Search for the Reaction $\mu^- + \mathrm{Cu} \to e^+ + \mathrm{Co}$

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We have searched for the reaction $\mu^- + \mathrm{Cu} \to e^+ + \mathrm{Co}$, which is allowed by the lepton conservation scheme that assigns the same lepton number to e^-, μ^+, ν_e, and $\bar{\nu}_\mu$. One event was observed which was consistent with the above reaction, while the expected background was $\simeq 0.02$ events. Although we cannot be certain whether the process was detected, we can set an upper limit on the branching ratio relative to ordinary muon capture of $R \leq 2.6 \times 10^{-8}$ (90% confidence level).

The distinction between electron neutrinos and muon neutrinos[1] and the absence of some hypothetical interactions, such as $\mu \to e\gamma$, have led to the formulation of several potentially valid schemes of lepton conservation.[2] Among these, the hypothesis that there is one additive lepton number[2,3] with values $+1$ for e^-, μ^+, ν_e, and $\bar{\nu}_\mu$, -1 for their antiparticles, and 0 for all others is attractive, because no additional muon number is required, and the neutrinos ν_e and $\bar{\nu}_\mu$ are the negative and positive helicity components of one four-component neutrino. Pontecorvo[4] has noted that if the reaction $\mu^- + Z \to e^+ + (Z-2)$ exists, possibly as a manifestation of a hypothetical first-order weak process,[4,5] $\mu^- + \Delta^{++} \to e^+ + \Delta^0$, then this scheme would be singled out as the correct one.

This Letter describes a search[6] for the reaction $\mu^- + \mathrm{Cu} \to e^+ + \mathrm{Co}$. The expected maximum energies of positrons due to the process in Cu^{63} and Cu^{65} are 102 and 90 MeV,[7] corresponding to $\mathrm{Cu}^{63} \to \mathrm{Co}^{63}$ and $\mathrm{Cu}^{65} \to \mathrm{Co}^{64} + n$ transitions, respectively. The experiment was performed using the 100-MeV/c backward muon beam (muons from $\pi^- \to \mu^- \bar{\nu}_\mu$ decay are emitted at 180° in the c.m. system) from the Space Radiation Effects Laboratory synchrocyclotron. The total number of muons stopped in the targets was 6.22×10^{10} during two runs with slightly different setups.

Figure 1 shows the experimental setup used in the second run, when 85% of the data were accumulated. Muons were degraded with CH_2 absorbers and stopped in either of two Cu targets, target 1 (1.36 g/cm^2) or target 2 (0.886 g/cm^2). After a muon stop signal, $S_1S_2S_3\bar{S}_4$ or $S_1S_2S_3S_4\bar{S}_5$, there was a 10-nsec dead time, followed by a 400-nsec detection period, during which a particle emerging from the target and passing through the spectrometer would register coincidence $S_4S_5S_6S_7S_8\bar{S}_3\bar{S}_2\bar{S}_1$ or $S_5S_6S_7S_8\bar{S}_4\bar{S}_3\bar{S}_2\bar{S}_1$ as a potential event. The detection period allowed for 86.2% of the possible muon captures[8] in Cu to be detected. An event signal, defined above, triggered the spark chambers and initiated transfer of the following quantities to an on-line computer: the spark positions in the chambers, the time between the muon stop signal and the event signal, the time of flight between S_5 and S_6, and the pulse height of S_6. Examination of the pulse height and time of flight, along with the use of aluminum absorbers between S_6 and S_7, and S_7 and S_8, enabled us to identify positrons and to eliminate heavy charged particles produced by muon nuclear captures.

Events were considered valid when at least four of the spark chambers, SC_3 and SC_4 or SC_5, and SC_6 and SC_7 or SC_8, gave single sparks and the resulting trajectory satisfied the "goodness-of-fit" criteria discussed below. The momentum of a particle passing through the spectrometer was determined from the spark positions by an

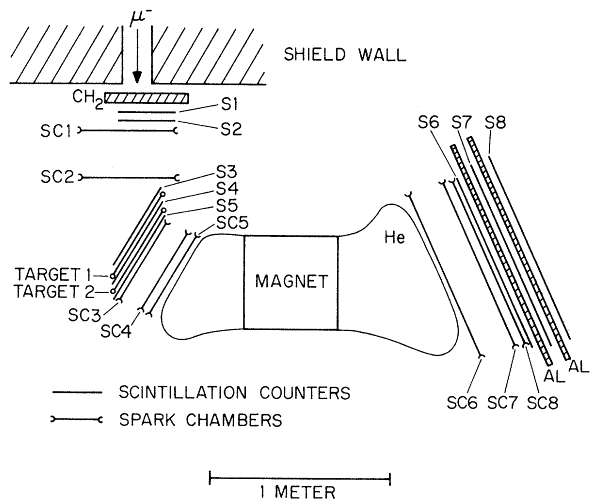

FIG. 1. Experimental setup: S_1–S_8 are scintillation counters, SC_1–SC_8 are magnetostrictive readout wire spark chambers, and He is a helium bag through the magnet set at a central field of 2.0 kG.

iterative method,[9] which fit the vertical and horizontal trajectories of the particle using the measured magnetic field distribution. The "goodness-of-fit" criteria for the calculated trajectories were obtained for various momenta using positrons from muon and pion decays and positive pions scattered from the targets.

The average fractional solid angle subtended by the spectrometer was determined from a Monte Carlo calculation as a function of particle momentum. It varied monotonically from $(2.0 \pm 0.2)\times 10^{-3}$ at 40 MeV/c to $(6.0\pm 0.6)\times 10^{-3}$ at 95 MeV/c for positive particles, and from $(1.0\pm 0.1) \times 10^{-3}$ at 60 MeV/c to $(6.0\pm 0.6)\times 10^{-3}$ at 100 MeV/c for negative particles. The efficiency of firing counters S_4 through S_8 and at least four of the required chambers was measured to be $(75.5\pm 7.0)\%$.

Six types of accidental coincidences were monitored continuously by putting S_8 or $S_6S_7S_8$ or S_5 in a random-time relationship with the other signals making up the event signatures from targets 1 or 2. A typical total rate of random events was 0.32×10^{-2} sec^{-1}, while the total rate of the event signature was 1.48×10^{-2} sec^{-1}. The difference between the real and accidental event rates was mainly due to electrons from muon decay which scattered through the spectrometer.

The 70-MeV positrons from $\pi^+\to e^+\nu_e$ were used to determine the abolute momentum scale and the momentum resolution. We found $\Delta p/p = 10\%$ and 5% for positrons originating from targets 1 and 2, respectively. As a check of the solid-angle calculation, the efficiency measurement, and the overall operation of the setup, we measured the $(\pi^+\to e^+\nu_e)/(\pi^+\to \mu^+\nu_\mu)$ branching ratio, R', in a short run. We found R' to be $(0.8\pm 0.3)\times 10^{-4}$, compared with the known value of $R' = (1.248\pm 0.028)\times 10^{-4}$.[10]

There were eleven events which satisfied the time-of-flight and pulse-height conditions for positrons and for which the trajectories satisfied the goodness-of-fit criteria. These events, all of the $\mu^-\to e^+$ type, are shown as a histogram in Fig. 2. After energy losses from radiation and collisions were restored, ten of the events had original momentum less than 64 MeV/c and one event from target 2 had an original momentum of 89.9 ± 3.5 MeV/c (detected momentum of 83.9 MeV/c).

Various processes were considered to account for this spectrum. The most significant was due to conversion of photons from radiative muon capture. The photons (averaged maximum energy ~90 MeV) could convert to e^+, e^- pairs, where

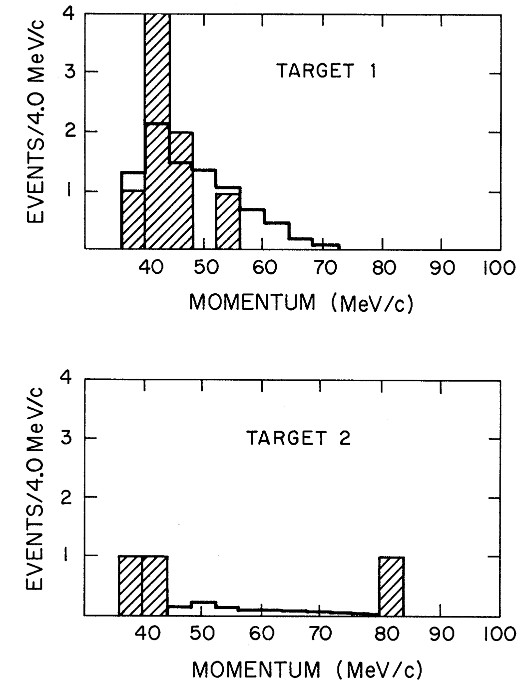

FIG. 2. The observed positron spectra (hatched) and the calculated spectra for positrons from conversion of radiative-muon-capture photons with energy $50 < E_\gamma < 91$ MeV (solid line).

the e^+ received most of the available energy and the e^- stopped undetected in the target. We calculated the expected number of events as follows:

(1) The number and distribution of photons expected from radiative muon capture were calculated in the range $50 < E_\gamma < 91$ MeV in steps of 2 MeV. This was done by normalizing a linear approximation of the theoretical spectrum of Rood and Tolhoek[11] for $50 < E_\gamma < 91$ MeV to the experimental branching ratio[12] of $(1.20\pm 0.18)\times 10^{-4}$ for the above range of photon energies.

(2) For each photon energy region the probability for producing an e^+, e^- pair was calculated for cases with electron energies $E_{e^-} \leq 3.5$ MeV (target 1) and $E_{e^-}\leq 1.5$ MeV (target 2) using the Bethe-Heitler equations.[13]

(3) The number of expected photons for each 2-MeV region was multiplied by the calculated conversion probability and by the proper solid-angle factor for the corresponding positron momentum, after average energy losses from collisions and radiation were subtracted.

The solid lines in Fig. 2 are the distributions calculated from radiative muon capture as described above. The expected numbers of positrons from conversion of photons with energy

$50 < E_\gamma < 91$ MeV were 8.7 ± 3.0 and 1.0 ± 0.4 in targets 1 and 2, respectively. We observed eight events from target 1 and two from target 2 that were consistent with conversion of photons in the above energy region. Only the event at 83.9 MeV/c seems to be inconsistent with radiative muon capture. The calculated number of expected events with momenta larger than 79.5 MeV/c from target 2 was 0.013.

Among the other possible sources of background considered were radiative pion absorption, radiative muon decay, scattering of high-energy electrons from muon decay, elastic scattering of beam particles, and proton emission following muon capture. All of these were expected to produce <0.01 events with momenta greater than 70 MeV/c.

If the event at 83.9 MeV/c were due to the process searched for, it would be consistent with the reaction $\mu^- + Cu^{65} \to e^+ + Co^{64} + n$. It would also be consistent with the Cu^{63} case considering a possible nuclear excitation of 10 to 20 MeV to a giant resonance state[14] in Co^{63}.

From the observation of only one possible event, we cannot state whether the reaction $\mu^- \to e^+$ has been detected. We can, however, place an upper limit on the branching ratio for the reaction relative to ordinary muon capture. Using the Poisson formula, we have

$$P_n(R) = [(ER + b)^n/n!] \exp(-ER - b),$$

where $P_n(R)$ is the probability that the branching ratio has the value R, $n = 1$ is the number of observed events, $b \cong 0.02$ is the expected background and $E = (1.892 \pm 0.026) \times 10^8$ is the effective number of trials. Normalizing $P_n(R)$ to unity at its maximum value, we found $R \leq 2.6 \times 10^{-8}$ at a 90% confidence level.

From a calculation by Kisslinger,[5] this branching ratio can be related to the ratio of the hypothetical coupling constant G for this interaction relative to the vector coupling constant G_v, $G/G_v \simeq (R/2.6 \times 10^{-6})^{1/2} \lesssim 0.10$.

The results of this search also yield a new upper limit on the branching ratio for the hypothetical process $\mu^- + Cu \to e^- + Cu$[15] relative to ordinary muon capture. Since no events consistent with this process were observed, we found $R(\mu^- \to e^-) \leq 1.6 \times 10^{-8}$ (90% confidence level) for the coherent process, i.e., the final-state nucleus remained in the ground state.

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