SEARCH FOR THE DECAY MODE: $\mu \to e + \gamma$ *

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One of the familiar and puzzling properties of the muon is the apparent absence of the decay $\mu \to e + \gamma$ (unaccompanied by neutrinos), although it is not forbidden by any known selection rules. It has been shown[1] that a relatively fast transition via strong or electromagnetic interactions is not to be expected, but on the basis of weak interactions, such as the currently fashionable intermediate vector boson theories, one may account for a rate in the range 10^{-3}-10^{-6} of the normal decay rate.[2] The exact calculated value depends on the specific properties assumed for the boson.[3] Experimentally, the results of several searches for $\mu \to e + \gamma$ indicate that the rate is less than about 10^{-6} of the normal decay rate.[4]

In addition, recent experimental limits have been placed on the allied processes $\mu \to 3e$ ($<5 \times 10^{-7}$ of normal decay)[5] and $\mu + N \to e + N'$ ($\lesssim 10^{-7}$ of capture rate).[6] The latter indicates that the low $\mu \to e + \gamma$ rate cannot be comfortably explained by assuming a narrow range of boson properties, such as an anomalous magnetic moment very close to 0.7 boson magneton.[7]

Alternatively, suggestions have been advanced for a new selection rule or conservation law to explain the absence of observed $\mu \to e + \gamma$ decays. Additive[8] and multiplicative[9] types of conservation laws have been proposed, both involving two sorts of neutrinos, one associated with electrons, the other with muons. Additional support for such a radical interpretation would be provided by a still smaller experimental limit on the $\mu \to e + \gamma$ process. A further search for this process, using spark chamber techniques, is reported here; the limits for the rate are reduced by one or two orders of magnitude from those reported in previously published work.

The physical features of the $\mu^+ \to e^+ + \gamma$ decay which would allow it to be detected in the presence of a much larger background of competing processes are that the positron and gamma ray (a) equally share the muon rest energy, and (b) are emitted collinearly. Previous counter experiments[4] have concentrated on energy selection but have had to relax the requirement of collinearity in order to intercept a reasonable solid angle. The possibility of combining high spatial resolution with the advantages of counter techniques is provided by the recent development of spark chambers.

Two factors determine the smallest limit which can be detected: (a) the over-all sensitivity and (b) the indistinguishable background. (a) Using a counter system with an over-all efficiency (including solid angle) of a few percent, it is necessary to have about 10^{10} muon decays in the target in order to observe a partial rate of a few parts in 10^8. (b) The limiting background comes from those decays with inner bremsstrahlung, $\mu \to e + \gamma + \nu + \bar{\nu}$, in which the neutrinos carry away little energy and momentum. With good angular resolution (limited, in our experiment, to 3 deg by scattering in the target), and with moderate energy resolution, the background is also compatible with observing a partial rate of approximately 10^{-8}.

The actual experimental arrangement used is shown in Fig. 1. 48-Mev positive pions from the Nevis cyclotron (using the long duty-cycle arrangement) were slowed down in polyethylene and stopped in a 5-in. (high) by 8-in. (wide) by $\frac{1}{2}$-in. counter (No. 3), which was turned about a vertical axis so that its normal made an angle of 60 deg to the beam. The π-μ-e decay positrons emerging normal to the beam passed through the thin-plate spark chamber and were detected by counters No. 4 (24 in. by 24 in. by 1 in.) and No. 5 (24 in. by 24 in. by 6 in.). γ radiation in the opposite direction produced pairs in two lead converters ($\frac{1}{8}$ in. and $\frac{1}{16}$ in. thick) inside a second spark chamber and was thus detected in counters No. 6 (24 in. by 24 in. by $\frac{1}{2}$ in.) and No. 7 (24 in. by 24 in. by 6 in.). Two anticoincidence counters were used, No. 1 in the beam to eliminate prompt events and No. 2 (14 in. by 11 in. by $\frac{1}{2}$ in.) in front of the γ chamber to discriminate against positrons or other charged particles.

The spark chamber plates were constructed of 0.001-in. and 0.002-in. "hard" aluminum foil stretched over, and cemented to, steel hoops $\frac{1}{2}$ in. thick and $20\frac{1}{2}$ in. in diameter. The plates were mounted by posts on a Lucite plate, which formed the rear lid of an aluminum vacuum-tight box. Each box was fitted with two plate glass windows for viewing and a 0.010-in. Mylar window (10 in. by 10 in.) for particle entry. The chambers were filled with a commercial 95% Ne−5% He mixture at slightly above atmospheric pressure. Alternate plates of each spark chamber were connected to

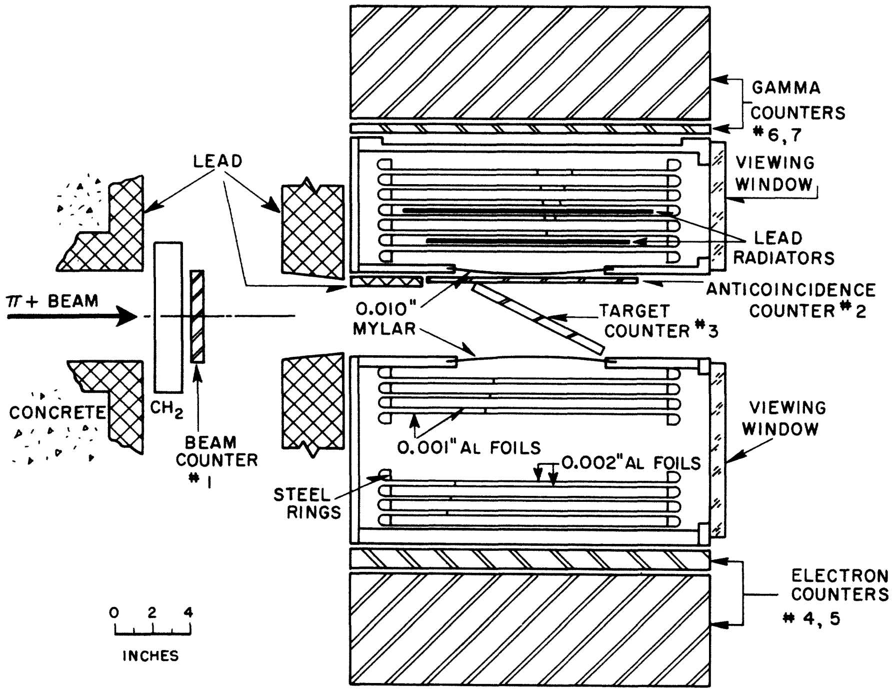

FIG. 1. Plan view of experimental arrangement. The lower spark chamber and counter assembly is for detecting electrons and the upper one for γ rays.

ground and to separate 2000-pf condensers charged to 9 kv. This condenser system was discharged through the spark chamber gaps by means of 5C22 thyratrons, with an over-all delay of $\frac{1}{2}$ microsecond between the arrival of the triggering particle and the discharge of the chamber. The two chambers were viewed together by a pair of cameras in 90-deg stereo, with each camera 10 ft behind a 30-in. diameter plastic field lens.

The spark chambers were triggered by a fast coincidence-anticoincidence among counters $34567\bar{1},\bar{2}$ indicating a positron$-\gamma$-ray event. The display of all counter pulses on appropriate 4-beam fast and 2-beam slow oscilloscope traces was photographed each time the spark chambers were triggered. In addition, a 1-3 coincidence pulse was delayed 6 μsec and displayed on a 10-μsec trace in order to indicate an incident pion preceding the event. The electron counter (No. 5) was set to trigger the coincidence at a level corresponding to a positron of about 30 Mev entering the electron spark chamber; the level in the γ counter (No. 6) corresponded to approximately 6 Mev ionization loss.

About 5×10^9 stopped π^+ mesons were examined in an effective time of about 200 hours, and 4600 pictures of possible radiative decays were taken. Of these, 72% failed to satisfy straightforward scanning criteria, which eliminated cosmic rays, accidental coincidences, and other spurious processes. For example, pictures showing a track in the first gap of the γ spark chamber, i.e., before the first lead plate was reached, were rejected. From the remaining 1300 pictures, an example of which is shown in Fig. 2, measurements were made of the angle $\theta_{e\gamma}$ between the positron track and γ ray. This was done by extrapolating the former track until it intercepted the target and connecting this point with the origin of the electron or pair track produced by the γ radiation in the lead.

Figure 3 shows the angular distribution of the measured events for values of $\theta_{e\gamma}$ between 165 and 180 deg. The relatively flat distribution is what would be expected from the inner bremsstrahlung process,[10] $\mu \rightarrow e+\gamma+\nu+\bar{\nu}$; any significant contribution from $\mu \rightarrow e+\gamma$ would reveal itself as a peak near 180 deg. The region within 3 deg of 180° is significant since this corresponds to the calculated mean scattering angle of electrons in the target counter. From the average rate of events in the interval between 165 and 180 deg, one would expect 4.2 events in the significant region. The actual number found is 5, consistent with a zero rate for the process $\mu \rightarrow e+\gamma$.

To translate this result into a limiting value of the ratio $R=(\mu \rightarrow e+\gamma)/(\mu \rightarrow e+\nu+\bar{\nu})$, the absolute sensitivity of the experimental arrangement was

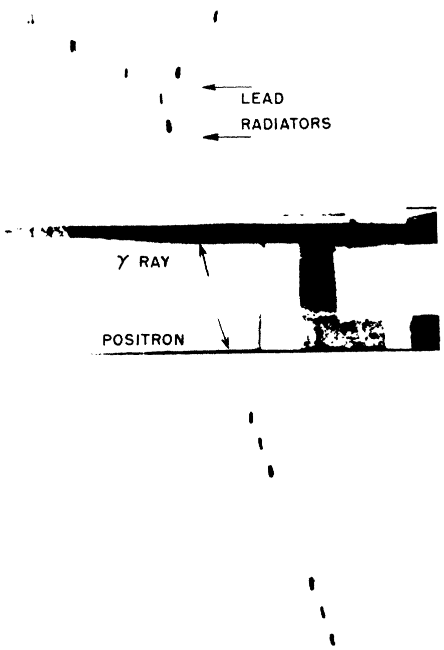

FIG. 2. Spark-chamber photograph of a radiative decay: $\mu \to e+\gamma+\nu+\bar{\nu}$. In the γ chamber, the first gap does not fire, but the γ ray is converted in the first lead radiator, and the resultant pair scatters to a wider opening angle in the second lead plate.

determined by additional measurements. The electron detection efficiency was measured by injecting monoenergetic positrons, separated by a simple wedge spectrometer from the μ-decay spectrum, into the electron spark chamber and counters. The ratio of the detection efficiency (70%) for possible 52-Mev positrons to that for the entire decay spectrum (within the same solid angle) was thus determined to be 1.9 ± 0.4.

The γ-ray efficiency was determined by studying the response of the γ-spark chamber-counter assembly to γ radiation from π^0 decays (obtained by stopping negative pions in LiH) in coincidence with a lead-glass Čerenkov counter. The measured efficiency for these γ rays, with a mean energy of 67 Mev, was 34%, which when extrapolated theoretically to 52 Mev gives a value of (28 ± 5)%.

1.91×10^8 decay positrons were recorded during the experiment. Therefore one detected $\mu \to e + \gamma$ event would correspond to a value of $R = 1/(1.9 \times 0.28 \times 1.91 \times 10^8) = 1.0 \times 10^{-8}$. (This corresponds to a total of 5.13×10^9 pions examined, with an over-all efficiency of 2%.) Our results give a value of $R = (5 - 4.2) \times 1.0 \times 10^{-8} = 0.8 \times 10^{-8}$ with a standard deviation of 2.3×10^{-8}. We conclude that R is less than 6×10^{-8} with a 90% confidence level.

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[1]G. Feinberg, P. Kabir, and S. Weinberg, Phys. Rev. Letters 3, 527 (1959).
[2]G. Feinberg, Phys. Rev. 110, 1482 (1958).
[3]M. E. Ebel and F. J. Ernst, Nuovo cimento 15, 173 (1960).
[4]S. Lokanathan and J. Steinberger, Phys. Rev. 98,

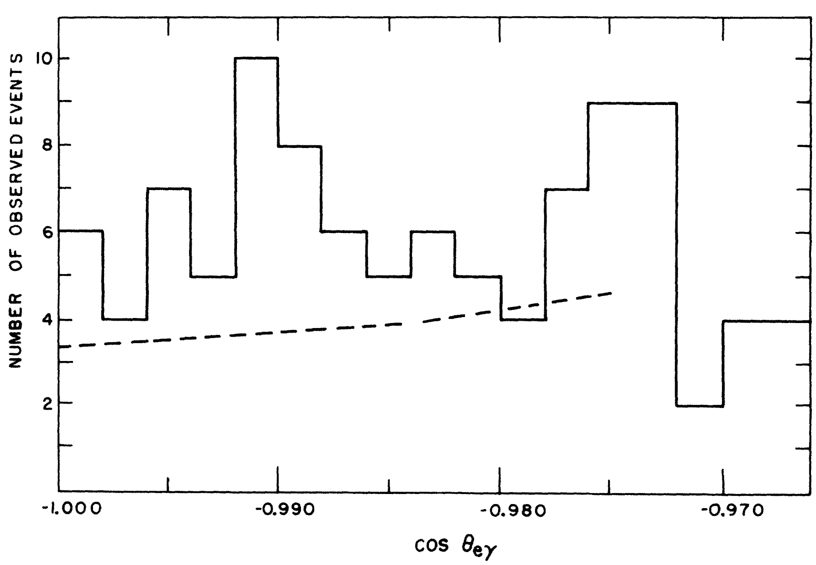

FIG. 3. Number of events per interval of solid angle versus $\cos\theta_{e\gamma}$ for angles between 180 and 165 deg. The sloping line indicates an estimate for the process $\mu \to e+\gamma+\nu+\bar{\nu}$ derived from the theoretical calculation,[10] into which has been folded an estimate of the detection efficiency for electrons and γ rays of various energies.

240 (1955); D. Berley, J. Lee, and M. Bardon, Phys. Rev. Letters 2, 357 (1959); T. O'Keefe, M. Rigby, and J. Wormald, Proc. Phys. Soc. (London) 73, 951 (1959); J. Ashkin, T. Fazzini, G. Fidecaro, N. H. Lipman, A. W. Merrison, and H. Paul, Nuovo cimento 14, 1266 (1959); S. Frankel, V. Hagopian, J. Halpern, and A. L. Whetstone, Phys. Rev. 118, 589 (1960). We understand that this group has also studied this process using spark chamber techniques.

[5]S. Parker and S. Penman, Nuovò cimento (to be published).

[6]M. Conversi, L. di Lella, G. Penso, and M. Toller, CERN Report, 1961 (unpublished).

[7]F. J. Ernst, Phys. Rev. Letters 5, 478 (1960).

[8]K. Nishijima, Phys. Rev. 108, 907 (1957); J. Schwinger, Ann. Phys. (New York) 2, 407 (1957); S. Bludman, Nuovo cimento 9, 433 (1958).

[9]G. Feinberg and S. Weinberg, Phys. Rev. Letters 6, 381 (1961).

[10]A. Lenard, Phys. Rev. 90, 968 (1953); B. E. Behrends, R. J. Finkelstein, and A. Sirlin, Phys. Rev. 101, 866 (1956).

NEW LIMIT ON THE $e+\gamma$ DECAY MODE OF THE MUON*

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The most recent measurements[1,2] of the decay rate for $\mu \rightarrow e+\gamma$ have set an upper limit of 10^{-6} on the value $R(\mu \rightarrow e+\gamma)/R(\mu \rightarrow e+\nu+\bar{\nu})$. This process is forbidden if the neutrinos coupled to muons are distinguishable from those coupled to electrons. If this were not the case, the decay could proceed via an intermediate charged vector boson or in second order in the weak interactions. Present theories for both processes are divergent and do not lead to exact predictions of the decay rate.[3-5] Ebel and Ernst[6] and Bludman and Young[7] have shown that the rate can be made to vanish for certain choices of the vector boson magnetic and quadrupole moments.

Recently, as part of a series of studies using spark-chamber techniques, we have made a preliminary run on various rare μ-meson decay modes. In this note we report on the decay $\mu \rightarrow e+\gamma$.

A sketch of the experimental apparatus is shown in Fig. 1. A beam of 200-Mev/c π^+ mesons produced in the external target of the 184-in. cyclotron at the Lawrence Radiation Laboratory was brought to rest in a plastic scintillator (counter 8) measuring 2 by 2 by 1 in. Counters 2 and 5 in coincidence detected positrons passing through the 7- by 7-in. aluminum spark chamber. Counter 5 was biased to accept positrons of greater than 12.5-Mev energy. Gamma rays from the target counter which did not actuate counter 4, but converted in the tungsten spark chamber, produced secondaries passing through 3 and 6. Counter 6 was biased to accept showers of electrons and gamma rays that deposited energies greater than 12.5 Mev. Coincidences in counters 5, 2, 3, and 6, but not 4, triggered the spark chambers and signals from counters 5, 6, 4, 3, 8, and 7 were displayed on oscilloscopes and photographed along with the spark-chamber tracks. Using the positrons in the meson beam, we calibrated the sodium iodide crystal response by adjusting the magnet system successively to 20, 30, 40, and 50 Mev/c.

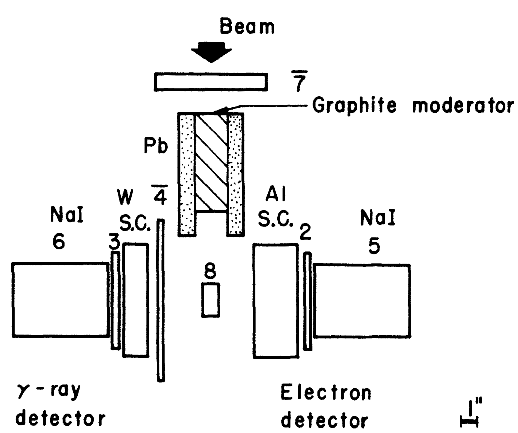
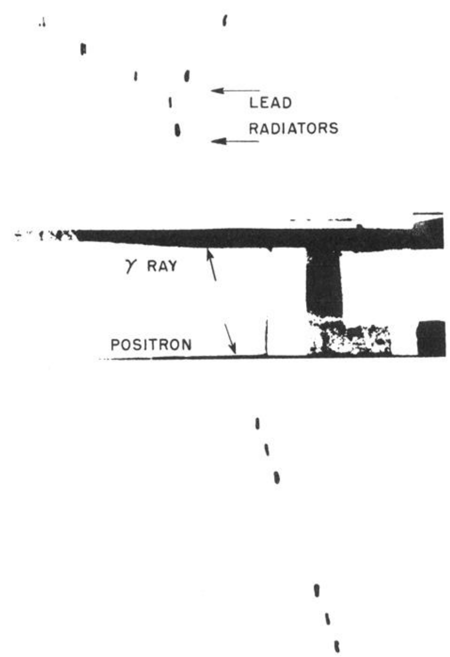


FIG. 1. Scale drawing of experimental arrangement. The numbered counters are plastic scintillation counters except counters 5 and 6, which are sodium iodide. Spark chambers are indicated S.C., one having six tungsten plates each 1.5 g-cm^{-2} thick, the other having six aluminum plates each 0.17 g-cm^{-2} thick.



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