$\mu \rightarrow e + \gamma$ 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

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

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 recalled³ 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 $R \cong 8 \times 10^{-7}$, 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 experimental¹ 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 517A Tektronix oscilloscope where pulses from counters 1, 3, and NaI are displayed through

FIG. 1. Layout of the experimental setup. Counters 1 ($20 \times 20 \text{ cm}^2$) and 2 ($15 \times 20 \text{ cm}^2$) are 1.3 cm thick. Counters 3, 4, and 5 are disks of 12.5-cm diameter, 0.65 cm thick.

appropriate delays. Events in which counters 1 and 3 are crossed simultaneously ("prompt events") can be readily recognized and rejected. The amplitude of the NaI pulse gives the energy released in the NaI crystal. Calibration was made by sending into the crystal γ rays of known energies from radioactive sources (Na^{22} and Co^{60}) and from Pb μ -mesonic atoms. A further point of the calibration curve was obtained from the end point of the energy spectrum of decay electrons from μ^- stopped in a thin polyethylene target. Pileup effects due to two particles losing comparable energies in the NaI counter at a time distance of no less than about 30 nsec could be recognized from the shape of the NaI pulse.

The spark chamber, the oscilloscope sweep, and their film advancement systems were triggered whenever a coincidence (12) was followed within 390 nsec by a coincidence among the pulses of counters 3, 4, 5, and NaI, provided the latter was greater than a given threshold. To reduce the rate of the pictures to a reasonable value this threshold was set during the main run at a level

corresponding to about 70 Mev released in the crystal.

The synchrocyclotron was operated with an internal vibrating target⁸ at a duty cycle of $\sim 30\%$. 90-Mev μ^- mesons from the muon channel⁹ were bent by a deflecting magnet and transported by four additional quadrupoles to the apparatus, which could thus be effectively shielded against background particles. The muon stopping rate was about $33\,000 \mu^-/\text{sec}$.¹⁰

The nine Cu plates of the SC (side of incoming muon) and the four Al plates (side of outgoing electron) had a 0.2-cm thickness and 18.18-cm^2 sensitive area. Twelve 0.6-cm gaps were available to see the tracks of particles crossing the SC. The chamber was filled with a mixture of Ne ($\sim 75\%$), He ($\sim 18\%$), and Ar ($\sim 7\%$) at atmospheric pressure. It was operated by a fast (80 nsec over-all delay) high-current ($\sim 5 \times 10^4$ amp) triggering system.¹¹ At an operating voltage of 20 kv, the SC had an efficiency greater than 95% over its sensitive time adjusted at ~ 700 nsec choosing a clearing field of 33 v/cm.

During the main run $2.39 \times 10^9 \mu^-$ mesons were stopped in the six central Cu plates of the SC (namely the fourth to the ninth, inclusive) selected for reliable identification of the μ^- and e^- tracks. Out of 2361 SC and oscilloscope pictures taken during the run, only five were retained, all others clearly showing, either on the SC views or on the oscillogram, the spurious nature of the corresponding event. The energies of the secondary particle, interpreted as an electron, can be well determined taking into account only energy losses by ionization in the SC plates and counters, since the bulk of the radiation losses is recovered by the NaI crystal. They are reported in Table I. One of the five events is illustrated in Fig. 2.

We have evaluated the branching ratio R using only the four events with energy between 90 and 110 Mev. The over-all efficiency for detection of electrons from process (1) in this energy interval has been determined by direct measurements with 100-Mev electrons and found to be 0.7 ± 0.1 . We recall that 92% of the μ^- are captured in Cu where their lifetime is 160 nsec. 91% of the capture electrons would fall within the 390-nsec time width of our electronics. The effective average solid angle for their acceptance is ~ 0.2 sr. The assumption that the four events are due to process (1) would give, therefore, $R = (1.6 \pm 0.8) \times 10^{-7}$. We have estimated, however, that the expected number of spurious accidental events is 4.9.

Table I. List of events fulfilling the requirements of space and time correlation. If the events were due to process (1), the secondary electrons would have the energies given in the last column. The actual electron path, determined through the two stereoscopic views of the SC, was used to obtain these energies.

Event No.	SC stopping plate	Energy released in NaI (Mev)	Total energy of secondary electron (Mev)
1391	8	85	98.8
2080	5	79	102.7
4047	7	68	76.8
4092	8	84	98.3
4474	5	84	105.2

FIG. 2. Spark-chamber views and oscillogram of event No. 4047. Though fulfilling all requirements of space and time correlation, this event was not used in deducing R because of its low energy (~ 77 Mev). In addition to the fast pulse seen on the oscillogram, the slow integrated pulse of the NaI counter was recorded on a 200-channel pulse-height analyzer. When possible (namely when no pileup effects spoiled in the slow pulse), a better determination of the energy released in the NaI crystal was thus achieved. The number of the channel in which the NaI pulse was stored (47 in this event) was reproduced in the oscilloscope picture by means of two neon decimal counter tubes.

These spurious events arise practically only from an accidental superposition, within the ~ 30 -nsec resolving time of the NaI counter, of a $\mu - e$ decay from the selected Cu plates of the SC and a background particle releasing in the NaI crystal enough energy to give, added to the pulse of the decay

electron, a total energy release consistent with that of a "capture electron." The expected number of 4.9 has been computed from the NaI background spectrum and from the spectrum of decay electrons from μ^- mesons bound in the lowest orbit of Fe atoms, experimentally determined with the same crystal.¹² Both ionization and radiation losses in the Cu plates of the SC have been taken into account. We find, therefore, no support to the possibility that the three events previously observed¹ be interpreted in terms of the coherent process (1) (if so, more than 50 events would have been recorded) and conclude that, if such a process exists at all, its branching ratio cannot exceed 2.4×10^{-7} (90% confidence level).

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