clusion can be drawn about the parity of the *K*.

We wish to thank G. Ascoli and R. D. Hill for useful discussions about the experimental data, and R. H. Dalitz, M. Ross, and G. Shaw for conversations about the theory.

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[1] P. T. Matthews and A. Salam, Phys. Rev. Lett. 2, 226 (1959).

[2] Summarized by M. F. Kaplon in the 1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), p. 171.

[3] Alles, Biswas, Ceccarelli, and Crussard, Nuovo cimento 6, 571 (1957).

[4] Jackson, Ravenhall, and Wyld, Nuovo cimento 9, 834 (1958).

[5] R. H. Dalitz, 1958 Annual International Conference on High-Energy Physics at CERN, edited by B. Ferretti (CERN, Geneva, 1958), p. 187.

[6] We use the terms "attractive" ("repulsive") in the usual field theoretical sense of the sign of the real part of the tangent of the phase shift at low energies being positive (negative). For a "repulsive" interaction, the question of whether the phase shift is dropping down from π (corresponding to a strong attraction) or going negative from zero (corresponding to a repulsion) can only be decided by the higher energy behavior (e.g., the sign of the effective range).

[7] J. D. Jackson and H. W. Wyld, Nuovo cimento (to be published).

[8] Dalitz showed that a_0 and a_1 must have the same sign.

[9] See reference 6. We note that a strong attraction is automatically consistent with the tentative conclusion of reference 3. It is not clear whether the experimental data of reference 3 are inconsistent with the other possibility of a repulsive, but strongly absorbing, interaction.

[10] R. H. Dalitz (private communication), and M. Ross and G. Shaw (private communication).

[11] P. T. Matthews and A. Salam, Phys. Rev. 110, 569 (1958); C. Goebel, Phys. Rev. 110, 572 (1958); K. Igi, Progr. Theoret. Phys. (Kyoto) 19, 238 (1958)

[12] S. F. Tuan, Phys. Rev. (to be published); also University of California Radiation Laboratory Report UCRL-8461 (unpublished).

UPPER LIMIT FOR THE DECAY MODE $\mu \to e + \gamma$

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In theories of the Fermi interaction, it has been suggested that the weak interactions all arise from the coupling of a vector current with a heavy charged boson.[1] One of the consequences of the existence of such an intermediate boson is the decay mode[2] $\mu \to e + \gamma$ which would be expected to occur with a branching ratio

$$R(\mu \to e + \gamma)/R(\mu \to e + \nu + \bar{\nu}) \sim 10^{-4}.$$

Experimentally an upper limit for this branching ratio has already been found[3-5] to be $\sim 10^{-5}$. Although the calculation based on the idea of the intermediate boson is ruled out by these measurements, the status of the theory of weak interactions demands a close examination of the possible decay modes of the muon. We have therefore continued the experiment previously reported[4] and improved upon the result.

The search for the $\mu \to e + \gamma$ decay mode was made by observing coincidences between a gamma detector and an electron detector placed on either side of a source of decaying positive muons. These were obtained by stopping the 60-Mev π^+ beam of the Nevis cyclotron in a lithium target. There, the π^+ mesons decayed into muons whose range was too short for them to escape from the target. The decay products were then counted in the two telescopes. The experimental arrangement is shown in Fig. 1. An event was defined b a fast coincidence between counts in the electron and gamma-ray telescopes with the requirement that none of the anticoincidence counters triggered at the same time. All counts were gated so they were recorded only if they occurred during a cyclotron beam burst.

In addition to the electronic selection of the events, an event was checked by photographing pulses displayed on two oscilloscopes. On one, a sweep speed of 20 millimicroseconds per centimeter permitted a rough check on the timing of one counter pulse from the electron telescope relative to two from the gamma-ray telescope. Displayed on a second oscilloscope, with a relatively slow sweep speed, were pulses from the remaining coincidence counters as well as 2′ and 3′ anticoincidence signals before they were pulse shaped. The signature of an event is shown in Fig. 2.

The efficiency of the electron telescope to detect 53-Mev electrons was estimated to be 0.75.

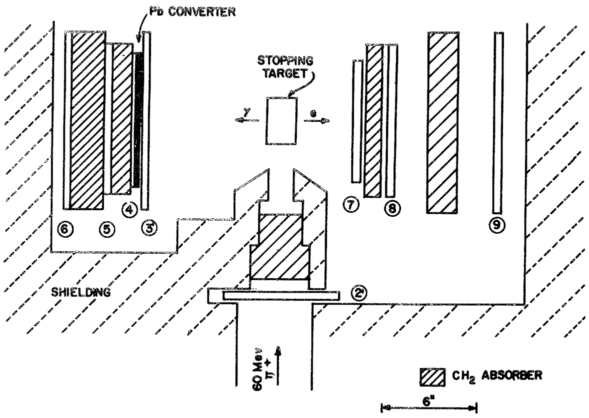

FIG. 1. The 60-Mev π^+ beam is stopped in the lithium target. Electrons are detected as a 789 coincidence. Photons are converted in the $\frac{3}{16}$-inch thick lead and are counted as a 456 coincidence in anticoincidence with 3′. All counters are plastic scintillators $\frac{1}{2}$ inch thick, except No. 4 counter which is $\frac{1}{4}$ inch thick. Counts coincident with incident beam particles were rejected by 2′. The shielding around the polyethylene absorber in the beam was lead and guarded against background from π^+ charge-exchange scattering.

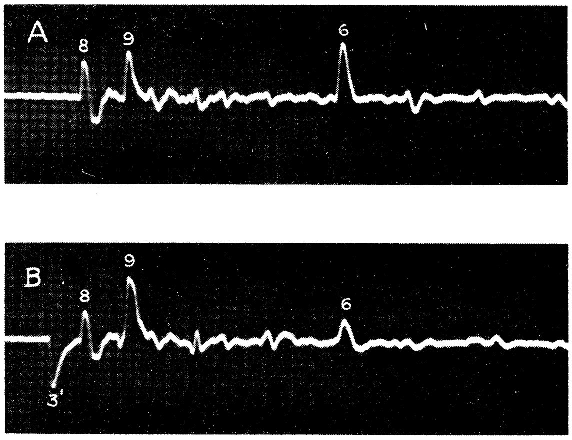

FIG. 2. Photographs of oscilloscope traces with a sweep speed of 1 μsec per centimeter. Trace A, with counter pulses 6, 8 and 9, is the signature of an event. One event was rejected on the basis of a trace which contained a pulse from the anticoincidence counter 3′. Trace B is an example of such an event.

The gamma-ray detector efficiency was calculated as a function of energy and was also experimentally determined with (a) the spectrum of gamma rays from the decays of π^0 mesons obtained by stopping the negative pion beam in a lithium hydride target,[6] and (b) attenuation measurements of electrons from the muon decays. The calculation and the measurements are in agreement, and from them is predicted a 0.15 probability for detecting 53-Mev gamma rays.

The sensitivity of the equipment to the $\mu \rightarrow e+\gamma$ decay mode was demonstrated by the observation of the radiative decay of the muon, $\mu \rightarrow e+\nu+\bar{\nu}+\gamma$, which, because of the simultaneous emission of an electron and gamma ray, is experimentally similar to the decay with no neutrinos. Several times throughout the run, the threshold energy requirements of the electron and gamma-ray detectors were lowered by removing the polyethylene absorbers, and under these conditions the measured counting rate was consistent with estimates of the radiative decay rate.[7] Other routine checks were made with the counters lined up in the direct meson beam, as well as by counting the gamma rays from the decays of charge exchange π^0 mesons produced by π^- captures in a lithium hydride target. For the latter test, a $\frac{1}{4}$-inch lead converter was placed in front of the electron telescope so that both detectors were sensitive to gamma rays.

The electron detector was used to measure the sample of decaying muons to which the detecting system was sensitive. Five counts were obtained as $e+\gamma$ coincidences out of 2.6×10^7 decay electrons. One of these counts was rejected upon examination of the slow oscilloscope photographs because an anticoincidence pulse failed to trigger electronically.

There are two sources of background which make significant contributions to the observed counting rate. One is the accidental counting rate between uncorrelated particles which register in both the electron and gamma-ray telescopes. The second is from real counts which originate from the radiative muon decay, $\mu \rightarrow e+\nu+\bar{\nu}+\gamma$. Backgrounds due to cosmic rays were eliminated by counting only during the cyclotron beam bursts, and by the use of an anticoincidence counter over the apparatus; while those which might arise from π^+ charge exchange scatterings were rejected by the 2′ anticoincidence counter placed in the pion beam.

The accidental rate was computed from the known gamma and electron counting rates and a measured value of the resolving time/cyclotron duty cycle. The last factor was obtained by measuring the accidental rate between uncorrelated decay electrons counted in both the electron and gamma-ray telescopes. For the sample of muons observed, 1.5 accidental counts were expected. The contribution to the counting rate due to the radiative decay has been calculated,[7] but since there are no previous experimental data the result is not considered reliable to better than a factor of two. An absolute lower limit to the expected number of counts from these decays is then 1.4 counts.

On the basis of four events, the analysis of the data with the background as discussed above yields a branching ratio $R(\mu \rightarrow e+\gamma)/\mathrm{R}(\mu \rightarrow e+\nu+\bar{\nu})$ which is probably less than 0.7×10^{-6}. The systematic error in the efficiency for detecting the $\mu \rightarrow e+\gamma$ decays is estimated to be not more than 30%, and the branching ratio is then found to be less than 2×10^{-6} with a 90% confidence level.

The authors are indebted to Dr. W. Chinowsky and Dr. A. Sirlin for discussions and to A. Garfinkel for his assistance with the experimental work, and they gratefully acknowledge the guidance and the valuable criticisms extended by Professor J. Steinberger throughout the course of the experiment.

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[1] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

[2] G. Feinberg, Phys. Rev. 110, 1482 (1958).

[3] S. Lokanathan and J. Steinberger, Phys. Rev. 98, 240 (A) (1955).

[4] Berley, Lee, and Bardon, Post-Deadline Paper, American Physical Society Meeting, New York, January, 1959.

[5] Davis, Roberts, and Zipf, Phys. Rev. Lett. 5, 211 (1959).

[6] Lithium hydride was chosen over other hydrogenous materials (polystyrene, polyethylene, water), in which we also found a substantial number of π^- captures by hydrogen, because the low conversion probability in the lithium made this substance more favorable for efficiency measurements.

[7] The transition probability for the radiative decay was computed from the formulas derived by Behrends, Finkelstein, and Sirlin [Phys. Rev. 101, 866 (1956)], by assuming a $V-A$ interaction. An analysis of the data obtained is now in progress and a further communication on the subject of the muon decay with inner bremsstrahlung will follow.

CORRECTIONS TO THE $3D$-$2P$ TRANSITIONS IN μ-MESONIC PHOSPHORUS AND THE MASS OF THE MUON

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The recent precise determination of the muon magnetic moment[1] has raised the question as to whether the lower limit for the μ-meson mass can be trusted with enough precision to demonstrate a clear discrepancy between the experimental value for the muon moment and its value predicted by standard quantum electrodynamics. Actually, by using the best lower limit known up to now,[2] the inequality

$$g_\mu > 2(1.00158 \pm 0.00022), \tag{1}$$

obtains, whereas quantum electrodynamics predicts[3]

$$g_\mu = 2(1.001165). \tag{2}$$

The discrepancy of a few parts in 10^4 requires a precise knowledge of the precision to which the lower limit of the muon mass can be trusted. Crowe's best value for that limit involves a tentative limit of error of 2×10^{-4}, although some corrections were only guessed and some others were not yet evaluated. Owing to the real importance of having the most precise value of the limit, this paper is devoted to a very careful examination of the corrections in order to reduce considerably the limit of error. A summary of the corrections we have been considering is listed in Table I.

The fine structure splits the $3D$-$2P$ transition into a triplet, the components of which have the following energies in electron-volts:

$$3D_{3/2} - 2P_{3/2}\text{: } [1]\ (425.42) m_\mu / m_e; \tag{3}$$

$$3D_{5/2} - 2P_{3/2}\text{: } [9]\ (425.65) m_\mu / m_e; \tag{4}$$

$$3D_{3/2} - 2P_{1/2}\text{: } [5]\ (427.75) m_\mu / m_e. \tag{5}$$

The numbers in square brackets are the relative intensities.

Fitch, Rainwater, and Koslov[4] have shown that the $3D$-$2P$ transition energy falls above the Pb K-edge energy and below the Bi K-edge. Therefore the Pb K-edge energy will provide a lower limit to m_μ/m_e. Using the very probable value[5] of (88015 ± 5) ev for the Pb K-edge energy, one

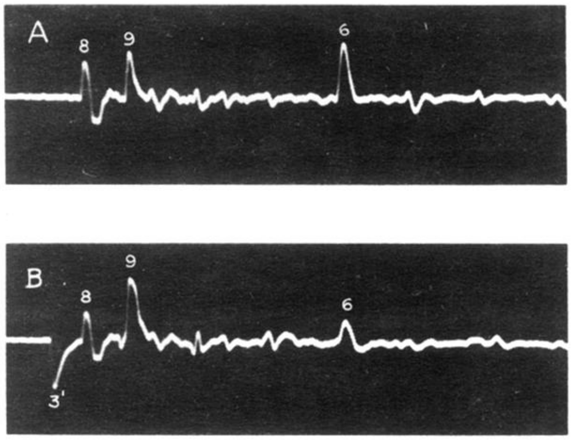

FIG. 2. Photographs of oscilloscope traces with a sweep speed of 1 μsec per centimeter. Trace A, with counter pulses 6, 8 and 9, is the signature of an event. One event was rejected on the basis of a trace which contained a pulse from the anticoincidence counter 3′. Trace B is an example of such an event.