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Sea-Level Mesons Stopped in Thin Pb and Al Foils. II. Low-Energy (1–5 Mev) Gamma Rays

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Low-energy gamma rays (1–5 Mev) associated with the stopped negative μ mesons, similar to those reported before, have been observed also in these experiments. Twenty-five meson-oriented electrons and pairs have been found in Pb associated with 23 of the 81 stopped negative μ mesons. They are "meson-oriented" in the sense that the single electron track (or apex of the pair) makes an angle less than $\pm 20°$ with the imaginary line running back to the end point where the meson is stopped. None of such events has been obtained from Al. Of the 25 directed events, 4 are single electrons emitted directly from the end point of the stopped negative μ mesons, one being fairly energetic and the other three rather slow. The other 21 are single electrons and pairs observed in each case at a foil different from that where the meson stops and are meson-oriented in the above sense. The reality of this angular correlation follows from the fact that the 81 photographs of negative mesons stopped in Pb show only 6 electron tracks which make an angle of $90° \pm 20°$ with the line back to the end point of the meson track (6/21 as many tracks for 6 times as much solid angle). An independent determination of the rate of the strays was made by examining a film of 575 pictures to see how many tracks point by chance toward or away from an arbitrary point in the chamber with a 20° tolerance. From both ways of counting accidentals it is concluded that, of the 21 meson oriented events, at most about $\frac{1}{3}$ can be explained as stray tracks. A crude analysis of the electron range in the Pb foils indicates that the majority of the "oriented electrons" and "oriented pairs" may be interpreted as having an energy of about 5 Mev and the rest an energy probably below 3 Mev. The multiplicity of the photons producing these electrons has also been estimated, after a correction has been made for the multiple scattering of the electrons in the first foil, where they are emitted, so as to include all the electrons other than those counted within the cone ($\pm 20°$) in the forward direction of the photons. *The value for the multiplicity obtained is about 4·5* per negative meson stopped. The energy and frequency of occurrence of these photons are thus consistent with that predicted in Wheeler's theory of meson transition between the Bohr orbits and with that expected from nuclear de-excitation following the μ-meson capture.

I. INTRODUCTION

In Part I, the preceding paper,[1] we have reported 81 and 36 negative μ mesons stopped respectively in thin Pb and Al foils. These events were obtained from continuous operation of a cloud chamber for an effective period of nearly 3000 hours. Only two pictures for Pb show some evidence of slow proton emission, and none has been found for Al. Moreover, no energetic electron pairs have been observed in either Pb or Al which can be attributed to high-energy photons of, say, over 15 Mev emitted from the stopped negative meson (or decaying meson). Therefore, we have concluded there as well as in our first reports[2] that following capture by a nucleus, the negative μ meson imparts only a small portion of its rest energy to the nucleus and that the remaining part must go off as neutral, nonelectromagnetic radiation, in order to escape observation in the cloud chamber.

In the present paper (Part II), we should like to discuss in some detail the low-energy (1–5 Mev) photons associated with the stopped negative μ mesons, for which much better statistics have been obtained now than in our first experiments.[2] Twenty-five single electrons and pairs have been found in Pb associated with 23 of the 81 stopped negative μ mesons, and none has been observed for Al. These electrons and pairs are lined up with a tolerance of $\pm 20°$ with the point at which the μ meson stops and hence will be called "oriented electrons" and "oriented pairs," respectively. In Sec. II we shall discuss the energies of these electrons and pairs, the chance coincidence of the stray tracks, the origins of the gamma rays responsible for the oriented electrons and pairs, and the mean multiplicity of the photons.

In Sec. III, the absolute rate of stopping of mesons is calculated for both Pb and Al in the present and previous[2] experiments. The results are compared with that of other workers in order to get a supplementary check that the experimental setup was in correct operation.

II. RESULTS AND DISCUSSION

All the data for the low-energy photons have been necessarily presented together with the stopped mesons in Table I of Part I, the preceding paper.[1] Since there is no satisfactory way to separate these data and show them here, we shall have to, when it is necessary, refer to this table of Part I in the following discussions.

Coming from the Pb foils are 20 meson-oriented electrons and pairs (see column II, Table I in Part I) with energy estimated ranging from 1 to 5 Mev similar to those found and discussed in our first experiments.[2] Their tracks are of the same age as the stopped meson tracks and are found pointing toward the end points of the stopped mesons within a cone of half-angle $\sim 20°$ as examined from both the direct and stereoscopic pictures. Thirteen are associated with twelve negative μ mesons stopped at the thick (0.018-inch) Pb foils, and seven with six mesons stopped at the thin (0.009-inch) Pb foils; and as before, none has been observed from the Al foils. Some of these are electron pairs and the rest are single tracks. Of the single electron tracks, one case, as presented in Fig. 1, is obtained which is

[1] W. Y. Chang, preceding paper, Phys. Rev. 95, 1282 (1954).
[2] W. Y. Chang, Phys. Rev. 74, 1236 (1948); Revs. Modern Phys. 21, 166 (1949).

quite similar in direction and energy (perhaps slower) to that shown in Fig. 7 of our first publication;[2] an electron track comes upward from the place where the meson stops and passes through two foils before it twice suffers large-angle scattering. In addition to the twenty, a similar oriented electron has been associated with an event in column III and another one with one event in column IV both of Table I in the preceding paper.[1] Both occur at thick foils, while the μ mesons stop, respectively, at thin and thick ones.[3] Three more slower electrons are observed to be emitted directly from the end of the stopped mesons (see column IV, Table I, Part I) as will be discussed in the following. So, altogether we have twenty-five meson-oriented electrons and pairs.

1. The Rough Energy Distribution of the μ-Oriented Electrons and Pairs

The estimation of the energy of these oriented electrons and pairs from the absorption in the foils is extremely difficult, because of the following reasons: (1) In the energy region concerned, the radiation loss is almost as important as the ionization loss. Since the thickness of each foil is much smaller than the radiation length, the radiation loss may fluctuate greatly. Therefore, it is difficult to allow a mean value for this loss. (2) The electron may suffer multiple scattering within each foil, and thus the actual path traversed in the foil may be greater than that determined from the direction

TABLE I. Rough energy distribution of μ-o-e's and μ-o-pairs.

(a) Range-energy relation (Al). We assume that it is approximately the same for Pb.

	Range in g/cm²				
	0.5	1	1.5	2	2.5
Energy in Mev	1.1	2.1	3.5	4.6	∼5.6

(b) Distribution of track length (in units of gas space).

	Track length in No. of gas spaces between foils			
	<1	1	2	3
Single (19)	3	9	6	1
Pair (6)	0	6	0	0

(c) Possible range in the foil. Note: (1) Thin foils (0.26 g/cm² each) and thick foils (0.51 g/cm²) alternately placed. (2) The secθ effect on the path.

	Track length in No. of gas spaces between foils[a]		
	1	2	3
Possible range in g/cm²	0.75–1.5	1.5–2.5 1.5–2	2.25–3

(d) Rough energy distribution. Total track length of each pair = 2 gas spaces.

	Energy in Mev			
	∼1–2	1.5–3.5	3.5–5	5–6.5
No. of μ-oriented electrons and pairs	3[b]	9	12	1[b]

[a] The lower limit is obtained by assuming the event to begin and end at a point half way of the foil thickness.
[b] These four electron tracks are observed to emerge from the end of four stopped μ^- mesons.

[3] A μ-oriented electron is also found at a thick foil with a meson decaying at a thin foil. This oriented electron may be due to either a photon from the radiation of a decay position, or a stray electron; see column V, Table I, Part I (not included in our statistics).

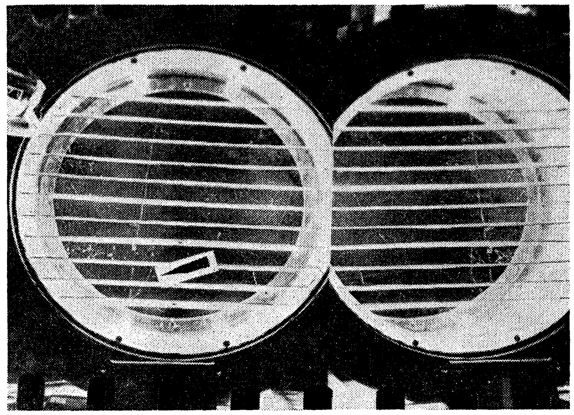

FIG. 1. A μ meson stops in the last Pb foil (0.018 inch), and a thin track is emitted from the end and moves upwards. After passing through two foils, it suffers scattering twice first from the eighth foil and then from the ninth and back to stop in the eighth foil. It is almost certainly an electron and its kinetic energy is probably between 5 and 6 Mev [see Table I(d)]. This is one of four such cases found in the present experiments. They are very probably Compton electrons, each ejected by a photon absorbed by the same foil in which the μ meson stops. See also Figs. 2 and 3. See text for discussion.

of emergence. (3) The location of the end points of the electron track is uncertain (due to finite foil thickness). No attempt will be made to allow for these corrections nor for the energy loss in the gas. For the estimate of energy, we have used the range-energy curve given in Montgomery's book,[4] which is for the ionization loss only. We have also applied the correction secθ in order to obtain the actual straight path in the foil, i.e., $l=t\sec\theta$, where t is the foil thickness and θ the angle made with the vertical by the electron track. The energy value obtained in this way may be expected to be smaller than the real value. The way of grouping of these oriented electrons and pairs is summarized in Table I(a), (b), (c), and (d), and the rough energy distribution is given in Table I(d). The lower limit to the possible range in each group of Table I(c) is obtained by assuming the track to begin and end at the midpoint of the foil thickness. The rough energy distribution in Table I(d) seems to show a general trend towards a maximum around 5 Mev. However, no great weight should be attached to this distribution, because of the crudeness of the method of measurement and hence of the analysis.

2. The Electron from the End Point of the Stopped Negative Meson

In addition to the electron listed in Table I of Part I (column II, top row) and also shown in Fig. 1 of the present paper, we have observed 3 other cases, all from the Pb foils (see column IV, Table I of Part I), where a thin, curved, and short track of the right age appears

[4] D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, New Jersey, 1949), Appendix E.

at the end of the track of the stopped negative μ meson. If the particle is an electron, its energy, after coming out of the foil, may be only of the order of a few hundred kev, and its initial energy could be of the order of 1 or 2 Mev [see Table I(d)] if it came from the atom (Auger effect or internal conversion) which has captured the negative μ meson or from a neighboring atom. It is not probable that both these 3 low-energy particles, presumably electrons, and those 3 more energetic ones (2, 1 for Pb and 1 for Fe, reported before in reference 2) are β particles emitted by the β-radioactive isotope formed after nuclear capture of the negative μ meson, because the sensitive time ($\sim$0.1 sec) of the cloud chamber is very much shorter than the mean life ($Tl^{206}\,\beta^-$, $\tau\sim3.5$ yr; $Tl^{207}\,\beta^-$, $\tau\sim4.8$ min; $Tl^{208}\,\beta^-$, $\tau\sim3.1$ min) of the radioactive isotope and the chance is extremely small for the beta and meson tracks to have the *same age*. Moreover, if they were the low-energy μ-decay positrons (1–5 Mev) from decaying positive μ mesons, their proportion to the total number of μ-decay positrons so far actually observed would be 5/52 for Pb and 1/9 for Fe, which are unbelievably large (see Part I), where 52 and 9 are the total numbers of μ-decay events observed respectively for Pb and Fe in both our present and previous[2] experiments. Furthermore, the fact that none of such low-energy electrons has been found from Al, where 26 μ-decay events have been obtained, also supports the above conclusion that these electrons cannot be low-energy μ-decay positrons.

Slow electrons (10–100 kev) associated with μ mesons stopped in emulsions have been observed by Cosyns and co-workers[5] and by Fry.[6] These have been interpreted as Auger electrons ejected from the radiationless transitions of the μ mesons. The theory of the more energetic Auger transitions for μ-meson capture was first worked out by Wheeler[7] and more recently by Burbidge and De Borde[8] for the elements in photographic emulsions. The agreement with the experimental results is not too close, comparison being made, however, only on the basis of the small number of tracks so far observed.

As were the two previous cases interpreted in our former report,[2] the present four cases, where the electron appears at the end of the stopped meson, may also more satisfactorily be attributed to Compton recoil or photoelectron tracks, which are ejected by photons emitted in the interaction of the negative μ mesons with the nucleus. The energetic one [see Table I(d), last column] may be a Compton recoil ejected from a neighboring atom by a photon emitted either when the μ meson makes the 6-Mev $2p\rightarrow1s$ jump, or when the μ-excited nucleus falls to the ground state. The 3 low-energy ones [see Table I(d), first column] may be Compton recoils ejected from the same foil by photons of the same group emitted from either the $2p\rightarrow1s$ transition or the nuclear de-excitation, and the electron energy may be degraded to the lower value by radiation and ionization loss. Or, some of the tracks may be due to photons from the $3d\rightarrow2p$ and $2s\rightarrow2p$ transitions. The observed frequency corresponds roughly to one photon from each μ-meson capture (see the following section on multiplicity). Of course, the statistics of these oriented electrons from the same foil are poor, and one may not put too much weight on the figure estimated for the multiplicity in this case. However, it is not inconsistent, considering statistics, with more accurate result on multiplicity as calculated from the larger number of the μ-oriented electrons and pairs from other foils.

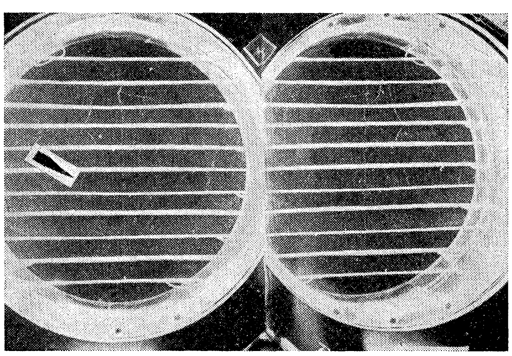

FIG. 2. The thin track between the sixth and seventh foils, as indicated by the arrow, appears to be oriented toward the end point of the stopped meson, which is the bent track ended at the fifth foil. It has the same age as the track of the stopped meson. It is very probably an electron ejected from the foil by a photon associated with the stopped meson. It is one of more than 20 similar cases so far observed (see Fig. 3) in the present experiments. The straight track through the chamber may be a faster μ meson or proton.

3. The μ-Oriented Electrons and Pairs Observed at a Different Foil

Figures 2 and 3 show 3 μ-oriented electrons and pairs out of the total 21 observed at foils different from those at which the negative μ mesons stop. In Fig. 2 a negative μ meson stops at the fifth Pb foil (0.018 inch), and in the gas space between sixth and seventh foils a thin track of *the right age*, presumably an electron track, is oriented toward the end point of the stopped meson. The energy of the electron is probably below 3 Mev. Figure 3 shows one oriented electron and one oriented pair both of the *right age* associated with one negative μ meson stopped at the fifth Pb foil (0.018 inch). The single electron between the second and third foils is reasonably assigned an energy below 2 Mev, while the pair between the eighth and ninth foils is estimated to have an energy of the order of 5 Mev. (See Table I.)

[5] Cosyns, Dilworth, Occhialini, Schoenberg, and Page, Proc. Phys. Soc. (London) **A62**, 801 (1949).
[6] W. F. Fry, Phys. Rev. **83**, 594 (1951).
[7] J. A. Wheeler, Revs. Modern Phys. **21**, 133 (1949); E. Fermi and E. Teller were the first to analyze the lower-energy Auger processes [Phys. Rev. **72**, 399 (1947)].
[8] G. R. Burbidge and A. H. De Borde, Phys. Rev. **89**, 189 (1953).

(i) *Angular Correlation*

The 21 oriented electrons and pairs which are found coming from the foils different from those where the negative mesons stop, have a definite angular correlation with the end points of the stopped mesons. As mentioned before, these 21 electrons and pairs have been found within a cone of half-angle $\sim 20°$ about the line joining the end point of the stopped meson to the beginning point of the electron. Practically it is not possible to determine a significant angular distribution of these tracks, because of the small number and because of the difficulty in measuring the angle due to small length of the tracks. Instead, we have counted the electron tracks within a similar cone in a direction perpendicular to the above line from the 81 pictures containing the stopped negative μ mesons. The number found in this way is about 6, which is much smaller than the 21 found in the forward cone and is about the "chance coincidence" of the stray tracks (see following). This is 6/21 as many tracks for about 6 times as much solid angle.

It is well known that the emission of a secondary electron (a pair or a Compton electron) produced by a high-energy photon has as its direction of preference the direction of the photon. The root-mean-square angle is of the order of magnitude of $[\langle\phi^2\rangle_{\mathrm{Av}}]^{\frac{1}{2}} \propto mc^2/E$, where E is the energy of the primary photon and m the mass of the electron. For 6-Mev photons the expected spread in angle from this source is only about $\frac{1}{12}$ radian, negligible in comparison with the 20° or $\frac{1}{3}$ radian tolerance adopted in our definition of "μ-meson-oriented electron and pair." More important is the spread due to multiple scattering. To demonstrate this effect, we may estimate the root-mean-square *projected* angle of scattering of a 6-Mev electron in the foils from the following formula:[9]

$$[\langle\phi_y^2\rangle_{\mathrm{Av}}]^{\frac{1}{2}} = (\zeta/2)^{\frac{1}{2}} 21/\beta cp, \qquad (1)$$

where ζ is the foil thickness in radiation units and βcp in Mev. The rms projected angles are thus found to be about 36° and 25° for the electrons in the thick (0.51-g/cm^2) and thin (0.26-g/cm^2) foils, respectively. These angles are of such a size as to make the observed spread in angles seem not too unreasonable. Thus, as will be seen, in calculating the multiplicity of the photons we have corrected the observed number of the oriented electrons and pairs for the spread in angles due to multiple scattering.

(ii) *Chance Coincidence of Stray Tracks; the Origins of the Photons*

To study the effect of the stray electron tracks, we took 575 pictures by using a single tray of counters. It is found from examining these 575 pictures that, on the average, there are about 13 stray electron tracks of the *right age* in each 10 pictures. The probability that such an electron track point accidentally toward or away from the end point of the stopped negative μ-meson track is approximately

$$1.3\times 2\times \pi(20/57.3)^2/4\pi \sim 6/80. \qquad (2)$$

By comparing this figure with 21/81, it becomes evident that the stray electrons are far from being able to account for the 21 μ-oriented electrons and pairs observed in our present experiments. To check the above calculation, we have re-examined the same roll of film to see how many of the stray electron tracks point (within a cone of half-angle $\sim 20°$) accidentally toward or away from an arbitrary point inside the chamber. It has been found that there are about 9 such tracks in 575 stray tracks, i.e., $9/575 \sim 1/63$, still smaller than 21/81.

It, therefore, seems to us that these 21 μ-oriented electrons and pairs found in the present experiments are much more reasonably interpreted in the same way as the other four electrons which are observed to be emitted from the end points of the stopped negative μ mesons. That is, they appear to be much better attributed to the photons from the two following sources: (1) the extra-nuclear transitions between the Bohr orbits by the incoming negative μ meson, and (2) the nuclear-de-excitation of the nucleus, to which a small fraction of the negative μ meson's rest energy has been imparted (see Part I) and which may have been left excited after the emission of 1 or 2 neutrons.[10] The energies of these electrons are compatible with those predicted in Wheeler's theory[11] and with those expected from the nuclear de-excitation (see our previous paper[2]

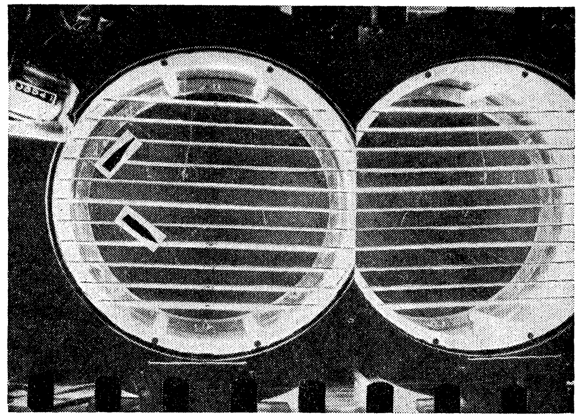

FIG. 3. A pair and a single electron, both of the same age as the track of the stopped meson are seen oriented toward the end point of the single stopped meson, which is ended at the fifth foil. They are indicated by the arrows in the direct view. The energy of the single electron may be below 3 Mev and that of the pair is probably about 5 Mev or less. They are very probably ejected by two photons emitted from the stopping of the negative μ meson (compare Fig. 2).

[9] B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York, 1952), p. 68.

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

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

and the following discussion of multiplicity in this paper).

Gamma rays associated with the stopping of negative μ mesons have also been recently reported by Rainwater and co-workers,[12] who used a μ-meson beam from the cyclotron, and have been discussed briefly by Cooper and Henley.[13]

(*iii*) *The Mean Multiplicity of the Photons*

It is of importance to estimate the multiplicity, m, i.e., the number of photons of a certain energy actually emitted when one negative μ meson is stopped and captured by a nucleus. It may be calculated by the following equation:

$$Nmt/L=n/\sigma, \tag{3}$$

where N is the number of negative mesons stopped; t, the effective path traversed by the photons calculated as if the foil system consisted of spherical shells (see Table IV, Column I, Part I); L, the mean free path of the photon; n, the number of μ-oriented electrons and pairs of the corresponding energy actually observed, and σ is the ratio of this number to the total number, that would be expected from Gaussian distribution; i.e., σ is a correction for the multiple scattering of the electrons just ejected through the foil and will be called the M.S. correction factor. No correction is made for the angular spread of the electron emission involved in the processes of conversion from photons to electrons, the root-mean-square angle being only of the order of 6°.

It may be noted that the application of multiple scattering theory to the present case cannot be too significant statistically, because, in the first place, the number of the oriented electrons and pairs observed is small, and secondly, the energies of these electrons have been only roughly estimated. Moreover, only a crude estimate has been made for the value of t. However, it may be still possible and of interest to get a general idea, however crude it may be, of the multiplicity as a check on the origin of these photons.

As mentioned before, the rough energy distribution of the electrons as shown in Table I(d) has indicated a general trend towards a maximum around 5 Mev. Therefore, for the convenience in calculating the photon multiplicity, we may take all of the 21 electrons and pairs as having an energy of 5 Mev corresponding approximately to the photons from the $2p\to 1s$ transition. Of course, part of these may come from the nuclear de-excitation and also probably from the other extra-nuclear orbital transitions such as $3d\to 2p$ and $2s\to 2p$. To calculate the M.S. correction factor, σ, we have to calculate first the root-mean-square total angle[9] of multiple scattering of the electrons in the foils, which may be obtained from a formula similar to Eq. (1):

$$[\langle\phi^2\rangle_{\mathrm{Av}}]^{\frac{1}{2}}=21\xi^{\frac{1}{2}}/\beta cp, \tag{4}$$

where ξ is half the foil thickness in radiation units, assuming the electron to be emitted from this point and βcp in Mev. It is found that $[\langle\phi^2\rangle_{\mathrm{Av}}]^{\frac{1}{2}}=46°$ for a thick foil (0.51 g/cm²) and 32° for a thin one (0.26 g/cm²). The root-mean-square value of these two angles is about 41°, allowing for the fact that about $\frac{2}{3}$ of the electrons and pairs are emitted from the thick foils and $\frac{1}{3}$ from the thin ones. The value of σ corresponding to $[\langle\phi^2\rangle_{\mathrm{Av}}]^{\frac{1}{2}}=41°$ is found to be about 0.39; i.e., the number counted within a cone of half-angle approximately 20° includes only 0.39 of the total area under the Gaussian curve. The effective path length $t\sim 2.57$ g/cm² (see Table IV, column 2 and footnote in Part I); $L\simeq 20$ g/cm², $N=81$; $n=21-6=15$, where 6 is assumed to be the maximum possible number of the stray tracks. Hence, the multiplicity is found to be

$$m=\frac{15}{0.39}\times\frac{20}{81\times 2.57}\simeq 3.5. \tag{5}$$

As to the multiplicity of the photons absorbed in the same foil in which the meson is stopped (as discussed at the end of Sec. 2), it may be estimated as follows: Taking 22 g/cm² as the mean free path of a (2–4 Mev) photon and one g/cm² (corrected for the secθ effect) as the average path traversed in the stopping foil, one would then expect one secondary electron emitted at the same foil from a total of about 22 stopped negative μ mesons, or 4 in 88. In order to compare with the observed 4 in 81, it is sufficient to assume, on the average, only about one such photon emitted per negative μ-meson capture. Actually, one would expect two photons (instead of one) per stopped meson, namely one from the $2p\to 1s$ transition and another from the nuclear rearrangement. The figure one as estimated above is not inconsistent, within the poor statistics, with the figure two that would be expected.

The total multiplicity obtained from the two cases is, therefore, 4.5 per negative meson stopped with a probable uncertainty of a factor of 1.5 ± 1.

A total multiplicity of around 5 seems fairly reasonable, if one allows for the crudeness of the calculation, for two photons may satisfactorily be attributed to the extra-nuclear origin[11]—transition between the Bohr orbits, such as $2p\to 1s$ and $3d\to 2p$—and two or three to the nuclear de-excitation. A photon multiplicity of 2 for the nuclear rearrangement radiation does not seem to be incompatible with the nuclear models usually used.[14]

It may be noted that, using cosmic ray μ mesons, Hincks[15] (counting method) and more recently Harris and Shanley[14] (cloud chamber in a magnetic field) have

[12] James Rainwater, Phys. Rev. **90**, 349 (1953); V. L. Fitch and J. Rainwater, Phys. Rev. **92**, 789 (1953).

[13] L. N. Cooper and E. M. Henley, Phys. Rev. **91**, 480 (1953); **92**, 801 (1953).

[14] G. Harris and B. Shanley, Phys. Rev. **89**, 983 (1953).

[15] E. P. Hincks, Phys. Rev. **81**, 313 (1951).

TABLE II. Number of mesons arriving per second at sea level within a unit solid angle about the vertical, and stopped in one gram of Pb.

Experiments	Working period, sec	Effective solid angle,[a] sterad	Material	Grams in chamber	Equivalent[b] in grams of Pb	Number of mesons stopped (+ and −)	Number stopped per gram Pb per sec per sterad
Previous	3.35×10^6	0.011	Pb	5.6	5.6	44	1.4×10^{-6}
Previous	3.74×10^6	0.019	Al	0.76	1.5	23	1.4×10^{-6}
Present	5.40×10^6	0.027	Pb	4.3	4.3	151	1.2×10^{-6}
Present	5.04×10^6	0.027	Al	0.88	1.7	68	1.5×10^{-6}
George and Evans[c]							4×10^{-6}air(2×10^{-6})[d]
Rossi[e]							4.6×10^{-6}air(2.3×10^{-6})[d]

[a] The solid angle Ω is calculated from $\Omega=N/(I_vA)$; N = observed number of all mesons (fast and slow) entering the telescope and the foil system per sec. N is 45/(3600) and 85/(3600) for Pb and Al, respectively, in the previous experiments and 150/(3600) in the present experiments. A is the average area of the foils ~150 cm² and 200 cm², respectively, for the previous and present experiments. I_v is the vertical intensity of hard component at sea level $=0.83\times10^{-2}$ cm^{-2} sec^{-1} sterad^{-1}. See reference e.

[b] Specifically, 0.85 g of Al has the same stopping power for 10-Mev mesons as 1.6 g of Pb. See reference d. 10 Mev is the typical energy of a meson which will stop in a foil half-way through the chamber.

[c] E. P. George and F. Evans, Proc. Phys. Soc. (London) **A63**, 1249 (1950).

[d] See reference 4.

[e] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

also confirmed the existence of these (1–5 Mev) gamma rays associated with the stopping of μ mesons.

Our results, analyzed along the above lines, seem to indicate that the total gamma-ray energy emitted per negative μ meson stopped in Pb may be about 15 Mev (tentatively, we assume, on the average, two 5-Mev lines and two 2.5-Mev lines emitted from each stopped negative meson). This figure is somewhat larger than the values obtained by Hincks[15] and by Harris and Shanley.[14] Assuming that about half of this total energy comes from the nuclear de-excitation, and taking the fact that usually about two neutrons[10] with kinetic energy presumably about 3 Mev each are emitted (very rarely a slow proton), then the energy imparted to the Pb nucleus by the captured negative μ meson is probably $2(3+6)+7+3=28$ Mev, where the number 6 in the parenthesis is the binding energy in Mev in Pb of a neutron and the last number 3 is the energy in Mev required to change Pb^{208} to Tl^{208}.

III. ABSOLUTE COUNTING RATE

To get a supplementary check that the experimental setup was operating correctly, we can calculate back from the total number of mesons stopped in the foils, from the working period, from the mass and atomic number of the stopping foils, and from the solid angle, and obtain a value for the absolute rate of stopping of mesons, in the present and the previous experiments for both Pb and Al. The results of such a calculation are presented in Table II, the values for the absolute stopping rate being given in the last column. The experimental results obtained by George and Evans (originally for emulsion and converted by these authors to values for air) and by Rossi (from analysis of many data) are included. For comparison with our own results, we have converted these workers' results to values for Pb as shown in parentheses. The consistency of our rates with each other and with the values of the other investigators is better than expected and does encourage belief that the μ mesons stopped in Pb and Al have received an unbiased investigation. Our rates are systematically smaller than those of George and Evans and Rossi, the average being about 30 percent smaller than the average of the two groups. This difference may easily be attributed, in addition to statistical error in our case, to the errors involved in estimating the effective working periods and solid angles in our experiments and in the conversion of stopping power from one element to another.

These experiments were completed at Princeton in 1949. The writer would like to take this opportunity to express his gratitude to his colleagues in the Cosmic Ray Laboratory at Princeton for their help in various ways, and, in particular, to Professor J. A. Wheeler for his enthusiastic support and profitable discussion in this work, and to Dr. J. R. Winckler, now at the University of Minnesota, for his valuable help in building the electronic controls. He also wishes to express his sincere thanks to Professor K. Lark-Horovitz, Head of the Physics Department at Purdue University, for his interest and support in the study of elementary particles.

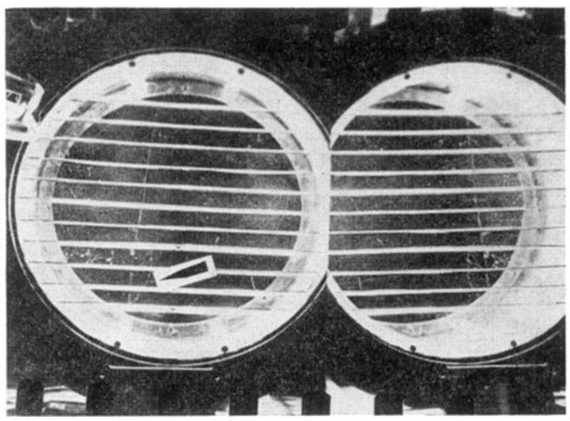

FIG. 1. A μ meson stops in the last Pb foil (0.018 inch), and a thin track is emitted from the end and moves upwards. After passing through two foils, it suffers scattering twice first from the eighth foil and then from the ninth and back to stop in the eighth foil. It is almost certainly an electron and its kinetic energy is probably between 5 and 6 Mev [see Table I(d)]. This is one of four such cases found in the present experiments. They are very probably Compton electrons, each ejected by a photon absorbed by the same foil in which the μ meson stops. See also Figs. 2 and 3. See text for discussion.

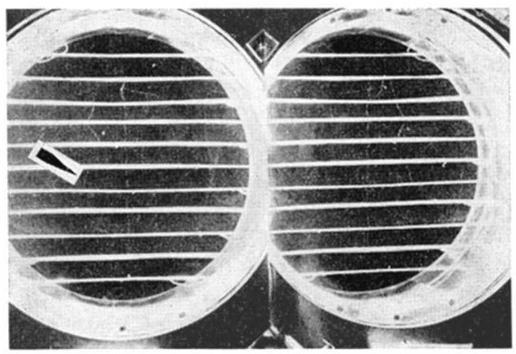

Fig. 2. The thin track between the sixth and seventh foils, as indicated by the arrow, appears to be oriented toward the end point of the stopped meson, which is the bent track ended at the fifth foil. It has the same age as the track of the stopped meson. It is very probably an electron ejected from the foil by a photon associated with the stopped meson. It is one of more than 20 similar cases so far observed (see Fig. 3) in the present experiments. The straight track through the chamber may be a faster μ meson or proton.

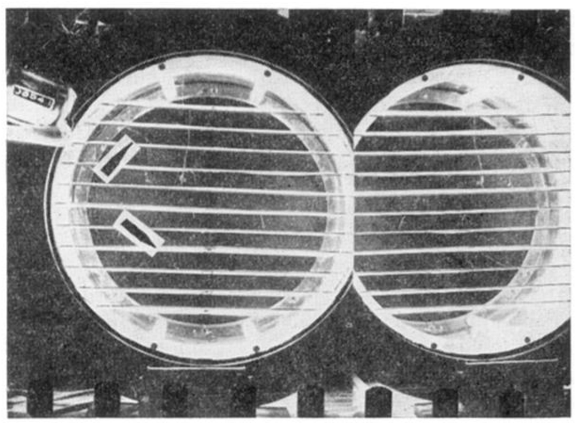

FIG. 3. A pair and a single electron, both of the same age as the track of the stopped meson are seen oriented toward the end point of the single stopped meson, which is ended at the fifth foil. They are indicated by the arrows in the direct view. The energy of the single electron may be below 3 Mev and that of the pair is probably about 5 Mev or less. They are very probably ejected by two photons emitted from the stopping of the negative μ meson (compare Fig. 2).