Search for $\mu \rightarrow e+e+e$*

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(Received 26 November 1962)

We have made a search for the neutrinoless decay mode $\mu \rightarrow e+e+e$. Positive pions from the Berkeley 184-in. synchrocyclotron were stopped in a lithium target. The detection of three decay particles not in coincidence with an incoming pion served to trigger two thin-plate spark chambers viewing the decays. The energy of the decay particles was measured with a combination of NaI counters and range telescopes. The spark chamber pictures were first scanned for events with three tracks meeting at a common point in the target. A requirement that no angle between any of the three tracks could be greater than 160° eliminated essentially all of the main source of background, namely, knock-on collisions of electrons passing through the target. Further requirements for the three tracks to be coplanar and for each particle to have at least 16 MeV eliminated all but one ambiguous event. For this event insufficient energy information was available. If we assume that one event to be $\mu \rightarrow e+e+e$, and with a calculated detection efficiency of 0.0083, an upper limit for the branching ratio for this mode can be set at 1.5×10^{-7} with a 90% confidence level.

INTRODUCTION

THE search for neutrinoless decay modes of the muon has been carried on with much vigor but without measurable success. Various experimenters have looked for $\mu \rightarrow e+\gamma$,[1] $\mu \rightarrow e+\gamma+\gamma$,[2] $\mu+N \rightarrow e+N$,[3] and $\mu \rightarrow e+e+e$[4] but no evidence for these decay modes has been found. The presence of an intermediate vector boson as well as higher order weak-interaction processes would allow these decay modes. Figure 1 illustrates the Feynman diagrams for the process $\mu \rightarrow e+e+e$. However, these diagrams are only valid if the muon and electron fields are coupled to the same neutrino field. The presence of two different kinds of neutrinos, as indicated by Danby *et al.*,[5] would rigorously forbid all of the neutrinoless decay modes of the muon.

Even if the selection rules permit the neutrinoless decay modes, the theoretical analyses are somewhat ambiguous. If one calculates the second-order weak-interaction diagram of Fig. 1(d)[6] a badly divergent integral results and the rate is proportional to the fourth power of a cutoff momentum. Calculations of the rate of $\mu \rightarrow e+\gamma$ have been made[7] using the intermediate vector boson and the result turns out to be highly dependent on the electromagnetic properties of the vector boson. Recently, Lee[8] has succeeded in calculating the $\mu \rightarrow e+\gamma$ rate in a nonambiguous way but the experimental rate is far below his result.

One could consider then, the negative experimental results of previous workers and of our own search for $\mu \rightarrow e+e+e$ as further evidence for two neutrinos.

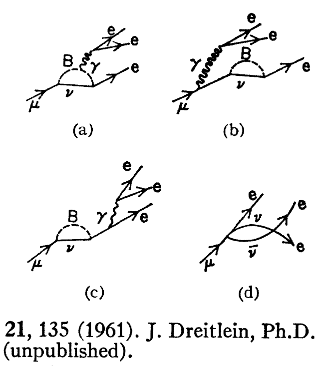

FIG. 1. (a), (b), and (c) are Feynman diagrams corresponding to the decay $\mu \rightarrow e+e+e$ via an intermediate vector boson; (d) corresponds to the second order weak-interaction process.

* Work supported by the U. S. Atomic Energy Commission.
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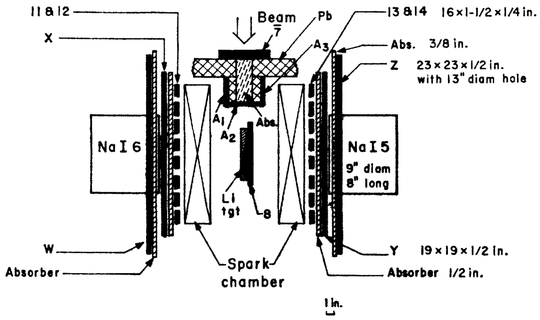

FIG. 2. The experimental arrangement.

Indeed, if one assumes that the neutrinos are different, so that the contributions of the charged lepton currents to the neutrinoless decays vanish, this experiment serves to set a low limit on the presence of neutral currents in the effective interaction.

EXPERIMENTAL ARRANGEMENT

Figure 2 shows the experimental arrangement. A positive pion beam of 200 MeV/c from the Berkeley 184-in. synchrocyclotron passed through counter $\overline{7}$, was moderated by a block of carbon and was stopped in a 1 in.×5 in.×5 in. lithium target. Lithium was used as a target material in order to reduce multiple coulomb scattering. The counter $\overline{7}$ was used to prevent prompt background events due to the scattering of pions and to allow time for the pions to decay into muons. To ensure that three decay particles were present two pairs of counters, 11 and 12, and 13 and 14, called the finger counters, were used. Figure 3 shows the construction of these counters. The outputs of the photomultipliers of the finger counters were fed into tunnel diode discriminators[9] and then into a tunnel diode coincidence circuit that was set to fire on any three out of four inputs. The logic, see Fig. 4, was completed by requiring a pulse from counters 8, X, and Y, and no pulse from counter A. The counter 8 ensured that a particle came from the target and the counters X and Y were the first counters in a range telescope arrangement. Counter A was used to reduce scattered background.

The characteristic signature of a $\mu \rightarrow 3e$ event is three electrons whose total energy equals 106 MeV. If the muon is at rest, as in our case, the three electrons are coplanar except for multiple scattering in the target.

The energy of the decay electrons was measured with a combination of range telescopes and NaI crystals. In our geometry the solid angle of the sodium iodide crystals was such that at least 1 electron could enter one of the crystals in about half of all $3e$ events. The range telescopes consisted of counters X and Y as a first set and W and Z as the second set. An electron would require 9 MeV to pass through counters X or Y and 16 MeV to reach counters W or Z. An electron would lose 12 MeV before reaching the NaI crystals. Counters W and Z had 13-in. holes cut in them to accommodate the NaI crystals because it was decided that the NaI counters should view the decay electrons with as little absorber as possible in order to attain maximum energy resolution. [As it turned out it would have been more useful to use an unmutilated range telescope and to leave out the NaI counters, because of the considerable area between the outer edge of the NaI crystals and the inner edge of the counters W and Z, and because the superior energy information provided by the NaI crystals was not needed. The only energy information for an electron headed toward this area would be that of the first range counter.]

Two 16 in.×16 in. spark chambers were used to view the decay electrons. The spark chambers were constructed of 1-mil aluminum foil stretched on Plexiglas frames. The chambers were assembled from three modular units, each consisting of three foils and two frames, giving two useful gaps per unit. These three units were spaced over an interval of about three inches. The chambers were filled with a mixture of argon and helium and were fired with a high-pressure triggered spark gap. The spark gap applied a voltage pulse of 15 kV to the chambers about 0.8 μsec after the actual event had occurred. Clearing fields of 10 V were used to suppress tracks from particles which passed through the chambers more than a microsecond before the voltage pulse was applied. The individual gap efficiency of the spark chambers was found to be greater than 0.95 for the chamber with one track in it and 0.75 for the chamber with two tracks. Since we required at least three out of the six gaps to fire before accepting a track there is an incurred loss of 8% in the efficiency for detecting $\mu \rightarrow 3e$ events. This loss is calculated by using the binomial distribution and observing what fraction of the time two or less gaps would fire.

The number of muons stopped was monitored by observing the decay electrons that went into the NaI crystal. The coincidences between 8, Y, and NaI 5 were counted and the known solid angle of $4\pi \times 0.046$ sr gave the number stopped.

Two oscilloscopes were photographed. One was a dual beam Tektronix 551 which displayed the two NaI pulses

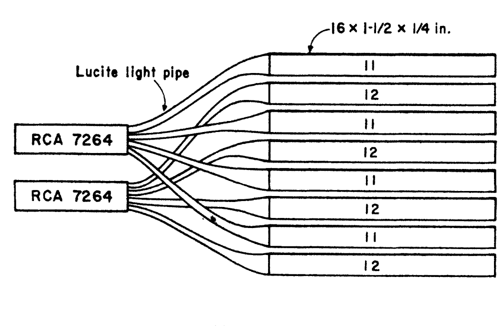

FIG. 3. Construction of the finger counters.

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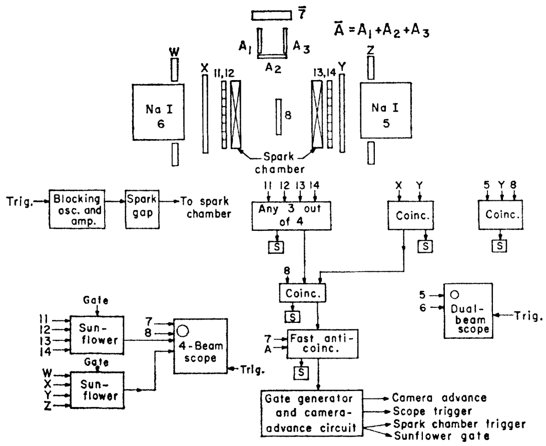

FIG. 4. Block diagram of the electronics.

and the other was a four beam modified Tektronix 517. Counters 7 and 8 were each put on a separate trace of the four beam scope. The outputs of W, X, Y, and Z were gated with a master pulse from the coincidence block, then were delayed each with respect to the others, mixed in the "sunflower," and put on one trace of the four beam scope. The sunflower is a group of twofold coincidence circuits; one input of each circuit is a common gate pulse. The outputs of 11, 12, 13, and 14 were put on the remaining trace.

BACKGROUND

The background in this experiment can come from accidental coincidences triggering the electronics or from processes that simulate $\mu \rightarrow 3e$ events. Because the particles that accidentally trigger the electronics usually come from different points in the target, the former process can be distinguished from $\mu \rightarrow 3e$ events by the requirement that the spark chamber pictures have three tracks that are concurrent in the target. In addition, the three tracks are not, in general, coplanar. Using these rejection criteria, combined with the expected number of accidentals calculated from the observed rates, the number of confusing pictures from this source of background is found to be negligible.

Several of the processes that could simulate $\mu \rightarrow 3e$ events are:

$$\mu \rightarrow e+\nu+\bar{\nu}+(\gamma \rightarrow e+e), \tag{1}$$

$$\mu \rightarrow e+e+e+\nu+\bar{\nu}, \tag{2}$$

$$e+e \rightarrow e+e \quad \text{(knock-on collisions)}. \tag{3}$$

Processes (1) and (2) have neutrinos to take up momentum and in general the three electron tracks will not be coplanar. Process (3) is by far the most serious because three tracks will be observed and they will be coplanar. The simulated event could be, e.g., a high-energy electron originating from a stopped muon in counter W making a knock-on collision in the target. All of the necessary electronic requirements would be satisfied and the event could not be distinguished from a $\mu \rightarrow 3e$ event.

There are two properties of these knock-on collisions that can be used to distinguish them from $\mu \rightarrow 3e$ events; the total energy and the angular distribution of the scattered particles with respect to the incident particle. We shall show that by a suitable choice of biases on these properties we can eliminate all of the knock-on background.

A kinematical restriction that exists in two body collisions of equal mass is that there must be an angle $\theta_{\min}$ between the incident particle and one of the two emerging particles such that $\cos\theta_{\min} \leq -(1-m/T)$, where T = incident energy ($T \gg M$). For $T=10$ MeV, $\cos\theta_{\min} \leq = 0.95$. We have a range telescope for those electrons that enter the counters W and Z and a bias of 12 MeV for those electrons that enter the NaI counters.

If we set the energy bias at 16 MeV and an angular bias of $\cos\theta_{\min} \geq -0.95$ one can see that a knock-on collision cannot simultaneously satisfy both criteria. As these biases erode the efficiency for detecting true $\mu \rightarrow 3e$ events, they were chosen to minimize this loss and to maximize the rejection of knock-on background. The remaining background comes from chance coplanar events of processes (1) and (2) and from knock-on collisions where there is insufficient energy information, i.e., when some of the electrons are headed toward the areas not covered by either the NaI counters or the last range telescope counters.

SCANNING AND ANALYSIS

With 3.2×10^9 stopped pions, 39 000 pictures were taken. The spark chamber pictures were first scanned for events in which three tracks were concurrent in the target. Approximately 10% of the pictures satisfied these requirements; most of these, however, had two tracks that were within several degrees of colinearity and being attributed to knock-on collisions were rejected in the first scan as a preliminary step to set the angular bias of $\cos\theta_{\min} \geq -0.95$. Two hundred and fifty-eight events were measured on a digitized scanning machine and the coordinates of the individual sparks on each of the two 90° stereo views were punched on IBM cards. An IBM 1620 computer program determined a least squares fit to a straight line for each track and then spatially reconstructed the event. Forty-nine events satisfied the criteria that $\cos\theta_{\min} \geq -0.95$.

To determine the coplanarity of each event, the quantity Σ is defined as $\Sigma = (\theta_{12}+\theta_{23}+\theta_{13})/2\pi$. For a coplanar event, $\Sigma=1$; and for a noncoplanar event, $0 \geq \Sigma < 1$. The multiple Coulomb scattering in the lithium target and in counter 8 will affect the coplanarity of a $\mu \rightarrow 3e$ event and if we compute this effect on Σ we find that we would have to consider all Σ's between 0.98 and 1 as coplanar. $\Sigma=0.98$ corresponds to the maximum deviation in coplanarity of a configuration in which one of the electrons was scattered about $2\frac{1}{2}$ times

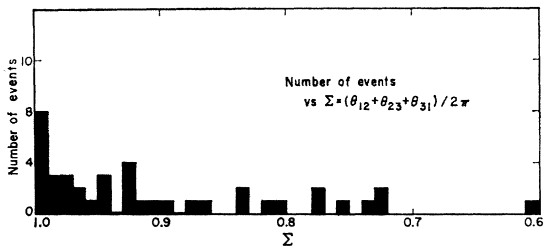

FIG. 5. Number of events vs Σ.

the rms multiple Coulomb scattering angle. The efficiency for detecting $\mu \rightarrow 3e$ events is reduced by 8% by this effect. The 43 events are plotted as a function of Σ in Fig. 5 and it is seen that 11 satisfy the requirement that $\Sigma \geq 0.98$.

Of these 11 events none satisfied the energy requirements of at least 16 MeV per particle. One event was ambiguous because two of its particles were headed toward areas not covered by either the NaI counter or the last set of range telescope counters. The energy of the third particle was 16 MeV or greater because it passed through the counter W. Hence, we conclude that there could be at most only one possible $\mu \rightarrow 3e$ event.

The 43 events as seen in Fig. 5 would not be inconsistent with the hypothesis that they are due to $\mu \rightarrow 3e+\nu+\bar{\nu}$ decays. Parker and Penman[4] observed five events which could be attributed to this decay mode. Our rate for $\mu \rightarrow 3e+\nu+\bar{\nu}$ is about twice that observed by Parker and Penman, but our geometry is different and, since the angular distributions are not well known, it could very well be that the rates are geometry dependent.

RESULTS

The geometrical efficiency for detecting a $\mu \rightarrow 3e$ event was determined by a Monte Carlo type calculation. Using the matrix element of Fig. 1(d),[6] the momentum distributions are easily found to be $x^2(1-\frac{2}{3}x)$ for the like particles and $x^2(1-x)$ for the unlike particle where x equals twice the momentum in units of the muon mass time c, and the relativistic approximation $E \gg m$ has been made. The Monte Carlo program picked random configurations weighted by these distributions, oriented the configuration randomly in space and then computed a hit or a miss. The geometrical efficiency so obtained was $\Omega = 0.021$. The losses due to the angular and energy biases are also computed from the same program and the corresponding efficiency is $E_1 = 0.53$. A point which arises in this last calculation is that once the angular bias of $\cos\theta_{\min} \geq -0.95$ has been set and the losses computed, no more losses are incurred by invoking the energy bias because the particles are kinematically restricted by the angular bias to have more than 16 MeV.

We write the branching ratio for $\mu \rightarrow 3e$ as

$$R = \frac{C}{N\Omega E},$$

where C = number of $\mu \rightarrow 3e$ observed, N = number of muons stopped in the target, Ω = geometrical efficiency for detecting a $\mu \rightarrow 3e$ event, and E = product of the various efficiencies. Now

$$N = \frac{N'(1+f)}{\Omega_{5Y8}/4\pi},$$

where N' = number of $5Y8$ coincidence counts observed $= 1.1 \times 10^8$; Ω_{5Y8} = solid angle of NaI_5 and is computed to be $4\pi \times 0.046$ steradians; f = ratio of muon decay electrons below bias to those above and is determined by folding the experimentally determined resolution function of the NaI crystals into the known normal muon decay spectrum. In this way f is found to be 0.4, and N is computed to be 3.2×10^9. The efficiency E is the product of the angular and energy bias efficiency, 0.53, the scanning efficiency, 0.95 determined by rescanning 20% of the data, the spark chamber gap efficiency, 0.90 due to the fact that we require at least three gaps to fire, and a correction of 0.90 due to the fact that 10% of all pictures had multiple tracks that could mask a $\mu \rightarrow 3e$ event. The product of Ω and E is found to be 0.0083 and for $C = 1$ the branching ratio is $R = 3.7 \times 10^{-8}$.

To obtain an upper limit to the $\mu \rightarrow 3e$ branching ratio with a 90% confidence level we look at the summed Poisson probability distribution

$$S(x) = \sum_x^\infty (m)^x \exp(-m)/x!,$$

where $m = N\Omega E R$ and x = number of events plus one. If we assume the one ambiguous event was not a $\mu \rightarrow 3e$ decay then $x = 1$ and for $S(x) = 0.90$, $m = 2.3$ and $R \leq 8.5 \times 10^{-8}$. If we assume the ambiguous event to be a $\mu \rightarrow 3e$ decay then $x = 2$, $m = 3.9$, and $R \leq 1.5 \times 10^{-7}$.

In view of the recent experiments[5] establishing the nonidentity of the interactions of neutrinos associated with muons and electrons our experiment serves to put an upper limit to the ratio of neutral to charged currents appearing in the effective interaction.

If G_n and G_c are, respectively, the neutral and charged current coupling constants then $G_n/G_c \leq 4 \times 10^{-4}$.

ACKNOWLEDGMENTS

We are grateful to James Vale and the crew of the 184-in. synchrocyclotron at the Lawrence Radiation Laboratory for their help during the course of this experiment. The Pennsylvania Group is grateful for the facilities which were provided for us, as visitors at the Lawrence Radiation Laboratory, during the course of the experiment.

Dr. G. Shapiro was of aid in setting up and running the experiment. S. Kounosu, and D. Wolfe assisted in all phases of the experiment. B. Dieterle, H. Dost, M. Ossar, C. Schultz, and W. Troka assisted in the actual running of the experiment.