Upper Limit for Muon-Electron Conversion in Sulfur

A. Badertscher, K. Borer, G. Czapek, A. Flückiger, H. Hänni, B. Hahn, E. Hugentobler, A. Markees, U. Moser,[a] R. P. Redwine,[b] J. Schacher, H. Scheidiger, P. Schlatter, and G. Viertel

Department of High Energy Physics, University of Berne, CH-3012 Berne, Switzerland
(Received 11 October 1977)

The anomalous neutrinoless conversion of stopped negative muons into electrons has been searched for in sulfur. No electron with an energy above 93 MeV was found. The upper limit for the branching ratio relative to ordinary muon capture is 4×10^{-10} at the 90% confidence level.

The conversion of muons into electrons in nuclei might occur according to unified gauge theories of electromagnetic and weak interactions at a level of 10^{-10} relative to ordinary muon capture.[1-3] There is postulated a formal analogy between strangeness-changing (e.g., $K_L^0 \to \mu^+ + \mu^-$) and lepton-flavor–changing neutral weak currents (e.g., $\mu^- + A \to A + e^-$). Both processes are strongly suppressed by the Glashow-Iliopoulos-Maiani mechanism.[4]

Anomalous neutrinoless muon capture has been studied most recently in the process $\mu^- + \mathrm{Cu} \to \mathrm{Cu} + e^-$ by Bryman *et al.*[5] For the branching ratio an upper limit of 1.6×10^{-8} (90% confidence level) has been reported. We have searched for $\mu^- + \mathrm{S} \to \mathrm{S} + e^-$ at Schweizerisches Institut für Nuklearforschung (SIN). Our experimental signature of this process is a 105-MeV electron in the final state. The layout of the experiment is shown in Fig. 1. Pions were produced in a thick Be target at 90° to the primary proton beam direction. The pion beam of 120-MeV/c momentum was focused on the entrance of a superconducting muon channel and degraded by 6.5 g/cm^2 of carbon. Most of the pions decayed into muons inside the 5-m-long muon channel. This solenoid with an axial field of 4.5 T was coupled to a superconducting Helmholtz coil (Andromeda),[6] which was operated at 3.5 T. In the center of the Helmholtz coil was mounted a cylindrical streamer chamber, 20 cm in diameter and 4 cm in depth, which operated at room temperature. The chamber contained a sulfur ring target of 0.7 g/cm^2 radial thickness, 4 cm diameter, and 4 cm depth. For an average proton current of 25 μA the muon stop rate in the target was approximately 10^6/sec.

Charged particles with momentum larger than 70 MeV/c and emitted at an angle near 90° relative to the muon-beam axis could escape the magnetic field of 3.5 T and reach the outer trigger counters. Most of the electrons from bound-muon decay, however, were trapped inside the mag-

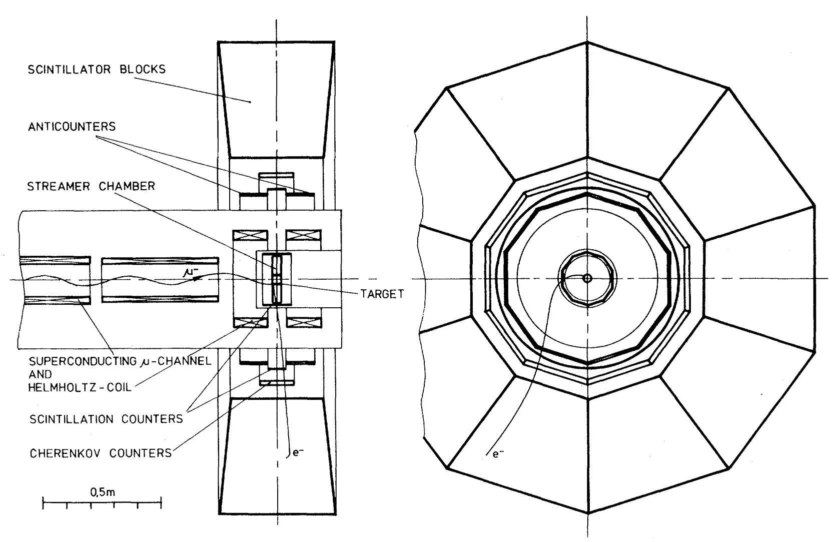

FIG. 1. Lay-out of the μ-e–conversion experiment. In both views, there is shown the track of a hypothetical muon-produced 105-MeV electron, bent in a central magnetic field of 3.5 T.

net. The solid-angle acceptance for outgoing particles was 13%. The streamer chamber was triggered by scintillation and Lucite Cherenkov counters in a ring arrangement (Fig. 1). The Cherenkov counters rejected background particles with $\beta < 0.67$. The outer 50-cm-thick plastic scintillators (calorimeter) were used for discrimination against low-energy background and allowed for a rough energy measurement (resolution of 40% full width at half-maximum FWHM for 100-MeV electrons). The trigger pattern was required to correspond roughly to the curvature of a 100-MeV electron and was recorded, together with the pulse height in the calorimeter for each event, on magnetic tape.

Since the μ-e conversion on nuclei was searched for at a very low level of occurrence, and since this process is characterized by the emission of one particle, an electron of 105 MeV, we chose a track-visualizing detector. The streamer chamber used in the experiment operated in the avalanche mode, had a memory time of 800 ns, and was monitored by a TV system. The events were recorded on film. Details of the streamer chamber and the image intensifiers will be published elsewhere. The momentum resolution has been determined with 70-MeV positrons from the $\pi^+ \to e^+ + \nu_e$ decay at rest using a reduced magnetic field of 2.7 T and was found to be $\pm 3.1\%$. The number of captured muons was measured with a Ge(Li) detector by means of nuclear γ rays of 1.2 MeV from $\mu^- + \mathrm{S} \to \mathrm{P}^* + \nu_\mu$ followed by $\mathrm{P}^* \to \mathrm{P} + \gamma$. The two intrinsic background processes of this experiment were bound-muon decay[7] (muon decay in orbit) and radiative muon capture[8] followed by internal or external γ conversion with an asymmetric electron-positron pair. Cosmic-ray background, mostly muons and fast neutrons, could be reduced sufficiently by various anticounters and by heavy shielding. Another kind of background arose from radiative pion capture with converted γ rays. With our internal-target arrangement 30% of the stopping particles were pions. This prompt background could be suppressed sufficiently by pulsing the primary proton beam.[9] The pulser system was implemented by SIN[10] and consisted of a beam chopper near the ion source in the injector cyclotron and an additional cleaning of the proton beam with a deflector after a ring cyclotron. The pulser frequency of 400 kHz was adapted to the muon disappearing rate in sulfur. Our apparatus was only made sensitive in a 1-μs-long gate during the beam-off period, when the prompt background was suppressed by a factor of about 10^7. The number of remaining pions in this gate and their time distribution were monitored with a special beam telescope downstream of Andromeda.

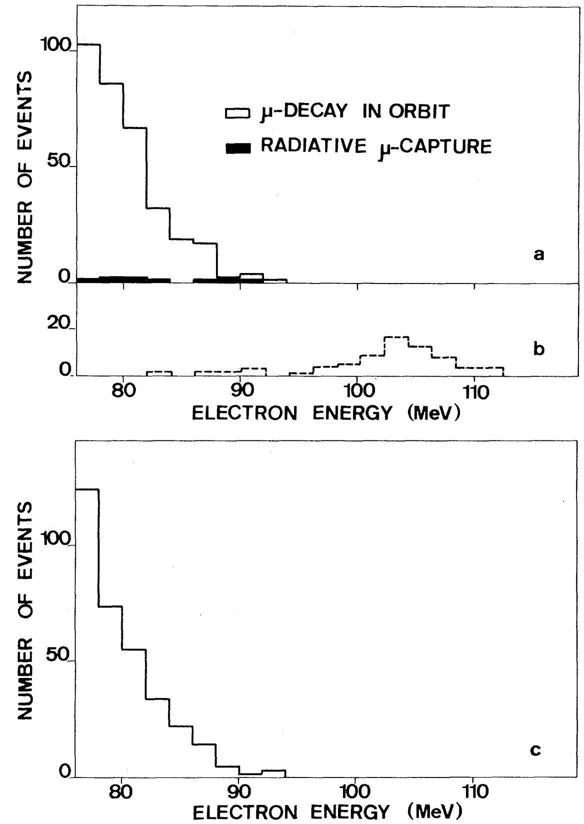

FIG. 2. (a) Simulation of background and (b) simulation of signal by the Monte Carlo method. For a hypothetical μ-e-conversion branching ratio $R_{\mu e} = 10^{-8}$, 69 events are obtained. (c) Observed electron spectrum.

We present here the result obtained during a four-week run. A total of 1.2×10^{11} muons have been captured in sulfur within the beam-off gate. Figures 2(a) and 2(b) show electron spectra obtained by Monte Carlo simulation—2(a) for the two intrinsic muon backgrounds and 2(b) for μ-e conversion at a hypothetical branching ratio of 10^{-8}, assuming a momentum resolution of $\pm 4\%$. The measured electron-energy spectrum, as shown in Fig. 2(c), agrees well with the calculated background. No event, however, has been found above 93 MeV. This result allows us to compute an upper limit for the μ-e conversion process on sulfur, as follows.

The number $N_{\mu e}$ of events expected for a given branching ratio is

$$N_{\mu e} = N_c(\Omega/4\pi)\epsilon_t\epsilon_c\epsilon_f\epsilon_r R_{\mu e} = N_c a R_{\mu e},$$

where $N_c = 1.2\times10^{11}$ is the total number of captured muons during the gate, $\Omega/4\pi = 0.13$ is the solid-sngle acceptance, $\epsilon_t = 0.9$ is the trigger-counter efficiency, $\epsilon_c = 0.75$ is the calorimeter acceptance (energy cut at 55 MeV) for electrons in the energy interval between 95 and 112 MeV, $\epsilon_f = 0.75$ is the fraction of useful streamer-chamber pictures, $\epsilon_r = 0.8$ is the assumed fraction of μ-e–conversion electrons appearing in the energy interval between 95 and 112 MeV,[11,12] $a = 0.05$ is the total acceptance, and $R_{\mu e} = \sigma(\mu^- + \mathrm{S} \rightarrow \mathrm{S} + e^-)/\sigma(\mu^- + \mathrm{S} \rightarrow \text{capture})$ is the branching ratio.

Since no event has been observed and one event would have corresponded to a branching ratio of 1.6×10^{-10}, the following upper limit on the branching ratio can be set:

$$R_{\mu e} < 4\times10^{-10} \text{ (90\% confidence level).}$$

The branching ratio for μ-e conversion in nuclei can be expressed in terms of "effective" form factors[1,11]:

$$R_{\mu e} = \eta(A, Z)\lambda_{\mu e}^2,$$

where $\eta(A, Z) \simeq 1$ for sulfur and

$$\lambda_{\mu e}^2 = [\,|f_{E0}(-m_\mu^2) + f_{M1}(-m_\mu^2)|^2 + |f_{M0}(-m_\mu^2) + f_{E1}(-m_\mu^2)|^2]/8G_F^2 m_\mu^4.$$

Therefore our experiment yields the following limit on the amount by which the "effective" μ-e form factors must be reduced compared to the β-decay coupling:

$$\lambda_{\mu e} < 2\times10^{-5} \text{ (90\% confidence level).}$$

We wish to thank the beam-pulser group, especially Dr. P. Lanz, A. Märki, and Dr. U. Schryber for their outstanding work. Also we are greatly indebted to the SIN machine crew for the sucessful operation of the cyclotron together with the pulser. We are extremely grateful to I. Horvath and G. Vécsey for construction and operation of the cryogenics. We thank M. Hess, Dr. H. Kaspar, T. Marti, and E. Ramseyer for their invaluable collaboration in this experiment, and our technical staff of the University of Berne for their great effort. Finally we express our gratitude to Professor J. P. Blaser and Professor H. J. Gerber for their support and encouragement.

This work was partially supported by the Swiss National Science Foundation and by SIN.

[a] Present address: Los Alamos Scientific Laboratory, Los Alamos, N.M. 87545.

[b] On leave of absence from Los Alamos Scientific Laboratory, Los Alamos, N.M. 87545.

[1] W. J. Marciano and A. I. Sanda, Phys. Rev. Lett. 38, 1512 (1977).

[2] G. Altarelli, L. Baulieu, N. Cabibbo, L. Maiani, and R. Petronzio, Nucl. Phys. B125, 285 (1977).

[3] S. Barshay, Phys. Lett. 66B, 246 (1977).

[4] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[5] D. A. Bryman, M. Blecher, K. Gotow, and R. J. Powers, Phys. Rev. Lett. 28, 1469 (1972).

[6] G. Czapek, B. Hahn, A. Markees, J. Schacher, I. Horvath, G. Vécsey, W. Gross, H. Operschall, H. Kuckuck, and F. Wendler, to be published.

[7] P. Hänggi, R. D. Viollier, U. Raff, and K. Alder, Phys. Lett. 51B, 119 (1974); H. P. Bürki, Diploma work, Department of Theoretical Physics, University of Berne, 1974 (unpublished).

[8] H. Primakoff, Rev. Mod. Phys. 31, 802 (1959).

[9] G. Czapek, B. Hahn, A. Markees, and J. Schacher, Nucl. Instrum. Methods 105, 609 (1972).

[10] See, e.g., SIN-Jahresbericht, 1976.

[11] S. Weinberg and G. Feinberg, Phys. Rev. Lett. 3, 111, 244(E) (1959).

[12] R. H. Helm, Phys. Rev. 104, 1466 (1956).