Sea-Level Mesons Stopped in Thin Pb and Al Foils. I. Possible Emission of Charged Nuclear Particles and Related Events

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Further cloud-chamber experiments are described on the stopping of sea-level mesons in thin foils of Pb (5 of 0.009 and 6 of 0.018 inch) and Al (8 of 0.004 and 3 of 0.032 inch). Eighty-one negative μ mesons are seen to stop in the Pb foils (50 in the thick foils and 31 in the thin ones). *Only two cases show some evidence of slow proton or alpha emission,* as indicated by a heavy dot at the end of the stopped negative meson. In the case of Al, there are 36 negative mesons stopped, 12 and 24 in the thin and thick foils, respectively. None of these cases gives any observable evidence of a nuclear event at the place where the negative meson stops. From these statistics, upper limits have been estimated for the probability of nuclear ejection of protons and alpha particles of different energies. It is thus found that, to be ejected from a Pb nucleus with reasonable probability, a proton must have an energy between 3 and 12 Mev, in agreement with the emulsion results of other workers. For Al, since no nuclear event has been observed, it is concluded that the maximum probability of nuclear ejection must be less than 10 percent for a proton of an energy in the above range. An alpha particle in this energy range is improbably emitted from either an Al or a Pb nucleus. As in the previous experiments, no long-track and narrow-angle electron pairs have been observed in either Pb or Al which can be attributed to high-energy photons over 15 Mev emitted from the stopped negative μ meson (or decaying meson). Thus we find no high-energy gamma rays and evidence for the rarity of even low-energy nuclear events. Consequently we draw the same conclusions as in earlier less extensive experiments: that following the nuclear interaction *only a small part of the μ meson's rest energy is imparted to the nucleus*, and that the remaining part must go off as neutral, nonelectromagnetic radiation, to escape observation in the cloud chamber.

Altogether, 87 decaying mesons have been actually found from the two (previous and present) series of experiments. None of the decay electrons has been seen to move toward any one of the anticoincidence counters below the chamber. From this fact, the solid angle covered by the anticoincidence counters, and the absorbing material above the counters, one argues that the proportion of μ-decay electrons with energy smaller than 10 Mev is of the order of 1 in 60 or less.

I. INTRODUCTION

IN our previous communications,[1] cloud-chamber experiments were described on the absorption of slow μ mesons by thin foils of Al (0.002 and 0.032 inch), Fe (0.028 inch), and Pb (0.018 inch). Continuous operation of the chamber for an effective period of over 2600 hours showed the following: (1) No protons were observed for the 53 negative μ mesons stopped at the Pb, Fe, and Al foils (except one doubtful case from Pb). (2) No long-track and narrow-angle electron pairs of total energy, say, over 15 Mev, were observed from these elements which could be due to high-energy photons associated with the stopped negative μ mesons (or with the decaying mesons). Such photons would have been easily observed in the chamber because of the large absorption coefficient, particularly of Pb, for such high-energy gamma rays. Therefore, we were led to the following conclusions: (1) only a small portion of the rest energy ($\sim$100 Mev) of the stopped negative μ meson is imported to the nucleus and (2) the remaining portion must come off as neutral, nonelectromagnetic radiation, in order to escape observation in the cloud chamber.

Besides, evidence of low-energy gamma rays (1–5 Mev) was obtained from the observation of the meson-oriented electrons and pairs from Pb and Fe. They were "meson-oriented" in the sense that the single electron track or apex of the pair made an angle less than $\pm 20°$ with the imaginary line running back to the end point where the meson was stopped. Stray tracks were shown unable to account for these events. The energy and frequency of occurrence of these electrons were compatible with those predicted in Wheeler's theory[2] of meson transitions between the Bohr orbits before μ-meson capture and with those expected after capture due to de-excitation of the transformed nucleus. No evidence of such gamma rays was found for Al.

Since these results were reported, our experimental conditions have been somewhat improved in the hope that more definite and detailed information could be gained about the results mentioned above, particularly better statistics about the low-energy (1–5 Mev) photons associated with the stopped negative meson. Subsequent experiments with Al and Pb were completed in 1949 at Princeton. Part of the cloud-chamber pictures were examined also at Princeton, and the results were partly analyzed there and briefly reported on several occasions.[3] The examination of the pictures and analysis of the results were continued at Purdue and recently completed. They will be reported now in a more detailed and systematic manner. As will be seen, these new results substantially support all the previous results and conclusions.

It may be noted that similar findings to those obtained in these experiments have also been reported later by other workers, using μ mesons from both cosmic

[1] W. Y. Chang, Phys. Rev. **74**, 1236 (1948); Revs. Modern Phys. **21**, 166 (1949).

[2] J. A. Wheeler, Revs. Modern Phys. **21**, 133 (1949).

[3] W. Y. Chang, Phys. Rev. **76**, 170 (1949); Princeton Biennial Report, 1 July 1947–30 June 1949 (unpublished); Proceedings of the Echo Lake Cosmic-Ray Symposium (sponsored by U. S. Office of Naval Research and the U. S. Atomic Energy Comsion), 23–28 June 1949 (unpublished); Phys. Rev. **79**, 205 (1950).

TABLE I. Summary of results for μ-mesons stopped in Pb foils. A μ-o-e means a meson-oriented electron seen at another foil; similarly for μ-o-pair. Figures in each column give number of mesons stopped at a thick or thin foil. An A track means that the track has a proper variation of ionization and remains in a well-illuminated region. A B track means that the above two conditions for the track are less certain but are still good enough to identify the track.

Effective working period ~1500 hours	I. Meson stopped; nothing seen from the end		II. Meson stopped; μ-o-e or μ-o-pair seen at other foil		III. Meson stopped; a heavy dot from the end	IV. Meson stopped; a thin curved short track from the end	V. Meson decay	
	A	B	A	B			A	B
Thick Pb foils: (6×0.018 inch)	26	10	8[a] (+1)[b]	3[c]	1	2[e]	19 (45)[f]	8
Thin Pb foils: (5×0.009 inch)	16	6	5[d]	1	1[e]	1	10[e] (25)[f]	5

[a] One stopped meson track has 2 μ-o-e's. Three have a μ-o-pair each.
[b] This particular event is classified with the μ-o-e and μ-o-pair events because a secondary electron emerges at the end of the stopped negative meson track, moves upward through 2 foils, and suffers multiple scattering twice near the end (see Fig. 1 of Part II); energy is ~5 Mev.
[c] One has a μ-o-pair.
[d] One has both a μ-o-pair and a μ-o-e.
[e] One in each group has a μ-o-e from a thick foil. The one associated with the decaying meson (column V) may be due to either a photon from the decay positron, i.e., bremsstrahlung produced in the same foil where the positive meson undergoes decay, or a stray electron.
[f] Figures in parentheses represent roughly the numbers of decaying mesons, which would have been observed, had the bottom anticoincidence counters not been used.

rays and high-energy machines. These will be mentioned in the sections concerning the results and their analysis.

For convenience of discussion, the results related with the possible emission of charged nuclear particles will be analyzed and discussed in this paper (to be called Part I), and the results for the low-energy gamma rays will be reported in Part II, a separate paper to follow.[4]

II. EXPERIMENTAL ARRANGEMENT

The apparatus and the experimental setup were practically the same as before,[1] except that the depth of the cloud chamber was increased from 5 inches to 8 inches and the solid angle of the defining counter telescope was increased accordingly. The number of mesons entering the chamber via the telescope was found to increase to about 150 per hour, being approximately 2 to 3 times larger than that in the previous cases (see Table II of the following paper). The details concerning the electronic controls and the construction of the cloud chamber used have been published elsewhere.[5]

Two series of experiments were carried out, one with thin Pb foils and the other with thin Al foils. In the experiments with the Pb foils, five 0.009-inch foils (half the thickness in the previous experiments)[1] alternated with six 0.018-inch foils inside the chamber. They were not covered with any thinner foils of Al or other material. With the thinner Pb foils, one would have a larger chance to observe low-energy protons (if any) emitted by the Pb nuclei after capturing negative μ mesons. Also, more detail might be revealed of the μ-meson-oriented electrons and pairs. The length of the electron tracks in the gas would be longer because of smaller absorption in the foils and the direction of the tracks could be better determined because of smaller multiple scattering in the foils. The absence of the 0.002-inch reflecting Al foils used in previous experiments removed a slight ambiguity as to which material gave rise to the events.

In the experiments with Al foils, eight 0.004-inch and three 0.032-inch foils were symmetrically placed inside the chamber. This arrangement was the same as in the previous experiments except that here the thinner foils were twice as thick as before. As before, the three 0.032-inch foils served only to identify the stopped particles. Using eight thicker foils, we hoped to increase (1) the statistics of the stopped mesons which were rather small in the previous experiments, and (2) the chance of observing the μ-meson-oriented electrons and pairs which were not found before.

The same techniques as used before were employed here also to identify the particles stopped at the foils, i.e., the variation of ionization in the different gas spaces supplemented by the multiple scattering in the foils and knock-on electrons in the gas.

[4] W. Y. Chang, following paper, Phys. Rev. **95**, 1288 (1954).
[5] W. Y. Chang and J. R. Winckler, Rev. Sci. Instr. **20**, 276 (1949).

III. RESULTS AND DISCUSSION

About 7500 pictures were taken in an effective working period of about 1500 hours in the experiment with Pb, and about 6000 pictures in about 1400 hours in the case of Al, the different types of results being presented in Tables I and II. In the following, these different kinds of results will be discussed briefly and conclusions will be compared with those reached in the previous experiments. As mentioned before, the results

TABLE II. Summary of results for μ mesons stopped in Al foils.

Effective working period ~1400 hours	I. Meson stopped; nothing seen from the end[a]		II. Meson stopped; μ-e decay	
	A	B	A	B
Thick Al foils: (3×0.032 inch)	18	6	11 (23)[b]	3
Thin Al foils: (8×0.004 inch)	9	3	4 (9)[b]	1

[a] A and B are used to indicate the quality of the cloud chamber pictures. For definitions see Table I.
[b] The figures in parentheses represent the numbers of decay positrons (some of them perhaps are decay electrons) corrected roughly for those excluded by the anticoincidence counters.

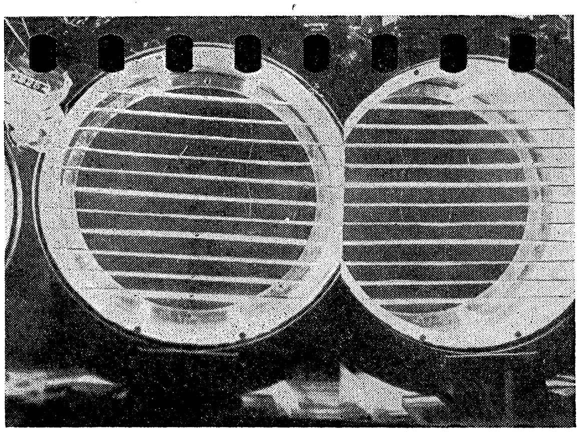

FIG. 1. A μ meson stops in the seventh Pb foil (0.018 inch). It undergoes decay with the decay electron moving upward to the top of the chamber. Neither of the two "stray" tracks is of the same age. See Fig. 2. (The thin and long line in the stereoscopic picture is due to a scratch in the negative.)

for the low-energy gamma rays will be presented in a separate paper (see reference 4).

1. Mesons Decaying at the Foils

Figures 1 and 2 are two typical μ-decay pictures out of a number of cases where a slow meson undergoes radioactive decay in a Pb or Al foil. In Fig. 1 the meson stops and decays in the seventh Pb foil (0.018 inch), while in Fig. 2 the event takes place in the ninth Al foil (0.032 inch). In both cases (like many others), the decay electrons (thinner tracks) move approximately upwards, for the reasons discussed below. The variation in ionization of these decaying meson tracks serves as a very reliable standard of reference to identify those other mesons which stop in the foils and give rise to nothing observable at their end points.

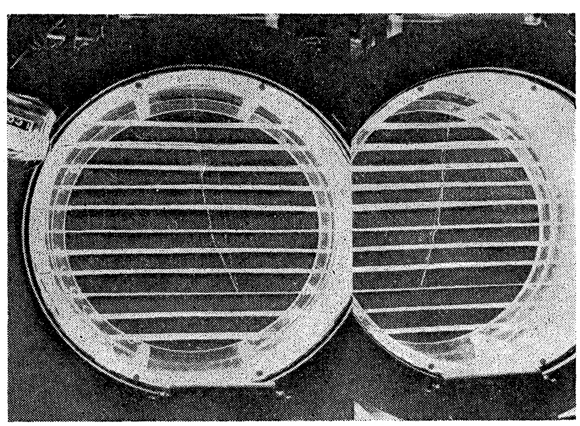

FIG. 2. A μ meson stops in the ninth Al foil (0.032 inch) with the decay electron moving to the chamber top. The variation of ionization of decaying mesons such as this is usually taken as a reliable standard of reference for identifying mesons stopped in Al or Pb foils without decay. (See Fig. 1.)

The numbers of mesons decaying in the Pb and Al foils are shown in the last columns of Tables I and II, respectively. It is seen that in each element fewer decaying mesons have actually been observed than the stopped negative mesons. This was noticed also in our first experiments and was then and is now, too, due to the fact that the bottom circumference of the cloud chamber has been surrounded with the anticoincidence counters which have covered roughly $\frac{2}{5}$ of the entire solid angle and thus have excluded those decay electrons moving into this solid angle. This is evidenced by the fact that in all of the μ-decay pictures none of the 87 decay-electron tracks, observed in both the previous and present experiments, is seen directed toward any one of the anticoincidence counters below the chamber.

The figures in parentheses are the values corrected by this solid angle factor and hence represent roughly the numbers of decay electrons which would have been actually observed had the bottom anticoincidence counters not been used. These figures are now closer to those of the stopped negative μ mesons; the difference is comparable with the statistical fluctuation if allowance is made for the rough estimate of the above solid angle.

As just mentioned above, none of the 87 decay electrons is seen to move toward any one of the anticoincidence counters below the chamber. This fact may be taken as a basis for obtaining information about the proportion of the low-energy μ-decay electrons: The chamber and counter walls, etc., are estimated to be about 5 g/cm^2 thick (Cu equivalent), corresponding roughly to the range of a 10-Mev electron. The geometrical disposition of the anticoincidence counters as discussed above shows that approximately $0.4\times 87/(1-0.4)\sim 60$ decay electrons moving toward the anticoincidence counters would have been observed if their energy were smaller than 10 Mev. Therefore, one may argue that the proportion of μ-decay electrons with energies smaller than 10 Mev is of the order of 1 in 60 or less. This proportion of the low-energy ($\sim$10 Mev) delay electrons deduced from our experiments is in approximate agreement with the extrapolated portion of the experimental curves.[6]

2. Meson Stopped; Nothing Seen at the End

Figures 3 and 4 are two representative pictures out of many pictures which do not show any observable charged particle coming out from the end of the stopped negative μ mesons. In Fig. 3 a μ meson is stopped at the fifth Pb foil (0.018 inch) and nothing is seen at its end. Figure 4 is a similar picture showing a μ meson stopped at the sixth Pb foil (0.009 inch) again without anything accompanying its end; a thinner track

[6] Leighton, Anderson, and Seriff, Phys. Rev. **75**, 1432 (1949); Sagane, Gardner, and Hubbard, Phys. Rev. **82**, 557 (1951); H. Bramson and W. W. Havens, Phys. Rev. **83**, 861 (1951); Bramson, Selfert, and Havens, Phys. Rev. **88**, 304 (1952); R. W. Williams, Phys. Rev. (to be published).

appears in the gas space between the eighth and ninth foils and is obviously a much younger track.

In the case of Pb foils, we have actually observed a total of 123 stopped mesons as shown in Table I. Seventy-six of these, as seen in columns 1 and 2 (48 from the 0.018-inch foils, and 28 from the 0.009-inch foils), do not appear to give rise to any observable[7] particle from the place of the foils where they stopped. This number (plus those in columns 3 and 4) which do not decay is approximately equal to the number of mesons which do decay at the foils after correction for those excluded by the anticoincidence counters below the cloud chamber, as shown in the last column of the table. Therefore, these 76 (+5) mesons are regarded as negative μ mesons. The failure to observe any proton emitted except the two possible cases in column 3, when a negative μ meson is captured by a Pb nucleus, is exactly what was found in our first experiments,[1] where no proton was observed from 27 negative μ mesons stopped at 0.018-inch Pb foils. Of course, in the present experiments, the statistics are more than twice as good and the data give information about foils having half the previous thickness, i.e., only 0.009 inch.

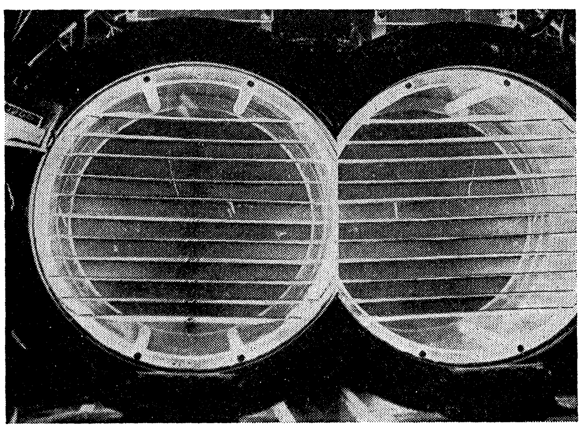

FIG. 3. A μ meson stops in the fifth Pb foil (0.018 inch). No charged particle is observed to come out from the end. The thickness of the foil is about the range of an 11-Mev proton. It is a picture of quality *A* (see Table I for definition), without being accompanied by any tracks of the same age.

It may be noted that soon after the report of our first results,[1] Wang and Jones[8] also announced similar negative results for much thicker foils, i.e., 0.032-inch Al and 0.25-inch Pb.

In the Al foils (Table II), altogether 55 μ mesons have been found to stop. Of these, 36 (24 from the 0.032-inch foils and 12 from the 0.004-inch foils) do not emit any observable particle from the end of their range. Since this number is roughly equal to the corrected number of mesons decaying in the Al foils, the 36 mesons are reasonably regarded as negative μ mesons stopped in the foils as in the case of Pb. The absence of proton emission in the nuclear capture of a negative μ meson by Al checks our first experiments.

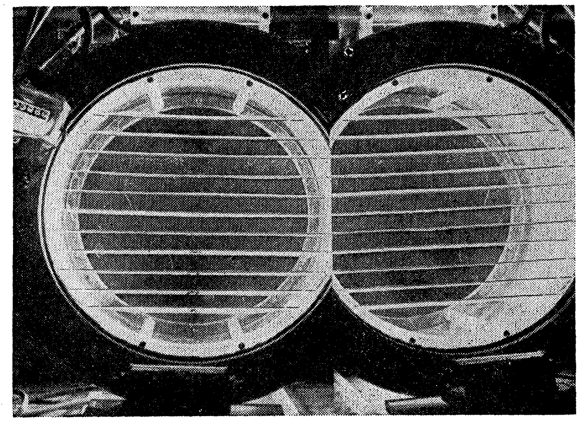

FIG. 4. A μ meson stops in the sixth Pb foil (0.009 inch). No observable charged particle is emitted from the end, though the foil thickness is only about the range of a 5-Mev proton. None of the few "stray" tracks has the same age.

3. Possible Emission of a Heavy Charged Particle. Discussion of the Stopped Negative μ Meson

So far, we have found only two cases (and these only in Pb) where a very slow, heavily ionizing particle could be emitted after the nuclear capture of a negative μ meson. These are shown in column 3 of Table I. The identification in each of the two cases cannot be entirely certain, for the heavy dot does not extend far in the gas space from the end of the stopped meson. However, it seems reasonable to attribute the heavy dot to the short track of a proton or alpha particle of extremely

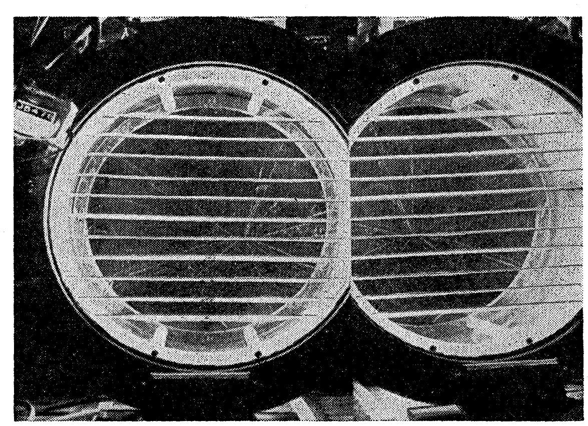

FIG. 5. A star of more than 15 particles produced in the seventh Pb foil (0.018 inch). Total kinetic energy involved is probably larger than 400 Mev, if the star particles are protons. It is very probably produced by a fast proton, or a locally produced fast π meson.

[7] Except one, which has been attributed to an electron of approximately 5 Mev ejected by a photon from the stopped negative μ meson. See reference b of Table I and Fig. 1 of the following paper (reference 4).

[8] K. C. Wang and S. B. Jones, Phys. Rev. 74, 1547 (1948).

TABLE III. Heavy-particle emission probability. The observed rate of events which admit interpretation as heavy particles is considered to be the product of the probability that the heavy particle will escape from the foil and the probability that the heavy particle will be emitted from the nucleus. The first factor is calculated. From its value and from the observed rate is then deduced an estimate or upper limit for the probability for heavy particle emission from the nucleus. In the calculation it is assumed that the probability distribution of the point at which the meson stops is uniform from top to bottom of the foil. Energy values lower than those listed in the table are not considered because the probability of barrier penetration would then seem negligibly small.

Material and foil thickness	Observed probability for μ^- to produce event interpretable as ejection of heavily ionizing particle	Conceivable interpretation of particle	Conceivable energy in Mev	Range[a] in g/cm²	Calculated probability to be seen if emitted	Upper limit to probability of nuclear ejections deduced from experiments
Pb 0.018 inch 0.51 g/cm²	1/50	Proton	12	0.51	0.4	0.05
			5.5	0.13	0.15	0.1
			3.7	0.07	0.06	0.3
		Alpha	10	$\sim 30\times10^{-3}$	0.02	(∼1)
			5	$\sim 10\times10^{-3}$	0.005	(∼4)
Pb 0.009 inch 0.26 g/cm²	1/31	Proton	8	0.26	0.4	0.08
			3.7	0.07	0.15	0.2
		Alpha	10	$\sim 30\times10^{-3}$	0.06	(∼0.5)
			5	$\sim 10\times10^{-3}$	0.01	(∼3)
Al 0.032 inch 0.22 g/cm²	<1/24	Proton	11.5	0.22	0.4	< 0.1
			5.5	0.055	0.15	< 0.3
			3.5	0.027	0.06	< 0.7
		Alpha	5	$\sim 4\times10^{-3}$		
			1.5	$\sim 1\times10^{-3}$		
Al 0.004 inch 0.027 g/cm²	<1/12	Proton	3.5	0.027	0.4	< 0.2
			1.5	6.5×10^{-3}	0.15	< 0.6
			1.0	3.3×10^{-3}	0.06	<(1.4)
		Alpha	5	$\sim 4\times10^{-3}$		
			1.5	$\sim 1\times10^{-3}$		

Emulsion results of	Proton energy	% of stopped μ^- mesons
George and Evans[b]	1–10 Mev	8.7±1.7
Fry[c]	1–10 Mev With max. int. at ∼5 Mev	∼5

[a] E. Segrè, *Experimental Nuclear Physics* (John Wiley and Sons, Inc., New York, 1953), Vol. I.
[b] See reference 9.
[c] See reference 10.

low energy. It should be noted that George and Evans[9] and also Fry,[10] using the emulsion technique, have also recently found a small percentage of stopped negative μ mesons which give rise to a low-energy proton.

Figure 5 shows one of a few cases so far obtained of nuclear events where several nuclear particles have been observed, but none of these cases can be positively identified as due to nuclear capture of a negative μ meson. In this picture, where the event occurs in the seventh Pb foil (0.018 inch), there are more than 15 particles in the star that are presumably protons. The initiating particle may be the one near the vertical, but its nature cannot be decided because of the uniformity of its ionization which is near minimum. The total kinetic energy involved in the star is probably larger than 400 Mev, and the event is very probably produced by a fast proton or π meson.

If a proton just escaping from the nucleus had too small an energy, it would be absorbed by the foil which has a finite thickness. Hence, no proton track could be observed in the chamber at the end of the negative μ meson range. One may estimate the range and the average solid angle and hence the probability that a proton of a given energy can come out of the foil, as indicated in Table III. For the convenience of calculation, the values for the foil-penetration probability as given in column 6 are calculated by assuming the initial proton energy (just escaping from the nucleus) to have a range equal to the foil thickness, about $\frac{1}{4}$ and about $\frac{1}{8}$ of the foil thickness, respectively. For an alpha particle, they are estimated from the ranges of the given energies (see column 4). The figures for the nuclear-emission probability as shown in the last column are obtained by dividing the observed possible rates in column 2 by the above probabilities. They represent the experimental upper limits to the probability of nuclear ejection corresponding to the different *initial* energies in column 4.

In the case of the thick Pb foils, if the one nuclear event observed is a proton of an energy between 5 Mev

[9] E. P. George and J. Evans, Proc. Phys. Soc. (London) **A64**, 193 (1951).
[10] W. F. Fry, Phys. Rev. **85**, 677 (1952); **91**, 481 (1953); H. Movinnaga and W. Fry, Nuovo cimento **10**, 308 (1953).

TABLE IV. Number of electron pairs expected if 15-Mev photons were emitted at the point where the meson stops. The photons are assumed to emerge in random directions, one photon from each stopped μ meson. The experiments show the *absence* of such electron pairs.

Material	Equivalent[a] number of spherical shells of foil system	Total effective path in g/cm²	Mean-free-path in g/cm² of 15-Mev photon	Number of stopped μ mesons not decaying	Number of stopped μ mesons decaying	Number of electron pairs expected from 15-Mev photons if emitted from: Those not decaying	Those decaying
Pb foils	~3-thin (0.78 g/cm²) ~3.5-thick (1.79 g/cm²)	2.57	14	81	42	15	8

[a] The figures given here are estimated only approximately from (1) the solid angle of the foil system to intercept the photons and (2) the effectively traversed path in the foils corrected for the secθ effect, where θ is the angle made with the vertical by the assumed photon, both (1) and (2) being averaged over different points in the chamber.

and 12 Mev (very probably it is), its probability of escaping the nuclear barrier, as seen from the last column, is between 10 and 5 percent. This percentage for the ejection probability seems reasonable theoretically, because a proton needs only roughly 10 Mev to surmount the Coulomb barrier of the Tl^{208} nucleus. Also, it is consistent with the emulsion results of George and Evans[9] and Fry,[10] as can be seen from the bottom table of Table III (of course in the latter case one has to allow too for certain absorption by the grains of the emulsion). Similar considerations show that it is much less probable that the event represents a proton of 3 Mev or less because of the unreasonably large barrier transmission probability for this energy, and that for the same reason it cannot represent an alpha particle of 5 or 10 Mev. Similarly, the event obtained from the thin Pb foil is very probably a proton of an energy between 4 and 8 Mev and it is very improbable that it is an alpha particle of 5–10 Mev. If the blobs observed in Pb were alpha particles of, say, 10 Mev, the probability of escaping nuclear barrier as deduced from the experiment would be 50 or 100 percent. This value is impossibly large when one remembers the potential barrier of Tl^{208} for an alpha particle. In fact, experimentally these blobs do not seem to have sufficient ionization to be very slow alpha particles.

So far no nuclear event has been observed in association with the μ^- mesons stopped at Al foils, and consequently no definite upper limit can be deduced from our experiments for the nuclear-ejection probability. It seems a little surprising that Al shows no nuclear event. The potential barrier of Mg^{27} (about 3 Mev) for a proton is much smaller than that of Tl^{208} and is also much smaller than the neutron binding energy in Mg^{27}. For this reason one would expect proton emission with probability comparable with that of the neutron emission, the latter being actually observed from Pb.[11]

[11] M. F. Crouch and R. D. Sard, Phys. Rev. **85**, 120 (1952), and earlier papers of Sard and co-workers.

4. Absence of High-Energy Photons

In the present experiments, as in the previous ones, we have not observed in Pb or Al any meson-oriented electron pair which can be attributed to a photon of energy greater than 15 Mev emitted from the stopped negative μ meson (or from the decaying mesons). If high-energy photons were actually emitted in these cases, we should have observed many pictures showing long and narrow-angle electron pairs associated directionally with the stopped μ mesons, because of the large absorption coefficient of the foils, particularly of Pb, for such high-energy photons. In Table IV, we have made some estimates to see how many high-energy electron pairs would have been actually observed in our present Pb esperiments, if high-energy photons were emitted from the stopped μ mesons. Both the efficiency of detection and the probability of conversion into pairs have been approximately allowed for. Only one such photon is assumed to be emitted (in a random direction) from each stopped μ meson. It is seen that we should have observed about 23 such long and narrow-angle pairs in our experiments, and more if the assumed photons had energy higher than 15 Mev.

The absence of high-energy photons and the rare evidence of only two possible low-energy nuclear events lead us to the same conclusions as found before that *the negative μ meson*, when captured by a nucleus, *only imparts a small fraction of its rest energy* (~100 Mev) *to the nucleus* and that *the remaining portion must go off as neutral, nonelectromagnetic radiation* in order to escape cloud-chamber observation. A theoretical account of this result has been given by Tiomno and Wheeler,[12] in terms of the charge exchange reaction $\mu^- + p \rightarrow n + \nu$. Our results are consistent with the theoretical predictions.

[12] J. Tiomno and J. A. Wheeler, Revs. Modern Phys. **21**, 153 (1949).

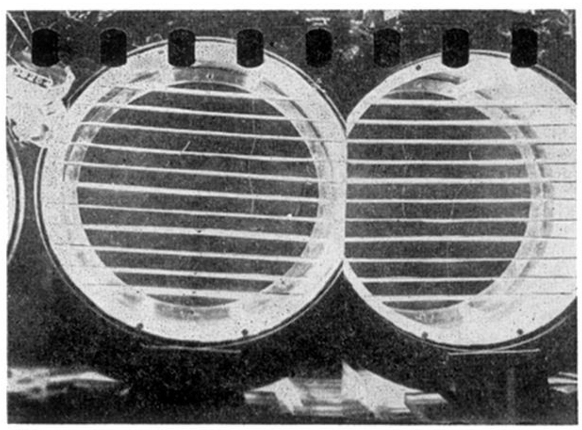

FIG. 1. A μ meson stops in the seventh Pb foil (0.018 inch). It undergoes decay with the decay electron moving upward to the top of the chamber. Neither of the two "stray" tracks is of the same age. See Fig. 2. (The thin and long line in the stereoscopic picture is due to a scratch in the negative.)

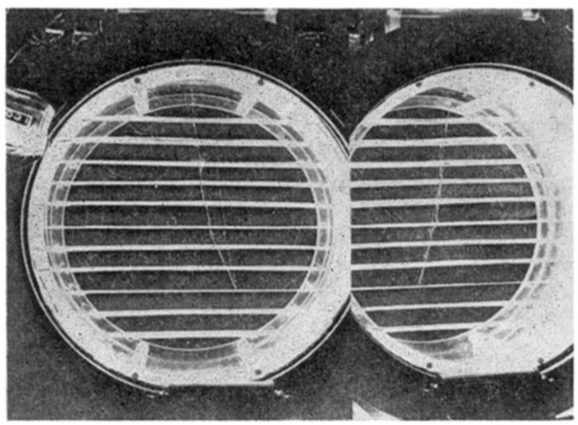

FIG. 2. A μ meson stops in the ninth Al foil (0.032 inch) with the decay electron moving to the chamber top. The variation of ionization of decaying mesons such as this is usually taken as a reliable standard of reference for identifying mesons stopped in Al or Pb foils without decay. (See Fig. 1.)

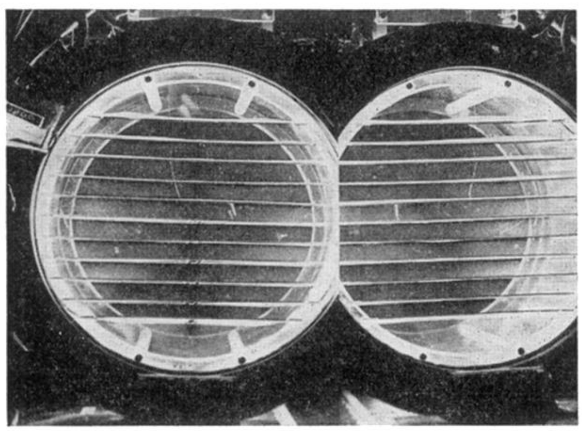

FIG. 3. A μ meson stops in the fifth Pb foil (0.018 inch). No charged particle is observed to come out from the end. The thickness of the foil is about the range of an 11-Mev proton. It is a picture of quality A (see Table I for definition), without being accompanied by any tracks of the same age.

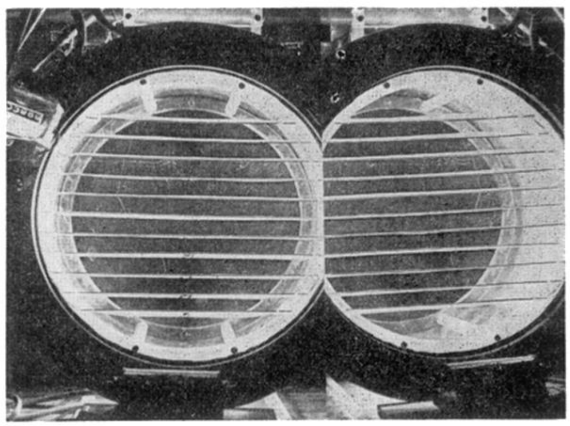

Fig. 4. A μ meson stops in the sixth Pb foil (0.009 inch). No observable charged particle is emitted from the end, though the foil thickness is only about the range of a 5-Mev proton. None of the few "stray" tracks has the same age.

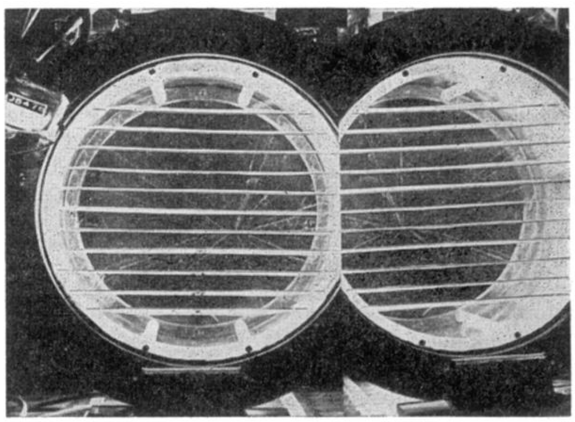

FIG. 5. A star of more than 15 particles produced in the seventh Pb foil (0.018 inch). Total kinetic energy involved is probably larger than 400 Mev, if the star particles are protons. It is very probably produced by a fast proton, or a locally produced fast π meson.