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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 $\mu \to e+\gamma$ have set an upper limit of 10^{-6} on the value $R(\mu \to e+\gamma)/R(\mu \to e+\nu+\bar{\nu})$. 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 $\mu \to e+\gamma$.

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.

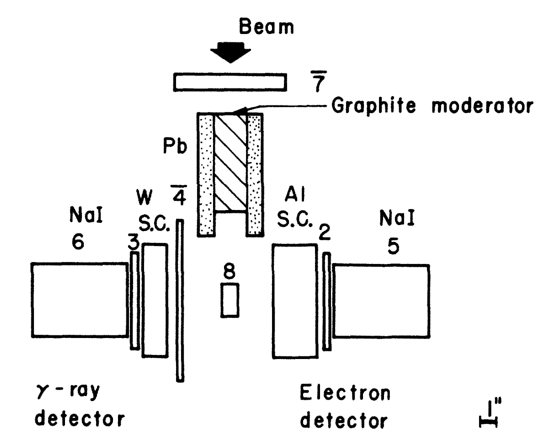

FIG. 1. Scale drawing of experimental arrangement. The numbered counters are plastic scintillation counters except counters 5 and 6, which are sodium iodide. Spark chambers are indicated S.C., one having six tungsten plates each 1.5 g-cm^{-2} thick, the other having six aluminum plates each 0.17 g-cm^{-2}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

During the course of the run, 1.2×10^8 positrons from the normal muon decay were detected in counters 2 and 5. The oscilloscope traces were first scanned with the requirements that pulses appear in counters 8 and 3, with none in 7 and 4. In this way we rejected events in prompt coincidence with entering beam particles and obtained a check on the reliability of the $\bar{4}$ counter. These criteria reduced the number of spark-chamber tracks to be scanned to 397. Of this number, 157 were rejected because no track appeared in the gamma chamber and were presumably due to chance events consistent with the logic. Seventy-three events showed two electron tracks in the aluminum chamber and were rejected in the analysis.

Figure 2 shows a plot of the angular correlation of the positrons and gamma rays. No noticeable spike in the angular correlation at zero degrees is observable. To verify that these events are due to $e\nu\bar{\nu}\gamma$ decays, we have plotted in Fig. 3 as a dashed-line histogram the pulse-height distribution of the positron pulses in counter 5. The theoretical electron spectrum from $e\nu\bar{\nu}\gamma$ decay obtained by Fronsdal and Überall[8] was evaluated for our geometry by assuming that all gamma rays (a) greater than 20 Mev and (b) greater than 40 Mev were detected in the gamma counter. Fortunately, the shape of this spectrum does not depend markedly on the gamma threshold. Thus, even though the efficiency as a function of gamma-ray energy of our tungsten-chamber–NaI system is not well known, we can use these spectra to compare with our experimental results.

The theoretical electron spectrum, corrected for the resolution of the positron counter for positrons of various energies, is plotted in Fig. 3. For comparison we show the shape expected for positrons from the $\mu\to e+\gamma$ decay. It is clear that the surviving events are from the $e\nu\bar{\nu}\gamma$ decay, and in fact we find that the absolute number of events agrees with the theoretical prediction to about a factor of 2, the main uncertainty coming from our poor knowledge of the efficiency for detecting the lower energy gamma rays after conversion in the tungsten spark chamber. The limiting factor in distinguishing collinear e-γ events from the e-γ angular distribution in the $e\nu\bar{\nu}\gamma$ decay is multiple scattering of the positrons in the 1-in. target and in the aluminum electrodes of the spark chamber. We have calculated that 80 % of true e-γ events would appear collinear to within 10.6 deg and have restricted our attention to those 26 events. (Deviation from collinearity is measured by extrapolating the positron track to the central plane of the target counter, counter 8, and constructing a line from there to the start of a track or shower in the gamma-ray spark chamber. The deviation from collinearity is measured at counter 8.) The counter-5 pulse heights of the positrons from the collinear (to 10.6 deg) events are also shown, as a solid-line histogram, in Fig. 3.

If there had been one collinear event with positron pulse height greater than 33 Mev, it would have corresponded to a decay branching ratio of 8×10^{-8}. Since no events were observed, the experiment gives 90 % confidence that the process

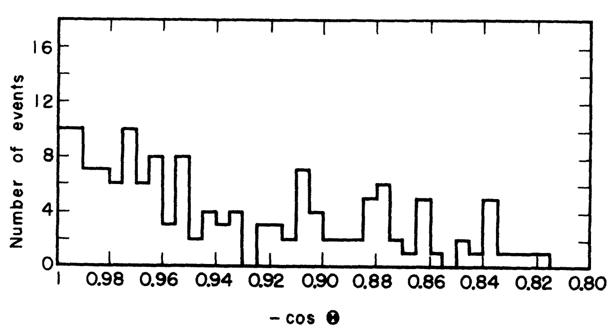

FIG. 2. Observed angular correlation of positron and gamma ray. Θ is the angle, at counter 8, between outgoing positron and gamma ray.

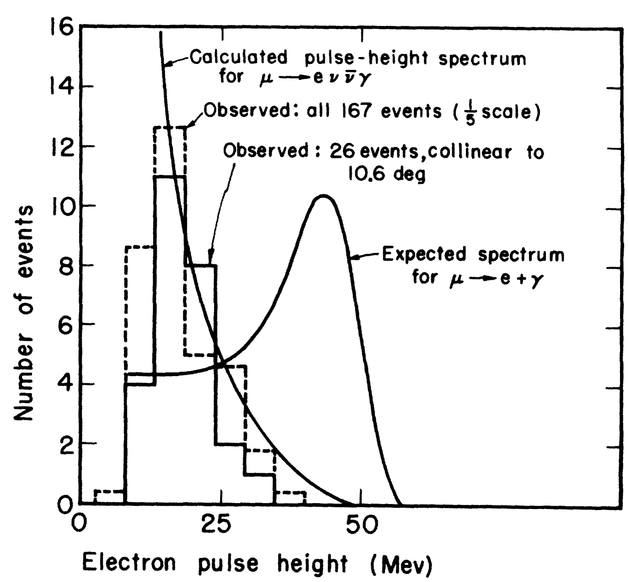

FIG. 3. Pulse-height spectra from positrons in NaI counter 5.

$\mu \rightarrow e+\gamma$ accounts for less than 1.9×10^{-7} of muon decays.

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SEARCH FOR CONVERSION OF MUONS INTO ELECTRONS

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The neutrinoless conversion of a muon into an electron, i.e., the process

$$\mu^- + N = N + e^-, \quad (1)$$

in which a μ^- bound in a Bohr orbit of a nucleus N is subsequently converted into an electron through coherent nuclear absorption, has recently been investigated by two groups.[1,2] In both experiments the sensitivity was sufficient to detect process (1) if it occurred with a branching ratio, R, of a few times 10^{-6} relative to ordinary muon capture. While no event has been recorded in one of these experiments,[2] three events were found in the other, against an expected background of 0.23 ± 0.04 accidental events.[1]

It should be recalled[3] that process (1) might indeed exist even if the process $\mu \rightarrow e+\gamma$, as yet unobserved,[4] is somehow forbidden. This is true independently of any specific assumption on the structure of the weak interaction, such as the hypothesis of the intermediate vector boson. Due to the virtual nature of the photon emitted and reabsorbed in process (1), the matrix element relative to the latter contains, in fact, monopole terms which do not exist in the process of muon decay into an electron and a real photon. The hypothesis of the vector boson, on the other hand, could also be reconciled with the experimental absence of process $\mu \rightarrow e+\gamma$, assuming for the boson an anomalous magnetic moment of appropriate values.[5] But process (1) should then exist, according to Ernst,[6] with $R \cong 8\times10^{-7}$, if the high-momentum cutoff is chosen equal to the boson mass.

A closer investigation of the possible existence of process (1) appeared desirable, therefore, from both an experimental[1] and a theoretical[3,5,6] point of view. The experiment reported here has a sensitivity about 20 times greater than the previous ones.[1,2]

The experimental setup, shown in Fig. 1, includes a monitoring telescope (plastic scintillators 1 and 2) for the incoming μ^-, a spark chamber, SC, where the muons are brought to rest, and a telescope for the outgoing electrons, formed by three thin scintillators (3, 4, and 5) and the large NaI crystal of CERN.[7] The NaI counter is used to measure the energy of the electron, which in the case of process (1) occurring coherently in Cu, is 103.8 Mev. The space correlation between the muon and the electron is seen in the two orthogonal stereoscopic pictures of the SC. Their time relationship is measured on the picture of the CRT of a 517*A* Tektronix oscilloscope where pulses from counters 1, 3, and NaI are displayed through