VI. CONCLUSION

The majority of sea-level penetrating showers are initiated by particles of about the same average momentum in carbon, aluminum, and lead, since the frequency of the showers follows an $A^{\frac{2}{3}}$ law. This average momentum, under the conditions of the experiment described here is 6 Bev/*c* or higher.

From the fact that no penetrating showers were observed in hydrogen, it may be concluded that multiple production of several mesons is very improbable at the energies of these showers and that the majority of sea level penetrating showers in heavier materials should be attributed mainly to plural production.

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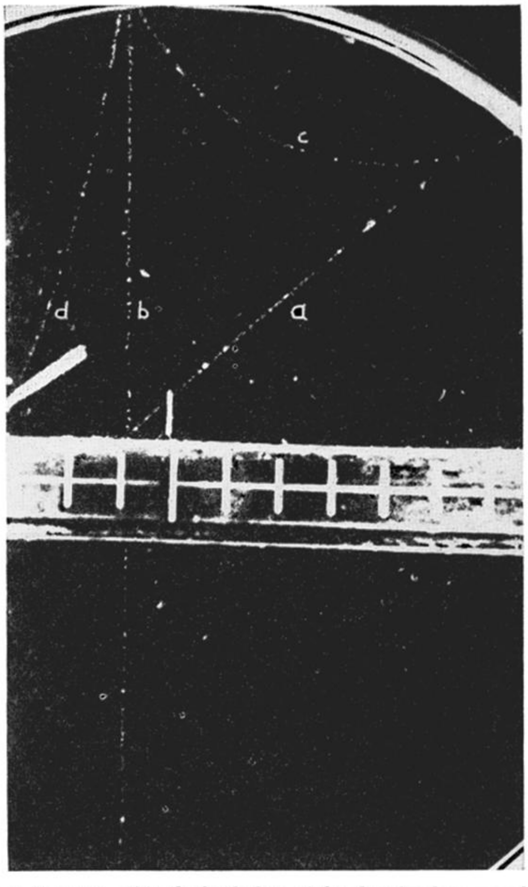

FIG. 4. Star formed in the lead plate of the chamber by a very high energy particle.

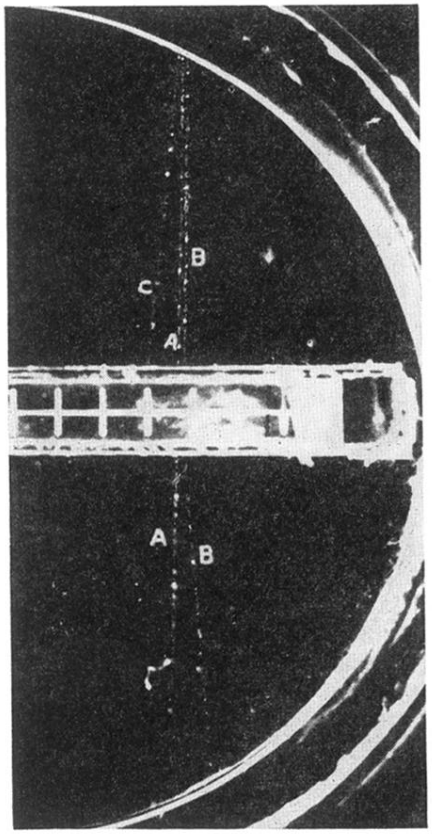

FIG. 6. Front camera view of event sketched in Fig. 5.