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A Cloud-Chamber Study of Meson Absorption by Thin Pb, Fe, and Al Foils*,†

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Cloud-chamber experiments are described on the absorption of slow mesons by thin Al (0.002 and 0.032 inch), Fe (0.028 inch), and Pb (0.018 inch) foils, which (a) set an upper limit on the probability of meson-induced emission of protons and (b) give evidence for the emission of 1–5-Mev gamma-radiation when a meson is caught in Pb. Variation of the ionization from foil to foil is used as the technique to identify protons, mesons, and electrons near the end of their range, cloud-chamber pictures of these three types of particles being given for illustration.

In each element many pictures have been obtained in which a particle identified as a meson stops at a foil without giving rise to an observable heavy charged particle or a decay electron. To stopped mesons of this kind is therefore ascribed a negative charge. This assignment is consistent with the observation of a roughly equal number of mesons which do decay. The particles identified as stopped negatives are distributed as follows: Pb−27; Fe−14; Al−12. If on the average one proton was ejected per stopped negative meson, then the protons—to have remained in every instance within the thin foils—would have to have energies less than about 4 Mev in the case of Pb and Fe, and less than about 1.5 Mev in the case of Al. But from Pb, with a nuclear potential barrier about 10 Mev high, no proton will ever escape with appreciable probability if its energy is as low as 5 Mev. Consequently, it is concluded that *no protons are emitted when a negative μ-meson interacts with a Pb nucleus*. The present experiments are *consistent* with a similar absence of meson-induced protons from the nuclei of Fe and Al (potential barriers about 5 Mev and 3 Mev, respectively). However, statistics for these two elements are insufficient to *prove* that no protons ever emerge from these substances. The results obtained in Pb argue that the *meson imparts only a small part of its rest energy to the nucleus* and that *the remainder*—to escape cloud-chamber observation—*must be given off as a neutral, non-electromagnetic radiation*. This last conclusion is reached from the fact that we have not observed tracks of high energy electron pairs of energy, say, over 20 Mev, which can be due to photons associated with the stopped negative mesons (or with the decaying mesons). Thus, we conclude that *mesons which do not decay disappear by a charge-exchange reaction* of the form

$$\mu^- + (\text{original nucleus}) \rightarrow \left\{\begin{array}{l}\text{nucleus of same mass}\\ \text{number, of charge}\\ \text{number one unit}\\ \text{smaller, and of only}\\ \text{moderate excitation}\end{array}\right\} + \mu_0 \text{ (a neutral entity).}$$

A much smaller portion of the rest energy may come off in the form of gamma-rays. Thus, in the case of Pb, 7 meson-oriented secondary electron tracks have been obtained from 7 of the above 27 stopped negatives. A similar track was found for Fe, and none for Al. These electrons have energies between 1 and 5 Mev. The frequency of occurrence of these electrons and their orientation always towards the point where the meson disappeared are evidence that they are definitely associated with the reaction of the negative μ-meson with the nucleus. We conclude that these *meson-associated photons arise* (1) *outside the nucleus, due to meson jumps between Bohr orbits* and (2) *within the nucleus, following reaction of the negative μ-meson with the nucleus.* The energy and frequency of occurrence (much higher than chance) of these electrons are compatible with those predicted in Wheeler's theory of meson transition between Bohr orbits and with those expected from nuclear excitation as a result of negative μ-meson capture followed by neutral meson (or neutrino) emission.

I. INTRODUCTION

Lack up to now of a systematic cloud-chamber study of the fate of stopped negative μ-mesons has left in doubt two fundamental questions about the transformations of these particles: (1) do the mesons make radiative transitions from one Bohr orbit to another? (2) what happens to the rest energy of the meson when it reacts with a nucleus? These questions are especially interesting in view of other evidence about the μ-meson.

Mesons had been thought until 1947 to be directly related to nuclear forces along the lines proposed by Yukawa.[1] Consequently, it had been expected that negatives stopped in solid material would disappear by reaction with the nucleus long before there had been time to undergo free decay. The anticipated behavior was found in

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† Part of the results presented in this paper were reported at the Washington meeting of the American Physical Society on May 1, 1948; Phys. Rev. 74, 1236 (1948).

[1] H. Yukawa, Proc. Phys. Math. Soc. Japan 17, 48 (1935).

iron in experiments of the Rome group,[2] but in carbon they found that negative mesons underwent decay. That this unexpected result could not be due to trapping of the meson in an orbit isolated from the nucleus was shown by Fermi and Teller.[3] Moreover, Sigurgeirsson and Yamakawa[4] found that the relative probabilities of decay and of nuclear reaction varied in a systematic way with atomic number, Z, reaching equality for $Z=Z_0$ of the order of 10. The absolute rate of nuclear reaction determined by way of this comparison with the decay time was so much lower than that originally anticipated that it had to be concluded that ordinary mesons have an extraordinarily low rate of interaction with atomic nuclei.

The determination of the *rate* of the meson-nuclear reaction from decay experiments left completely undetermined the *energy transfer* to the nucleus in this process and gave little evidence about the *nature* of the process itself. On the qualitative character of the reaction other observations, however, gave interesting clues. Negatives stopped in iron give off electrons neither by normal decay after the lapse of a microsecond—as would be detected in the usual decay experiments—nor by accelerated decay at still shorter times, according to early experiments of Rasetti as recently analyzed by Piccioni.[5] Neither electrons nor any other charged particles appear at the end of the track in the very few cases where a particle identified as a negative meson stops in the gas of a cloud chamber.[6] About heavy negative mesons, photographic emulsions give extensive evidence on star production. However, from such emulsion work it has so far been possible only indirectly to draw conclusions about the $\sim$200-mass negatives. Few, if any,[7] of these entities cause ejection of heavy charged particles from the nuclei of those elements (Ag, Br) which (1) are heavy enough to give nuclear reaction a strong preference compared to radioactive decay ($Z \gg Z_0 \sim 10$) and (2) are present in a substantial abundance in the emulsion. About μ-meson-induced ejection of heavy particles from other nuclei there appears to be no evidence except the important observation of Sard, Conforto, and Crouch,[8] confirmed by Groetzinger and McClure,[9] that roughly two neutrons are released in lead for each meson—interpretable as a negative—which is stopped in that substance.

The most obvious means to unravel the mechanism of the meson-nuclear reaction is to investigate the disposition of the $\sim$100-Mev rest energy brought in by the incident negative. (1) If in the elements other than Ag or Br a large part of this energy goes into nuclear excitation, then evidence on this point should be obtainable from suitable cloud-chamber experiments. Heavy mesons, with only 40 percent more rest energy than μ-mesons, are known to produce stars which on the average have several prongs.[10] Moreover, cyclotron experiments[11] show that the number of prongs is not a rapidly varying function of energy. Consequently, several prongs should also be expected on the average if the $\sim$200-mass mesons deliver up their energy to the nucleus. Of course the typical star particle has an energy of only a few Mev. Thus it is necessary to use many very thin foils, and to employ several elements, in order properly to test via cloud-chamber experiments the possibility of emission of charged heavy particles. (2) It might be supposed that most of the $\sim$100 Mev goes to a high energy neutron. However, the momentum, more than 400 Mev/c, taken off by such a particle would be far too great to be provided by any known or easily imaginable nuclear process. Obviously no light particle nor even any single nucleon could take up the recoil consistently with the law of conservation of energy. Of course equal division of the energy would be

[2] M. Conversi, E. Pancini, and O. Piccioni, Phys. Rev. **71**, 209 (1947).
[3] E. Fermi, E. Teller, and V. Weisskopf, Phys. Rev. **71**, 314 (1947); Fermi and Teller, Phys. Rev. **72**, 399 (1947).
[4] T. Sigurgeirsson and A. Yamakawa, Phys. Rev. **71**, 319 (1947); Rev. Mod. Phys. **21**, 124 (1949).
[5] O. Piccioni, Phys. Rev. **73**, 411 (1948).
[6] A few cases have been collected by O. Piccioni, Phys. Rev. **73**, 411 (1948).
[7] C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, Nature **160**, 463 (1947); *ibid.* **160**, 486 (1947); above authors and H. Muirhead, Nature **159**, 694 (1947). Recent unpublished Berkeley results kindly communicated to this laboratory by Dr. Lattes give more definite evidence in the same direction. See also C. F. Powell and co-workers, Nature (1949) in press.
[8] Sard, Ittner, Conforto, and Crouch, Phys. Rev. **74**, 97 (1948).
[9] G. Groetzinger and G. W. McClure, Phys. Rev. **74**, 341 (1948).
[10] C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, Nature **160**, 463 (1947); *ibid.* **160**, 486 (1947); above authors and H. Muirhead, Nature **159**, 694 (1947).
[11] E. Gardner and V. Peterson, Phys. Rev. **73**, 533 (1948); Wendell Horning, Phys. Rev. **73**, 533 (1948).

possible between two nucleons projected in opposite directions, at least in principle; but even here one of the nucleons would have to traverse the rest of the nucleus, and would therefore produce a high energy nuclear disruption with emission of nuclear protons as well. Consequently the search for such events may be included under item (1). (3) If the 100 Mev goes off as gamma-radiation then—at least in the case of iron—the individual quanta must have energies less than 20 Mev, according to counter experiments of Piccioni.[12] To search for gamma-rays of energies from 100 Mev down to 1 Mev from stopped mesons it is desirable to use a cloud chamber containing a number of thin foils, and especially appropriate to study the case of lead, with its high cross section for photon absorption. (4) If neither electromagnetic radiation nor nucleon evaporation carries away the 100 Mev, then—electron emission already having been excluded—the only evident process left is one in which the meson imparts only a small fraction of its rest energy to the nucleus and itself goes off as some kind of penetrating neutral radiation, a neutral meson, or a neutrino.[13] If mesons which do not decay undergo this "charge-exchange reaction," then it is important to investigate the magnitude of the energy left in the nucleus as evidenced by the frequency or scarcity of meson-induced emission of protons. For this purpose it is most desirable to secure by the cloud-chamber technique many tracks of mesons stopped in very thin foils. (5) If the charge-exchange reaction occurs but gives the nucleus so little excitation that proton emission is extremely rare, such an outcome might mistakenly suggest that some mysterious reaction occurs in which the nucleus receives no excitation at all. For this reason it is important to note that a nuclear excitation in the charge-exchange reaction as low as 1–5 Mev would have positive and observable consequences in a cloud-chamber experiment with many thin foils. Thus, the nucleus can dispose of so small an amount of energy only via gamma-ray emission, and the gamma-rays will have an appreciable probability to eject electrons from thin foils suitably arranged in a cloud chamber. (6) Finally, cloud-chamber observations of precisely the same kind are desirable to look for Compton electrons and pair electrons ejected from matter by the characteristic radiations which are given off in the pre-reaction jumps of mesons from one Bohr orbit to another.[14]

In view of the importance of cloud-chamber studies of meson-induced reactions, a cloud chamber was especially designed and constructed for this purpose in 1947, and observations have been made through the greater part of 1948, up to date.

Section II describes this cloud chamber and associated electronic control equipment. Section III-A describes the procedure used to identify electrons, mesons, and protons. Section III-B discusses photographs of typical cases where the meson is observed to stop without producing any observable effect. The single observed case of heavy particle emission is discussed in Section III-C, and is shown to be not necessarily associated with any meson track.

In Section III-D the experimental evidence from III-B is used to show that the maximum excitation of the nucleus produced by reaction with a μ-meson is consistent with theoretical predictions based on the charge-exchange reaction hypothesis. In III-E are considered those cases where stopped mesons produce tracks reasonably interpretable as ordinary decay electrons. Section III-F gives the cloud-chamber evidence obtained in the present experiments for gamma-radiation in the 1–5-Mev range, and III-G discusses the interpretation of this radiation.

In Section IV a general discussion is given to the statistics of the present experiments. The meson absorptions of the three elements, Pb, Fe, and Al, are compared. In each element the expected rate of meson absorption is calculated and found to agree with the observed one.

II. EXPERIMENTAL ARRANGEMENT

The details of the construction and operation of the cloud chamber and the electronic details of the control unit will be published elsewhere. Here we are concerned only with those essentials related to the present experiments.

[12] O. Piccioni, Phys. Rev. **74**, 1236 (1948); Phys. Rev. **74**, 1754 (1948).

[13] J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. **21**, 144 (1949).

[14] J. A. Wheeler, Rev. Mod. Phys. **21**, 133 (1949).

The cloud chamber is of the rubber diaphragm type and has an inside diameter of about 12 inches. For eventual use with a magnet, the back (dead) space has been made as small as possible. To accomplish this, the position of the perforated brass plate, against which the diaphragm expands, and hence the expansion ratio, is varied from outside at the bottom circumference by means of a gear system. A brass ring is held rigidly to the bottom of the chamber by only four equally spaced brass rods. The length of these rods determines the depth of the chamber. The glass window and the glass cylinder are held together against the bottom part of the chamber by another ring which can be screwed onto the first ring. Neoprene rings are used for the vacuum seals. In this way we have the least amount of material surrounding the chamber proper (so as to reduce the number of useless anticoincidences to about $\frac{1}{4}$ of that for usual chambers), and the chamber depth can be easily varied (if desired) by simply changing the length of the four spacers (the rods) and the height of the glass cylinder. A depth of 5 inches has been used.

The fast expansion valve is of a solenoid type. A current of about one ampere is large enough to attract a thin iron disk (to make a good vacuum seal) against an opening of one-inch diameter, having a pressure of about 10 lb./in.^{2}. This current is supplied from a thyratron tube, which is triggered by the counter pulse to make an expansion. To have a definite expansion ratio for days, the back chamber pressure has been maintained at the same value for each expansion by a Mason-Neilan No. 40 reducing valve with the top chamber sealed against atmosphere.

A "Micro-File Recordak" Model E camera and a pair of G.E. 126 flash lamps have been used for taking photographs. Each lamp is focused with a parabolic mirror and operated by discharge of a 50-μf condenser at 2000 v. A large front-coated mirror is placed perpendicular to the chamber at one edge so as to have stereoscopic photography. The intervals—particle entry-expansion and particle entry-lamp flashing—are, respectively, about 1 (to 10) and 80 milliseconds. Linagraph Ortho films have been used.

A slow expansion unit has been used. A sequence of 4 or 8 slow expansions can automatically follow each fast expansion. It is found that in this way the background is small and uniform, especially in the case of a chamber containing many foils and of very infrequent expansion.

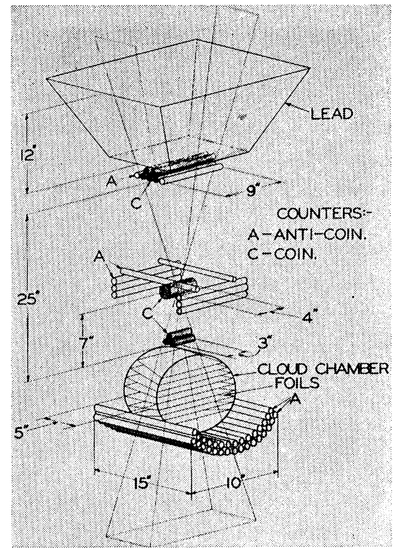

FIG. 1. Meson absorption experiment—apparatus.

The experimental arrangement for the nuclear absorption of mesons by thin foils is shown in Fig. 1. The foils (Pb, Fe, or Al) inside the cloud chamber are so inclined that the planes of the foils, when prolonged, meet at a line at the lens of the camera; i.e., when viewed at the lens, only the front edges are visible. Three different series of experiments have been performed, using Al, Fe, and Pb, respectively, as absorbing materials inside the chamber. The thickness of each Pb foil is 18/1000 inch, while that of each Fe foil is 28/1000 inch. Each foil is covered with 2/1000-inch Al foils on both sides, so as to increase reflected light for better illumination of the chamber. The total thickness (Fe or Pb plus Al) in either case is about the range of a 15-Mev proton. In the experiments with Al foils there are three foils of 32/1000 inch (about the range of a 11.5-Mev proton) and eight foils of 2/1000 inch (about the range of a 2.2-Mev proton). The thicker ones are equally spaced among the thinner ones and serve to identify the particles (cf. Section III-A). A vertical beam of mesons is defined by the threefold coincidence telescope above the chamber, the top two trays of which are protected against side showers by the anticoincidence counters, *A*

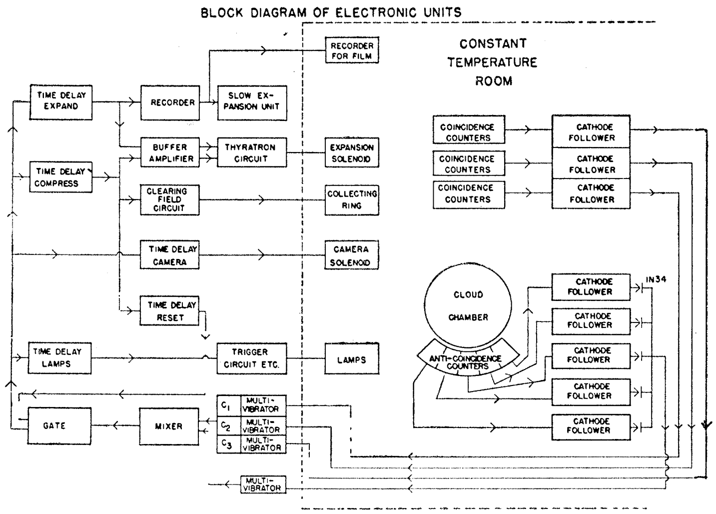

FIG. 2. Block diagram of electronic units for controlling the cloud chamber.

(unshaded). The lower circumference of the chamber is surrounded by double layers of many anticoincidence counters, A. It is seen that each meson going into the chamber must pass through one of the anticoincidence counters underneath if it is not absorbed at the foils or at the chamber and counter walls. It is expected to increase the intensity of slow mesons by putting the thick block of lead (about 12 inches) above the telescope. The apparatus as represented in Fig. 1, the preamplifiers (cathode followers), and the photographic unit are kept in a room, the temperature of which can be maintained constant within 0.1°C. The operation of the cloud chamber and the associated equipment is controlled automatically by an electronic unit (see below). The chamber has been found to work satisfactorily for days without readjustment.

In principle the chamber expands only when a particle stops in the foils or in the chamber and counter walls. In practice, however, it expands much more frequently because of the effects due to side showers, inefficiency of the anticoincidence counters at the bottom, scattering from the top part of the chamber unit, etc. Taking Fe or Pb as an example, on the average we have obtained one useful event (a meson stopped) in a total of about 60 pictures, which has taken roughly 20 hours. During this period about 1000 particles have entered the cloud chamber through the telescope. This absorption rate of mesons is compatible with that estimated from the solid angle and amount of material used, the meson intensity at sea level, and the absorption data of Koenig.[15] A discussion of statistics is postponed to Section IV.

It is seen that if only the coincidence telescope is used above the chamber without having the anticoincidence counters underneath, we will have to have about 1000 pictures in order to get one useful picture. Taking as usual 6 minutes for reconditioning the chamber, etc., there can be about 10 pictures taken per hour. Hence in this way it would take about 100 hours to obtain one useful picture instead of the above 20 hours. In the case of pure random expansion, the solid angle, through which the mesons enter the chamber and hit the foils unambiguously, may be larger than that in the above case by a factor of, say, as large as 20. Thus in this case one would expect one meson stopped per hour at one of the foils inside the chamber. To observe this stopped meson in a random manner, the chamber has to be expanded for a sufficiently large number of times until the total sensitive time is about one hour. Taking the sensitive time of each expansion as about 0.3 second, it requires then 12×10^3 pictures to yield one useful picture, which will take $(12\times10^3\times6)/60=1.2\times10^3$ hours. Therefore, it is practically impossible to perform such experiments by random expansion of the chamber.

Figure 2 shows the block diagram for the complete set-up of the electronics in the present experiment. Each of the eight preamplifiers is a

[15] H. P. Koenig, Phys. Rev. 69, 590 (1946).

single-stage cathode follower using 6C4 tubes. The outputs of the five preamplifiers for the anticoincidence counters are connected together through the crystals IN34 so that when one unit is operating the others will not be affected. The anticoincident counting tubes have been grouped into five (each group then has less than ten counters), and each group is connected to the input of a cathode follower. In this way, when one counter is responding to a particle, the others will be still ready to respond to a next one coming very close to the first. The first stage of each "coincidence amplifier" (and also the anticoincidence amplifier itself) is of a multivibrator type using 6AK5 tubes, which serves as a pulse sharpener. The last stages (c_1, c_2, and c_3) form the conventional Rossi coincidence circuit, also using 6AK5. The coincident and anticoincident pulses are then fed, respectively, to the two grids of the mixing tube 6L7.

All the time-delay units are of the multivibrator type; the relative time intervals are determined by the respective time constants CR. When a pulse passes through the gate, the various operations take place at prescribed time intervals. Meanwhile, the gate is closed to further incoming pulses. However, when the different operations are over, the gate is opened by a delayed pulse from the "time delay reset," and the apparatus is ready again for the next cycle of operation.

III. RESULTS AND DISCUSSION

A. Identification of the Particles

Before proceeding to discuss the individual cases where mesons stop and possible consequences arise, it may be desirable to describe briefly how to distinguish merely by ionization and range if a track is due to a proton, a meson, or an electron. It is not at all easy to distinguish by ionization the three types of tracks, if the energies of a proton, a meson, and an electron are, respectively, greater than about 100 Mev, 10 Mev, and 0.05 Mev. This is because of the fact that the ionization changes from a value, which is only about three times the minimum ionization (in air), to the minimum ionization (the latter being practically the same for all the three particles) as the energy increases from these limits. It is fortunate that here we are dealing with the three types of particles only near the end of their ranges, where ionization is different for different types of particles, and the variation of ionization along the range and ionization density are useful means to decide the nature of a particle. For example, the thickness of each Pb or Fe foil (plus 0.002-inch Al foils on both sides) used is about the range of a 15-Mev proton, a 5-Mev meson, or a 0.9-Mev electron. Having about 10 foils inside the cloud chamber, we are dealing approximately with protons of 0–50 Mev, mesons of 0–20 Mev, and electrons of 0–7 Mev. Assuming a particle stopped at the center of the thickness of a foil, we have calculated for a meson and a proton approximately the energy values at the successive gas spaces and also the approximate multiples of minimum ionization at the corresponding spaces. These are shown in Table I.

TABLE I. Variation of ionization at different gas (air) spaces (between 18/1000-inch Pb foils) assuming a particle stopped at the center of the thickness of a foil.

Meson		Proton	
Energy Mev	Multiples of minimum ionization		Energy Mev
12.5	2.9	8	32
11	3.2	9	27
9.3	3.8	11	23
6.7	4.8	15	16
2.5	10	24	8

Thus, when a proton stops at one of the foils, the track will appear heavy and somewhat uniform in the successive gas spaces or it may show a slight increase in ionization toward the end if the track is long enough. This is illustrated by an actual photograph shown in Fig. 3a (from film No. 19, Pb foils). This picture (the inclined picture here on the right is the stereoscopic view obtained from the mirror) shows a proton stopped at the sixth lead foil from the top. The first two top spaces were generally not well illuminated so that the portions of the track in these spaces appear faint. When an electron stops at a foil, the track will appear very thin (near minimum ionization) throughout the whole length, or at most show a sudden increase in ionization in the last gas space if it stops near the top surface of the foil. Figure 3b (from film No. 22, Pb foils) shows a track, which is identified as an electron, deflected to the right by the fifth foil and to the front by the sixth foil. Judged from the sudden increase in density of this last portion, the elec-

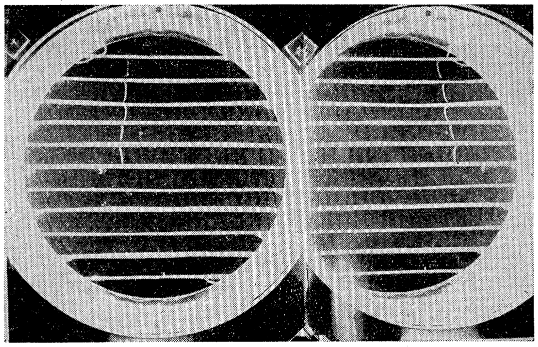

Fig. 3a. A proton stopped at the sixth foil (from film No. 19, 18/1000-inch Pb foils). Compare with the electron track in Fig. 3b and with the meson track in Fig. 4a.

tron must be quite near to the end of its range in the gas or the top surface of the last foil. When a meson stops, the track will have a gradual increase in density in the last two or three gas spaces (cf. Figs. 4a and 4b). It will have a more rapid increase in density in the last space if it stops near to the top surface of the foil (cf. Fig. 6a). Certainly, there are cases where the differences in ionization are not so distinct, and decision as to the nature of particles is not at all easy. Unequal saturation of the liquid mixture and non-uniform illumination in the different gas spaces may cause this difficulty. Whenever we have much doubt about the nature of some tracks, these tracks are not included in the statistics (cf. Table II). According to the above general method of differentiation, we have had fewer protons or electrons stopped than mesons stopped, each of the former approximately a little over one-fifth as numerous as the mesons.

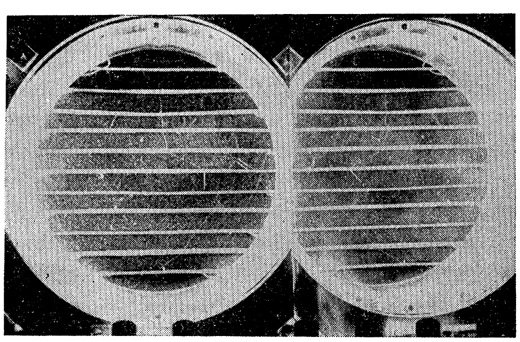

Fig. 3b. An electron near the end of its range (from film No. 22, 18/1000-inch Pb foils). Compare with the much heavier tracks in Figs. 3a and 4a.

The above general consideration also applies to the case of Al foils; however, in this case it is more difficult to identify the three types of particles because of too few thick foils—only three 32/1000 inch ones (plus the eight very thin ones)—and hence much smaller variation of ionization. Therefore, tracks of decaying mesons have been always used here as standards of ionization-variation for comparison to identify those mesons stopped at the foils without decaying (cf. Figs. 4c and 6b).

The degree of zigzag of a track due to multiple scattering, of course, also helps to distinguish these three types of particles.

B. Mesons Stopped; Nothing Observed at the End

Figures 4a, b, and c are three representatives (in different substances) out of over fifty pictures (besides those decaying ones—roughly an equal number in each element. Cf. Table II), each of which shows that a meson (presumably negative)[16] stops at a foil and no charged particle is seen to come out. Figure 4a (from film No. 17, Pb foils) shows, according to the above method of identification, that a meson comes down vertically and is deflected by the fourth foil to the left

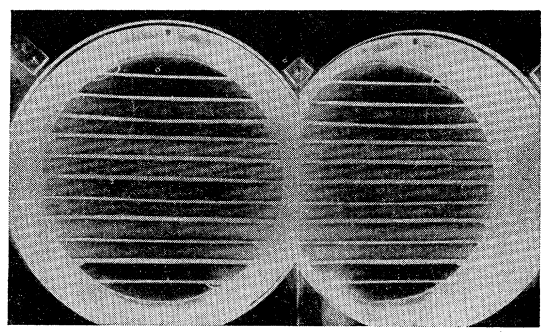

Fig. 4a. A meson stopped at the fifth Pb foil (from film No. 17, 18/1000-inch Pb foils). Presumably it is a negative meson, since no decay electron is observed. A 15-Mev proton could traverse the foil, but no heavy particle is seen here or in any other well defined case of a meson stopped in lead.

[16] Our criterion for identifying a stopped meson as negative is the following: when a meson is stopped at a foil and no decay electron is observed, it is thus considered as a negative meson (cf. Section III-E and Table II). Since in all these over 50 pictures no decay electrons are observed, these stopped mesons are therefore taken as negative mesons.

(see the direct picture on the left) and stopped at the fifth foil. It is almost in the plane of the cloud chamber and is well within the illuminated region too. Here no other track shows up at the end of the track. Figure 4b (from film No. 33, Fe foils) shows a stopped meson (here again nothing is observed to come out from the end) which has a longer path in the chamber. Thus, it provides a good example to show the variation of ionization in the different gas spaces. The variation of ionization is compatible with that given in Table I.

Pictures of the kind just discussed form the basis of our later conclusion that few if any protons are emitted with as much as 4 Mev when negative μ-mesons are captured in Fe and Pb.

In Fig. 4c (from film No. 37, Al foils) a nearly vertical meson track stops at the tenth Al foil, which has the thickness of 0.002 inch. It has been identified as a meson from the variation of ionization in the different gas spaces and also by comparison with the tracks of decaying mesons (cf. Fig. 6b), as mentioned above. Stereoscopic examination shows that it is nearly in the chamber plane and remains also in the well illuminated region. Here also no other track has been observed to come out from the point where the meson stops. It will be shown later that if, in the present experiments, a proton is emitted when a meson is captured by an Al nucleus, the energy of the proton must be smaller than 1.5 Mev in

TABLE II. Summary of results.

		I—Meson stopped: nothing observed		II—Meson decaying		III—Meson stopped: possible emission of a heavy charged particle		IV—Meson stopped: evidence of γ-ray from secondary electron track	
		A	*B*	*A*	*B*	*A*	*B*	*S*	*D*
I. Al foils Effective working period about 1040 hours	*Thin:*	3	1	1	1 (3)*	—	—	—	—
	Thick:	6	2	3	2 (8)*	—	—	—	—
II. Fe foils Effective working period about 640 hours		11	3	7	2 (15)*	—	—	1	—
III. Pb foils Effective working period about 930 hours		17	2	7	3 (17)*	—	1	1	6

Thickness of each Al foil—0.002 inch (8) and 0.032 inch (3)—used at the same time.
Thickness of each Fe foil—0.028 inch (11).
Thickness of each Pb foil—0.018 inch (11).
"*A*" means proper variation of ionization and in well illuminated region.
"*B*" means less certain but still good in the above two conditions.
"*S*" means electron track observed from the same foil where the meson stops.
"*D*" means electron track observed at some other foil in the picture of the stopped meson. Two out of six are pairs.

* These figures in parentheses represent roughly the numbers of decay electrons which would have been observed if the bottom anti-coincidence counters had not been used (see Section E).

order to remain within the foil. In this connection it may be interesting to mention a discussion by Piccioni[17] on the capture of negative mesons by nuclei.

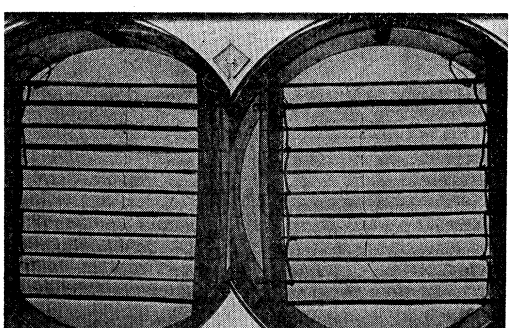

FIG. 4b. A meson stopped at the tenth Fe foil (from film No. 33, 28/1000-inch Fe foils). This is also one of many cases, as in Pb and Al, where a meson stops, but neither decay electron nor heavy charged particle is seen to be emitted.

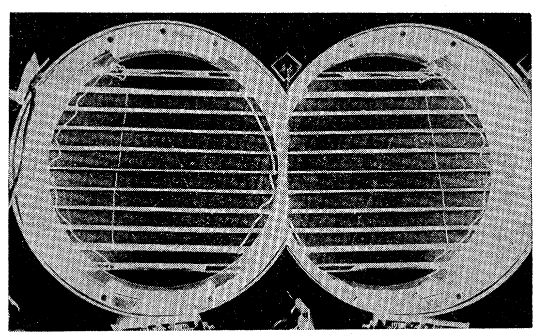

FIG. 4c. A meson stopped at the tenth *2/1000-Al foil* (from film No. 37, 2/1000-inch (8) and 32/1000-inch (3) Al foils). The identification is made from the variation of ionization by comparison with the tracks of decaying mesons. Here again no decay electron or heavy charged particle is observed at the place where the meson stops

[17] O. Piccioni, Phys. Rev. 73, 411 (1948).

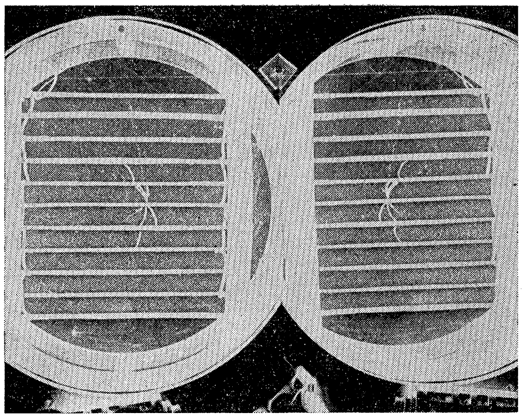

FIG. 5a. A star of six particles, probably produced by a fast proton, at the sixth Fe foil (from film No. 31, 28/1000-inch Fe foils). Total kinetic energy of the particles is about 90 Mev (as estimated from the ranges), if they are protons.

C. Possible Emission of a Heavy Charged Particle from a Stopped Negative Meson

So far we have obtained only five pictures with tracks clearly or fairly clearly identifiable as due to nuclear disintegration, two being connected with stars and the others with single heavy charged particles. Only one (of a single heavy charged particle) of these may be interpreted as nuclear disintegration by a stopped negative meson. However, even this one is not too certain, because the event occurs too near to the edge of the cloud chamber. Two of these pictures will be presented here.

Figure 5a (from film No. 31, Fe foils) shows a star of six particles, which has been produced at the central Fe foil. It is not clear whether this star is produced at the Fe foil (more likely) or at the Al foil which covers the Fe foil (cf. Section II). If the star particles are protons, the total kinetic energy associated with this star is of the order of 90 Mev. A thin and nearly vertical track, which is almost in the chamber plane, appears to meet the star at its origin. One might attempt to interpret this star as one produced by a negative meson after it is captured by a nucleus. The main difficulty in this interpretation is, however, obviously that the last portion as seen of the long track does not have large enough ionization density to indicate the end of a meson range. This fact is obtained especially from that little part (of one or two grains) between two of the star particles (see the direct picture). If it is a meson, its energy must be over 20 Mev just before it is stopped, as estimated from the ionization density. In this respect, this star can at least equally well be interpreted as one produced by a fast proton. The energy of the particle must be over 150 Mev, if it is a proton, as judged from the ionization density of the last portion of the track. Indeed, as far as energy is concerned, this latter interpretation is much more compatible with the total energy involved (total kinetic energy plus total binding energy of the six particles emitted) in the star production.

Figure 5b (from film No. 14, Pb foils) is the only case which may be interpreted as a nuclear disintegration produced by a stopped negative meson. The track on the left-hand side (in the direct picture) is probably a meson track near the end of its range and stopped at the third foil. The heavy track on the right-hand side is associated with delta-rays and is therefore very probably a proton track. Since stereoscopic examination shows that these two tracks actually meet at the same point, the picture may be interpreted as a nuclear disintegration by a stopped negative meson with the emission of a proton (possibly from an Al nucleus of the 0.002-inch Al foil covering the Pb foil. Cf. Sections D and G). The proton track is either scattered out of illumination or stopped at the second foil. Unfortunately, this event has occurred too near to the top of the chamber. This has made it difficult to see how the ionization of the tracks varies.

D. Discussion of the Stopped Negative Mesons

One might naturally expect a heavy charged particle (or more than one), say a proton, to be emitted when a negative meson is captured by a nucleus, because the rest energy of the meson is about 100 Mev. Besides the relatively less certain case as mentioned above, we have not been able to obtain such evidence in any other case (cf. Table II, columns I and IV), where n meson (presumably negative as mentioned ia III-B) appears to stop at a foil. Each foil has a finite thickness corresponding to about the range of a 15-Mev proton in the case of Pb and Fe, and to the range of a 2.2-Mev proton in the case of Al. A proton (if any) of lower energy will have a small chance to come out of the foil. Knowing the range of a proton of given energy in the foil, and supposing the disintegration event taking place at a given point inside the foil, one can estimate the average solid angle and hence the probability that a proton of that given energy can come out of the foil. In this way (for Fe or Pb plus the 2-mil Al) we get about 0.5 for the probability that a proton of 15 Mev will come out of the foil—about 0.2 for a proton of 7 Mev, and about 0.07 for a proton of 4 Mev. For Al the probability for a 2-Mev proton to come out of the thinner foil is about 0.5. The statistics of our present results (see figures in columns I, III, and IV, Table II) therefore indicate that, if on the average one proton were emitted per stopped negative μ-meson, *in both Fe and Pb the proton must have an energy smaller than about 4 Mev and in Al an energy smaller than 1.5 Mev, in order to remain within the thin foils.* In other words, only a small fraction of the total energy available ($\mu c^2 \sim 100$ Mev) would be carried away by a proton as its kinetic energy after coming out of the nucleus. (Similarly, we have estimated that the probability that a decay electron of 50 or 25 Mev will come out of the foil is practically unity.) However, from Pb, with a nuclear potential barrier of about 10 Mev,[18] a proton with an energy lower than 4 Mev must have negligible probability to escape from the barrier. Therefore, one comes to the conclusion that *no protons were emitted when the 27 negative μ-mesons interacted with Pb nuclei.* The same conclusion may be drawn for Fe and Al (nuclear potential barriers for a proton are, respectively, about 5 and 3 Mev). However, in these two cases the number of pictures obtained is smaller. The proof that no protons are ejected from these two elements is not so definite.

The results of our present experiment for Pb therefore indicate that *only a small part of the negative μ-meson's rest energy ($\sim$100 Mev) is imparted to the nucleus and that the remaining part must go off as neutral, non-electromagnetic radiation, to escape cloud-chamber observation.* Specifically, this last conclusion is reached from the experimental fact that so far *we have not observed high energy photons.* If photons of about or over 20 Mev were emitted when negative μ-mesons interacted with the Pb nuclei, they would be easily absorbed by the Pb foils because of the large total absorption coefficient of Pb for such high energy gamma-rays. As a consequence, of the 27 pictures of stopped negative mesons in Pb, a large fraction (more than ten) would contain meson-oriented electron pairs with long tracks (compare with Section F). But *no such electron pairs have been observed in the pictures of stopped negative mesons (also of the decaying mesons) in Pb, Fe, or Al.* This is in agreement with the result of Piccioni's counter experiment[19] for Fe. As a matter of fact, so far we have not observed in Pb, Fe, or Al any meson-oriented electron pair which can be attributed to a photon of an energy over 10 Mev emitted from the stopped negative μ-meson or from the decaying mesons.

A much smaller portion of the negative μ-meson's rest energy may be given off in the form of gamma-rays due to possible low nuclear excitation after interaction with the meson. We have observed eight low energy electron tracks which are oriented to the place where the negative meson stops and which are believed to be associated genetically with the stopped negative meson (see Section F).

E. Mesons Decaying

Figures 6a and 6b are two typical pictures out of more than 25 pictures actually observed (cf. Table II) which indicate mesons decaying. Figure 6a (from film No. 10, Fe foils and two half-

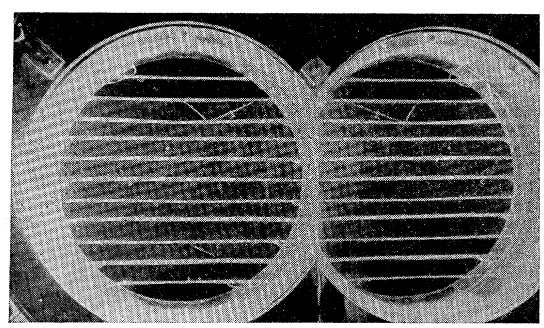

FIG. 5b. Possibly a nuclear proton ejected by a stopped negative meson (from film No. 14, 18/1000-inch Pb foils). The proton might possibly have come out of an Al nucleus of the 2/1000-inch Al foil, which covers the Pb foil (cf. Section II).

[18] H. A. Bethe, Rev. Mod. Phys. 9, 166 (1937).

[19] O. Piccioni, Phys. Rev. 74, 1236 (1948); Phys. Rev. 74, 1754 (1948).

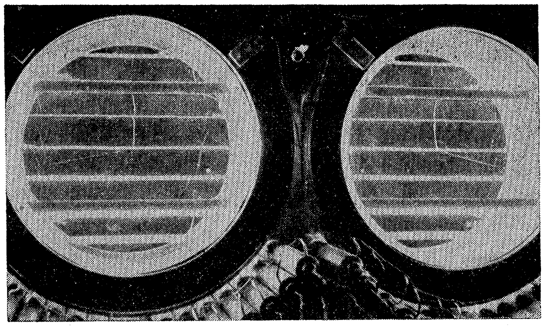

FIG. 6a. A meson decaying at the central Fe foil with emission of the decay electron to the left on the direct picture (from film No. 10, 28/1000-inch Fe foils).

inch-thick Pb plates) shows a vertical meson track stopped at the central Fe foil. The meson might have stopped near the top surface of the foil, as the density of the last portion of the track looks fairly high. A much thinner track emerges from the point, where the thick track ends, and moves below the Fe foil to the left (slightly toward the front). It is presumably a decay electron. Its end is not illuminated, and so nothing can be said about its energy. In Fig. 6b (from film No. 36, Al foils) a meson stops at the central foil, which has a thickness of 0.032 inch. It is seen that the ionization of the track does not vary very much in the different gas spaces because of the small thickness of the foils. However, it looks definitely thinner than a proton track. Tracks of this type have been used for reference to identify mesons stopped without giving out anything (cf. picture 4c). The decay electron as seen is emitted to the left and moving upwards. It is finally out of the chamber after passing through two 0.002-inch foils. All the other pictures of this type are similar to these two—the decay electron tracks look fairly straight and ends out of illumination—no estimate is possible for the electron energy from the range. In all the cases only one electron track is observed when a meson stops and decays at a foil.

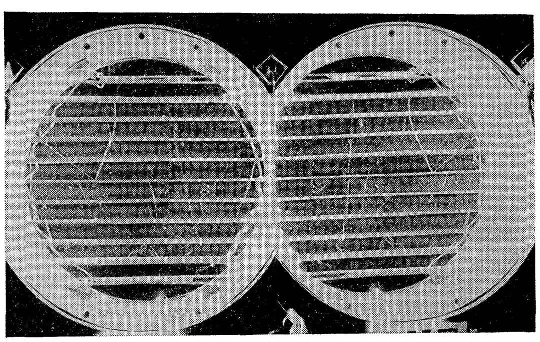

FIG. 6b. A meson decaying at the central Al (32/1000-inch) foil (from film No. 36, 2/1000-inch (8) and 32/1000-inch (3) Al foils). The decay electron is emitted upwards to the left in the direct picture.

We have so far observed fewer decaying mesons than stopped negative mesons in each of the elements Al, Fe, and Pb (cf. Table II). This discrepancy with the well-known approximate equality of abundance of positives and negatives must be chiefly due to the fact that the lower circumference of the cloud chamber has been surrounded with the anticoincidence counters. If a decay electron passes through one of the anticoincidence counters, the chamber will not expand, and hence the decay event will not be observed.[20] We have roughly estimated the solid angle subtended by these anticoincidence counters as $\frac{2}{5}$ of the total solid angle. Hence what we have observed in each element represents roughly only $\frac{3}{5}$, and the total numbers would have been then the observed figures, respectively, multiplied by $\frac{5}{3}$ if the anticoincidence counters had not been used. These are the numbers in the parentheses in Table II. The difference between these numbers so deduced and those to be expected is comparable with the statistical fluctuation, if one allows for the rough estimate of the above solid angle and the small number of pictures so far obtained.

F. Evidence of Low Energy (1–5 Mev) Gamma-Rays from Stopped Negative Mesons

Figure 7 (from film No. 15, Pb foils) is one of eight cases which give evidence for gamma-ray emission associated with the stopping of a negative meson. The long track stops at the last foil. The density of ionization increases, going downward to the end.[21] It is difficult to assign this

[20] The arrangement is therefore biased toward low energy decay electrons because of the anticoincidence counters underneath. So far we have not observed any decay electrons which move in a direction to any one of the anticoincidence counters. Decay electrons emitted in these directions must have a range greater than the thickness of the chamber (about 8 mm) and counter (about 1 mm) walls in order to trip the counters.

[21] The first and last (one or two) gas spaces in general have not been so well illuminated as the intermediate spaces. Therefore, the portion of a track in these spaces

track to any particle other than a meson. Meeting this track at its termination is a much lighter track which appears to stop at the fourth foil from the bottom. Since the ionization under the fourth foil from the bottom looks larger than that under the lower ones, the light particle is interpreted to be moving upwards. Stereoscopic examination shows that the end of this shorter track is inclined to the chamber plane but that it remains in the well illuminated region. If it is an electron, its energy, as estimated from its range in the foils, lies between about 2 and 5 Mev, a value much smaller than one would usually expect for a decay electron. We have a similar picture in the case of Fe (in film No. 30, Fe foils). Here the light particle is emitted in such a direction that it would have passed one of the bottom anticoincidence counters if it were not stopped at the foil. If it is an electron, its energy is of the same order of magnitude as that in Fig. 7. This case is not as clear as that in Fig. 7 because the chamber seemed to have been underexpanded in this case.

If we assume in either case that it is a decay electron having originally an energy of about 25 Mev[22] and dropping to 5 Mev by radiation process in the foils (much thinner than a radiation unit), the probability for such a loss in Pb (smaller for Fe) is estimated to be only about 0.2 percent. Consequently, it is much more reasonable to conclude that the electron was emitted originally with an energy of 5 Mev or less.

The low energy tracks in the above two pictures can be satisfactorily interpreted as Compton recoil or photoelectron tracks, which are ejected by photons connected with the nuclear interaction of the μ^- mesons (cf. following section). Granting this general mechanism, we have made an estimate, for Pb, of the probability that a 5-Mev photon of this origin be absorbed at the same foil (i.e., practically at the same point), where the μ^- meson is stopped, and hence a secondary electron be emitted. Assuming two high energy ($\sim$2–5-Mev) photons from one stopped negative meson (which seems to be reasonable), and taking 24 g/cm^2 as the mean free path of the 5-Mev photon and $\frac{1}{2}$ g/cm^2 as the average path traversed, one would expect one secondary electron emitted at the same foil from a total of about 24 stopped negative mesons. This is about what we have observed in the case of Pb (cf. Table II). Of course, the statistics are so low that it is hard to draw the conclusion definitely, yet the consideration given above offers so far the most satisfactory explanation of the two pictures (see Section G).

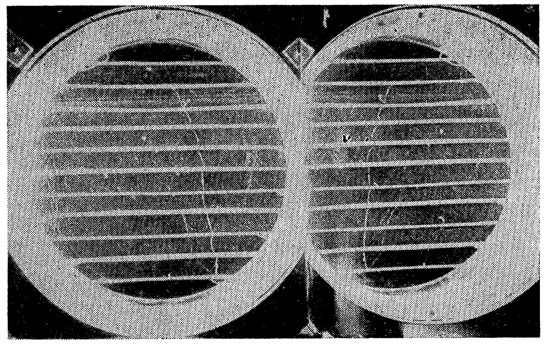

FIG. 7. The short and thin track is probably a secondary electron ejected by the radiation given off when the stopped meson (the longer and thicker track) made a transition between its quantum levels in the nuclear field or by the radiation from the nucleus slightly excited by the meson (from film No. 15, 18/1000-inch Pb foils). The energy is between 2 and 5 Mev, and is unreasonably small for a decay electron (see text and description of Fig. 9).

Besides the two cases of low energy electrons ejected from the same foil in which the meson is stopped, there are six cases of meson-oriented, low energy electron tracks ejected from neighforing foils. All six events are comprised among the 27 cases of negative mesons stopped in lead (cf. Table II). These events cannot be due to chance, but have to be interpreted as due to gamma-rays associated with the nuclear reaction of negative mesons, as will be seen from a closer examination of the observations.

Four of the six pictures mentioned above are single electron tracks, and the other two are pairs. One of these single tracks has a range covering two successive gas spaces and hence must have an energy between 2 and 3 Mev. The other three single tracks are short, lying only in a single gas space, but they do not seem to show much multiple scattering; their energy is not more than 2 Mev, and probably not very small in

will appear fainter than it really should be. In Fig. 7 the portions of the two tracks in the second gas space from the last should really have had higher density of ionization than they look, if illumination was the same as for the intermediate spaces.

[22] Anderson, Adams, Lloyd, and Rau, Phys. Rev. 72, 724 (1947).

comparison with 2 Mev. Figure 8 (from film No. 29, 0.018-inch Pb foils) shows one of these cases. A track identified as a meson stops at the seventh foil. It is inclined toward the front glass window of the chamber but is in the well illuminated region. In the gas space between the third and the fourth foils there is a short and thin track. This track is inclined in such a direction that it will meet the end point of the first track if it is prolonged. It is very probably a photoelectron track. The components of the two pairs have a range similar to that of the last three single tracks, lying only in a single gas space. Our statistics, though very low still, of these secondary electron tracks seem to be generally compatible with gamma-rays of energies between 1 and 5 Mev.

In general, a secondary electron produced by a high energy photon[23] has, as its direction of preference, the direction of the photon. Therefore, if a secondary electron is genetically associated with a stopped negative μ-meson, its track when prolonged must most probably meet the point where the meson stops. The chance for observing such a photoelectron at some neighboring foil in the chamber must be larger than at the same foil where the negative μ-meson stops. In the same way as before, we have estimated a figure of 4/24 for the total probability of observing such an event at any one Pb foil. The average path traversed has been estimated, in this case, as about 2 g/cm^2 of lead. It is seen that this expected probability, 4/24, is not incomparable with the observed one, 7/27.

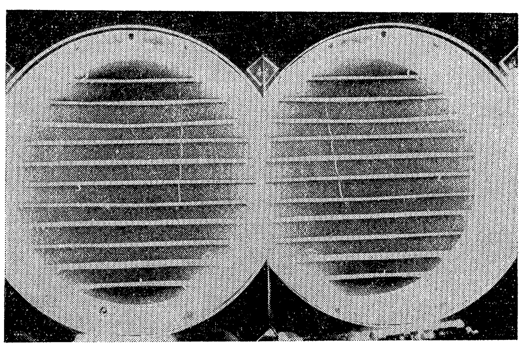

FIG. 8. The short and thin track in the gas space between the third and fourth foils is ascribed to an electron with energy probably a little below 2 Mev. It is reasonably interpreted as a photoelectron or Compton recoil electron, ejected by the radiation from the place where the long track, presumably a meson, appears to stop. The short track when prolonged meets the end of the long one in both stereoscopic projections. The number of such short, meson-oriented electron tracks is too large to be due to chance (see text). Some of the photons concerned may possibly have resulted also from nuclear excitation due to "nuclear capture" of the negative mesons (see text) (from film No. 29, 18/1000-inch Pb foils).

Low energy electron tracks are usually seen in cloud-chamber pictures. These electrons are presumably due to the photons in the cosmic rays. It is of interest to find the probability that such an electron track points accidentally toward or away from the end of the stopped negative μ-meson track. This can be estimated from (1) the average number of such slow electron tracks (of same age as the stopped meson track) per cloud-chamber picture, which is about one in our case, and (2) the uncertainty in the direction measurement of the track, which is at most $\pm 10°$. Thus, the total solid angle within which the track lies is $2\times\pi\times(10/57.3)^2$. The probability that such a stray electron track be mistaken as a secondary electron actually associated with the stopped negative μ-meson is $2\pi(10/57.3)^2/4\pi \sim 1/70$. This is about 6 percent of the number of cases which we have obtained.

It therefore seems to us that those electron tracks observed in our experiment are ejected by photons emitted from the stopped negative μ-meson. Since the number of such cases observed is still small, experiments have been planned with improved conditions for the study of these gamma-rays. We hope that more results will give better quantitative correlation between such secondary electrons and the stopped negative μ-mesons.

G. Discussion of the 1–5-Mev Gamma-Rays

Two sources of the above 1–5-Mev gamma-radiation have to be considered: the first, extra-nuclear; the second, nuclear. The total energy release expected on trapping of a negative μ-meson in the K-orbit of lead is calculated to be about 9.0 Mev.[24] Part of this energy will be released to atomic electrons via Auger processes in the initial stages of the trapping process.[25] As the meson transits towards orbits of lower quantum number

[23] W. Heitler, *The Quantum Theory of Radiation*, Second Edition (Oxford University Press, London, 1944), pp. 123, 156, 198.

[24] J. A. Wheeler, Rev. Mod. Phys. **21**, 133 (1949).

[25] E. Fermi and E. Teller, Phys. Rev. **72**, 399 (1947).

in an atom as heavy as lead, however, the mechanism of loss of energy via radiation will very soon surpass in importance the losses to electrons. Consequently, most of the 9 Mev will appear as radiation. Specifically, most of the mesons will make the $2p \rightarrow 1s$ jump, liberating a photon of about 4.4 Mev, and probably the majority of the particles will also make the $3d \rightarrow 2p$ transition, giving off a 2.6-Mev gamma-ray in the process. Thus, on the average it will be reasonable to expect in the neighborhood of 2 photons of extranuclear origin in the 1–5-Mev energy region per negative μ-meson stopped in lead.

The additional process of nuclear gamma-ray emission will provide the only means for the nucleus to dispose of excess energy insufficient for the evaporation of nucleons. Tiomno and Wheeler have discussed[26] the excitation of the nucleus to be expected in the so-called meson charge-exchange reaction,

$$\mu^- + P \rightarrow N + \mu_0.$$

They show that the energy transfer to the nucleus is in general less than 20 Mev. In the particular case of Pb^{208} (52.3 percent abundance), 5.0 Mev of this amount is required merely to change the charge by one unit to Tl^{208} ($=ThC''$),[27] leaving at most 15 Mev for nuclear excitation. The further energy required to evaporate a neutron[28] is about 5 Mev. Proton emission requires not only a heat of evaporation of this order but also roughly 10 Mev more to surmount the Coulomb barrier, so that such an emission process has negligible probability compared to neutron liberation. This is in agreement with our cloud-chamber observation, which gives, as mentioned before, no evidence (except one) of a proton track emitted at the place where a negative meson stops. Considering the curves of Tiomno and Wheeler for probability of any given energy transfer, and taking into account the fact that the neutron will ordinarily come off with less than 3 Mev of kinetic energy, and further allowing for the rare possibility that two neutrons may come off, one can easily show that after neutron emission can no longer proceed the residual nucleus is left with any excitation from zero Mev to the neutron evaporation energy, with comparable probability. Thus we conclude that the average excitation to be dissipated via nuclear gamma radiation will be of the order of 3–5 Mev (probably often distributed over more than one gamma-ray).[29]

TABLE III. Comparison of results for Al, Fe, and Pb (after reducing conditions to that for Pb).

	I—Meson stopped: nothing observed	II—Meson decaying	III—Meson stopped: possible emission of a heavy particle	IV—Meson stopped: evidence of γ-ray from secondary electron track	V—Total
I. Al foils	22	22	—	—	44
II. Fe foils	18	19	—	1	38
III. Pb foils	19	17	1	7	44

Thus in conclusion we may make the tentative estimate: approximately two extra nuclear gamma-rays, and one nuclear gamma-ray, in the 1–5-Mev interval, are emitted per stopped negative μ-meson. This prediction seems to account well for the observations.

IV. GENERAL DISCUSSION. THE STATISTICS

The results so far obtained are summarized in Table II, according to the types of events discussed above. In each case the tracks are classified

TABLE IV. Observed rates of absorption compared with expectations.

Element	Effective g/cm² used	Koenig's g/cm² to stop one percent	Observed averaged No. of mesons per hr. into chamber	Effective working period (hours)	Total No. of stopped mesons observed	Observed rate of absorption number/hour	Expected rate of absorption number/hour
Al	0.7	22.4	85	1040	23	1/45	1.2/45
Fe	3.5	24.1	45	640	30	1/21	1.3/21
Pb	4	30.6	45	930	44	1/21	1.2/21

[26] J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. **21**, 144 (1949).
[27] C. D. Ellis, International Conference on Physics, London (1934).
[28] For attempts to detect neutrons from Pb and for preliminary results, see Sard, Ittner, A. M. Conforto, and M. F. Crouch, Phys. Rev. **74**, 97 (1948); also G. Groetzinger and G. W. McClure, Phys. Rev. **74**, 341 (1948).
[29] H. A. Bethe, Rev. Mod. Phys. **9**, 220 (1937).

into A and B. An "A" track means that the track has a proper variation of ionization (cf. Section III-A) and remains in a well illuminated region. A "B" track means that the above two conditions for the track are less certain but still good enough to identify the track. The working period for Al was about 1040 hours, while for Fe it was about 640 hours, and for Pb about 930 hours. These are effective working periods (see below). In order to compare the results of Al, Fe, and Pb, we have reduced the experimental conditions for Al and Fe approximately to that for Pb, i.e., to: (1) the same solid angle of the telescope; (2) the same amount of material per cm^2 in the chamber; (3) the same stopping power as if Al and Fe had the same atomic number as Pb (cf. Table IV, column 3); and (4) the same working period. These results are put in Table III. Allowing for the low statistics and the roughness of the comparison, one can say that Fe, Al, and Pb would have stopped the same number of mesons under comparable conditions.

We have measured once in a while the total number of mesons going through the coincidence telescope into the cloud chamber, by switching off the bottom anticoincidence counters. These are the figures in column 4 of Table IV, and are in general agreement with those calculated from the solid angles of the telescope used in the different elements and the recent value[30] of the meson intensity at sea level. For the amount of each element actually used, we have calculated the rate of meson absorption from the above figure and the other quantities in Table IV. These are in the last column of the table and are roughly compatible with the observed rates (from columns 5 and 6) in the different substances. It is seen that the observed rates are all smaller than the expected ones. We have discarded as proton tracks about 20 percent of the stopped negative meson tracks—undoubtedly too high a proportion. This overestimate, together with the statistical fluctuation and the error in the estimate of the solid angle for detecting decay electrons, may well account for the above difference between the observed and expected rates of meson absorption.

The time spent by the foggy pictures, blank pictures, and pictures with broken emulsion has not been taken in evaluating the working periods. The number of these pictures is approximately 15 percent of the total number of pictures. The working periods given in the above tables are therefore the effective working periods, being thus about 85 percent of the total working periods in the different cases.

In conclusion I should like to express my gratitude to Professor J. A. Wheeler for his continued interest and stimulating discussion in this work. Thanks are also due Mr. D. B. Davis and his staff for their invaluable help in building the cloud chamber and the control units, etc., to Miss H. Maginnis for filling the counters, to Dr. T. Coor for his help in building the constant temperature room, and to Dr. R. R. Rau for frequent discussion of the cloud-chamber pictures.

[30] B. Rossi, Rev. Mod. Phys. 20, 537 (1948).

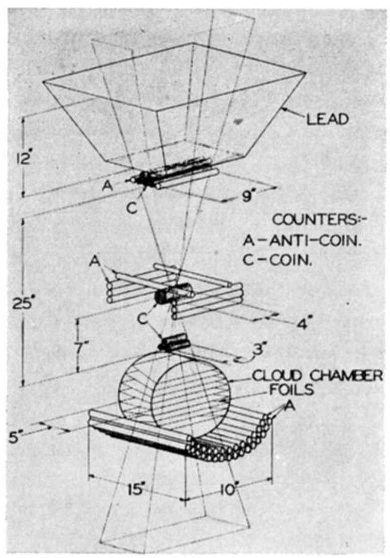

FIG. 1. Meson absorption experiment—apparatus.

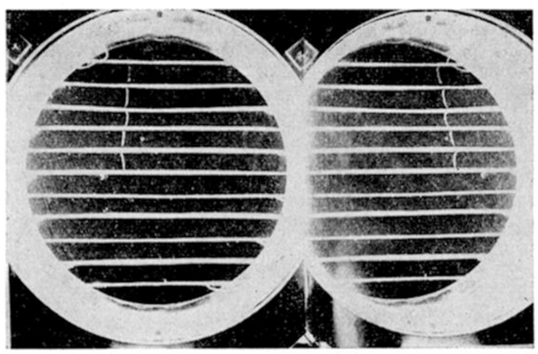

FIG. 3a. A proton stopped at the sixth foil (from film No. 19, 18/1000-inch Pb foils). Compare with the electron track in Fig. 3b and with the meson track in Fig. 4a.

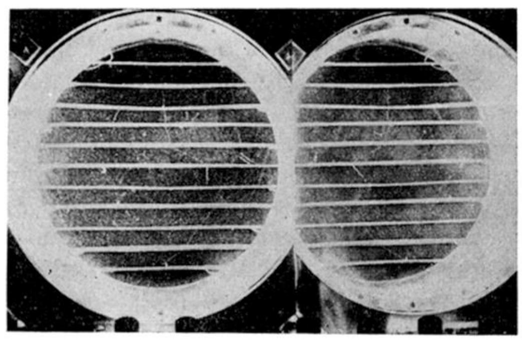

FIG. 3b. An electron near the end of its range (from film No. 22, 18/1000-inch Pb foils). Compare with the much heavier tracks in Figs. 3a and 4a.

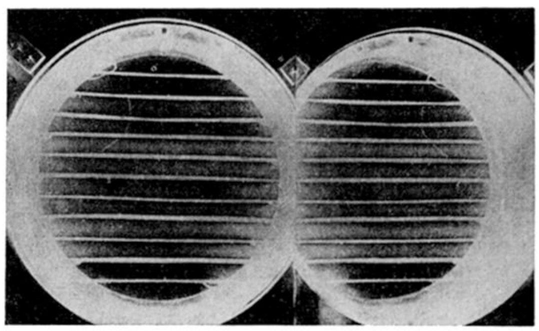

FIG. 4a. A meson stopped at the fifth Pb foil (from film No. 17, 18/1000-inch Pb foils). Presumably it is a negative meson, since no decay electron is observed. A 15-Mev proton could traverse the foil, but no heavy particle is seen here or in any other well defined case of a meson stopped in lead.

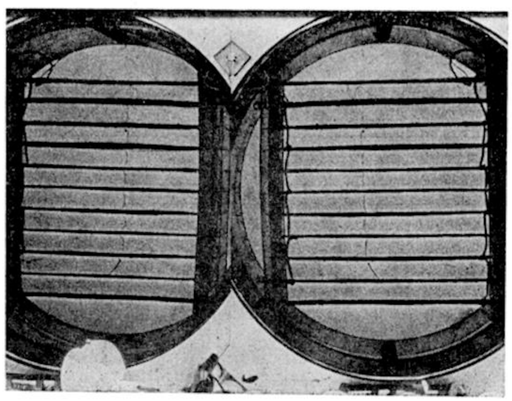

FIG. 4b. A meson stopped at the tenth Fe foil (from film No. 33, 28/1000-inch Fe foils). This is also one of many cases, as in Pb and Al, where a meson stops, but neither decay electron nor heavy charged particle is seen to be emitted.

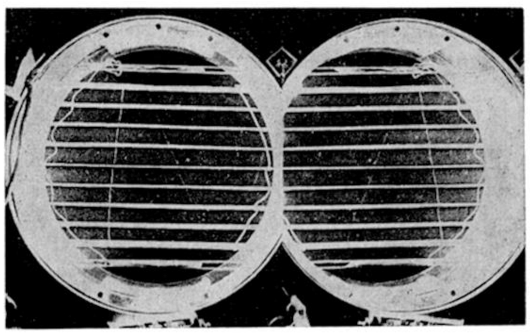

FIG. 4c. A meson stopped at the tenth *2/1000-Al foil* (from film No. 37, 2/1000-inch (8) and 32/1000-inch (3) Al foils). The identification is made from the variation of ionization by comparison with the tracks of decaying mesons. Here again no decay electron or heavy charged particle is observed at the place where the meson stops

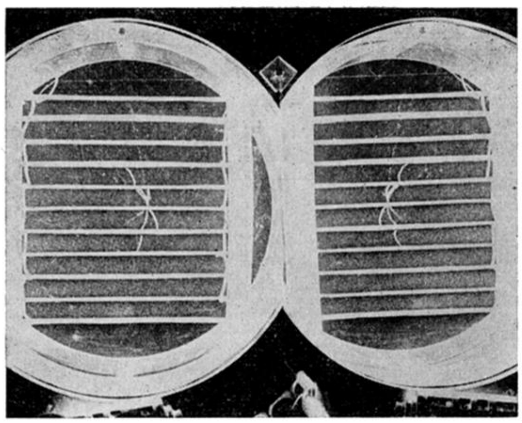

FIG. 5a. A star of six particles, probably produced by a fast proton, at the sixth Fe foil (from film No. 31, 28/1000-inch Fe foils). Total kinetic energy of the particles is about 90 Mev (as estimated from the ranges), if they are protons.

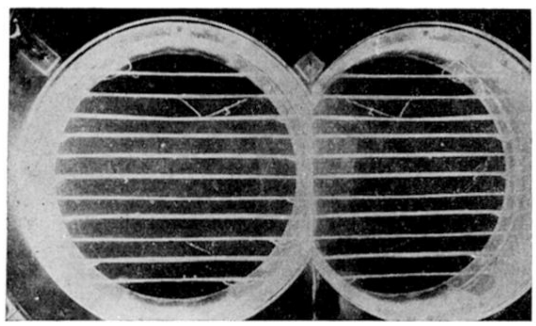

FIG. 5b. Possibly a nuclear proton ejected by a stopped negative meson (from film No. 14, 18/1000-inch Pb foils). The proton might possibly have come out of an Al nucleus of the 2/1000-inch Al foil, which covers the Pb foil (cf. Section II).

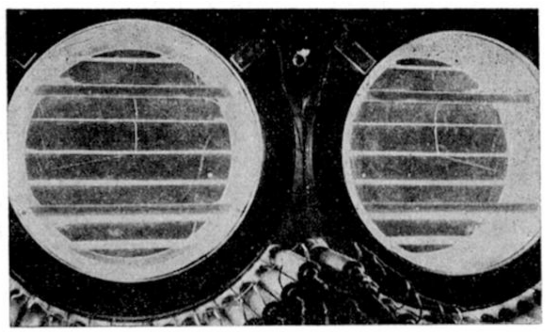

FIG. 6a. A meson decaying at the central Fe foil with emission of the decay electron to the left on the direct picture (from film No. 10, 28/1000-inch Fe foils).

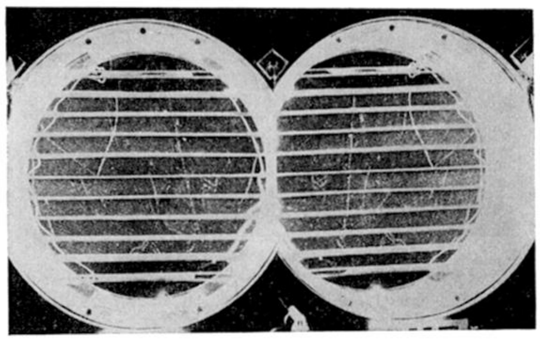

FIG. 6b. A meson decaying at the central Al (32/1000-inch) foil (from film No. 36, 2/1000-inch (8) and 32/1000-inch (3) Al foils). The decay electron is emitted upwards to the left in the direct picture.

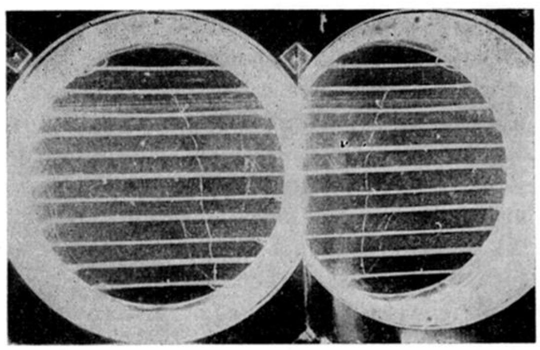

FIG. 7. The short and thin track is probably a secondary electron ejected by the radiation given off when the stopped meson (the longer and thicker track) made a transition between its quantum levels in the nuclear field or by the radiation from the nucleus slightly excited by the meson (from film No. 15, 18/1000-inch Pb foils). The energy is between 2 and 5 Mev, and is unreasonably small for a decay electron (see text and description of Fig. 9).

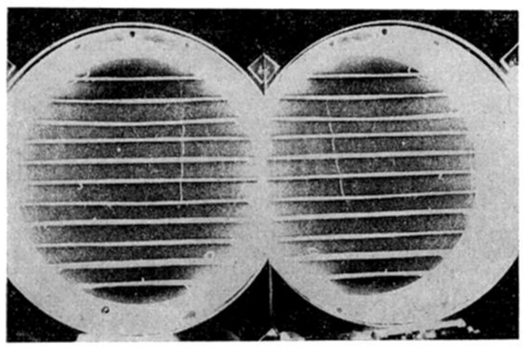

FIG. 8. The short and thin track in the gas space between the third and fourth foils is ascribed to an electron with energy probably a little below 2 Mev. It is reasonably interpreted as a photoelectron or Compton recoil electron, ejected by the radiation from the place where the long track, presumably a meson, appears to stop. The short track when prolonged meets the end of the long one in both stereoscopic projections. The number of such short, meson-oriented electron tracks is too large to be due to chance (see text). Some of the photons concerned may possibly have resulted also from nuclear excitation due to "nuclear capture" of the negative mesons (see text) (from film No. 29, 18/1000-inch Pb foils).