New Experimental Limits on $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow ee$ Branching Ratios

C. Mathiazhagan and W. R. Molzon
University of California, Irvine, California 92717

R. D. Cousins, J. Konigsberg, J. Kubic, P. Melese,(a) P. Rubin, W. E. Slater, and D. Wagner
University of California, Los Angeles, California 90024

G. W. Hart, W. W. Kinnison, D. M. Lee, R. J. McKee, E. C. Milner, G. H. Sanders, and H. J. Ziock
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

K. Arisaka,(b) P. Knibbe, and J. Urheim
University of Pennsylvania, Philadelphia, Pennsylvania 19104

S. Axelrod,(c) K. A. Biery, G. M. Irwin, K. Lang, J. Margulies, D. A. Ouimette, J. L. Ritchie,(d) Q. H. Trang,(e) and S. G. Wojcicki
Stanford University, Stanford, California 94309

L. B. Auerbach, P. Buchholz, V. L. Highland, W. K. McFarlane, and M. Sivertz(f)
Temple University, Philadelphia, Pennsylvania 19122

M. D. Chapman, M. Eckhause, J. F. Ginkel, A. D. Hancock, D. Joyce,(g) J. R. Kane, C. J. Kenney, W. F. Vulcan, R. E. Welsh, R. J. Whyley,(h) and R. G. Winter
College of William and Mary, Williamsburg, Virginia 23185

(Received 7 August 1989)

A search for the decays $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow ee$ has produced no examples of either process. When normalized to the decay $K_L^0 \rightarrow \pi^+\pi^-$, the 90%-C.L. upper limits on the branching ratios are $B(K_L^0 \rightarrow \mu e) < 2.2 \times 10^{-10}$ and $B(K_L^0 \rightarrow ee) < 3.2 \times 10^{-10}$.

PACS numbers: 13.20.Eb

The decay $K_L^0 \rightarrow \mu e$ is forbidden by conservation of the additive quantum numbers associated with electron- and muon-type leptons. Observation of this decay would therefore provide evidence for interactions outside the standard model of strong and electroweak interactions. The process is sensitive to extremely high mass scales. If the decay proceeds through the exchange of a virtual particle of mass M between μ and e leptons and s and d quarks, the rate is proportional to $1/M^4$. Assuming a $V-A$ coupling of weak-interaction strength, observation of this decay at a branching ratio of 10^{-10} would imply $M = 70$ TeV/c^2. The processes $K_L^0 \rightarrow \mu\mu$ and $K_L^0 \rightarrow ee$ are permitted in the standard model, but are highly suppressed flavor-changing neutral-current decays. An observation of the decay $K_L^0 \rightarrow ee$ significantly above standard-model predictions would be evidence for new physics. In this Letter, we describe a search for $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow ee$ at a sensitivity greater than that previously achieved.[1-4]

The experiment (E791) was carried out at the B-5 beam line of the BNL Alternating Gradient Synchrotron (AGS). A neutral beam of 4.1×15.0 mrad^2 (FWHM) was defined by collimators centered at 2.75° from a 2.41-GeV proton beam incident on a Cu target. Two sweeping magnets, one immediately following the target and one surrounding the last collimator, removed most charged particles from the beam. Decays in an 8-m-long region evacuated to 0.04 Torr were detected by the apparatus which followed.

The detector was designed to operate at high rates and to reject completely events from processes that could mimic the signal. The principal sources of such background originate from $K_L^0 \rightarrow \pi e \nu$ decays in which the neutrino has little energy. One background occurs if the pion decays or is misidentified as a muon. Excellent kinematic resolution is required to reject such events; this is achieved by requiring that the particle trajectories do not have kinks and that the event be consistent with a two-body decay of a K_L^0 originating from the production target. A second background arises if the pion is misidentified as an electron and the electron is misidentified as a muon. Misassignment of particle masses causes some of these decays to be reconstructed with a μe invariant mass at or above the K_L^0 mass. Discrimination against these events requires excellent particle identification.

Figure 1 shows a schematic view of the detector, whose major features have been described previously.[1]

Drift-chamber modules, each consisting of two x- and two y-measuring planes of wires with 120-μm resolution, measured the positions of charged particles at five locations before, between, and after two analyzing magnets. The regions between the drift chambers were filled with helium to reduce multiple scattering and nuclear interac-

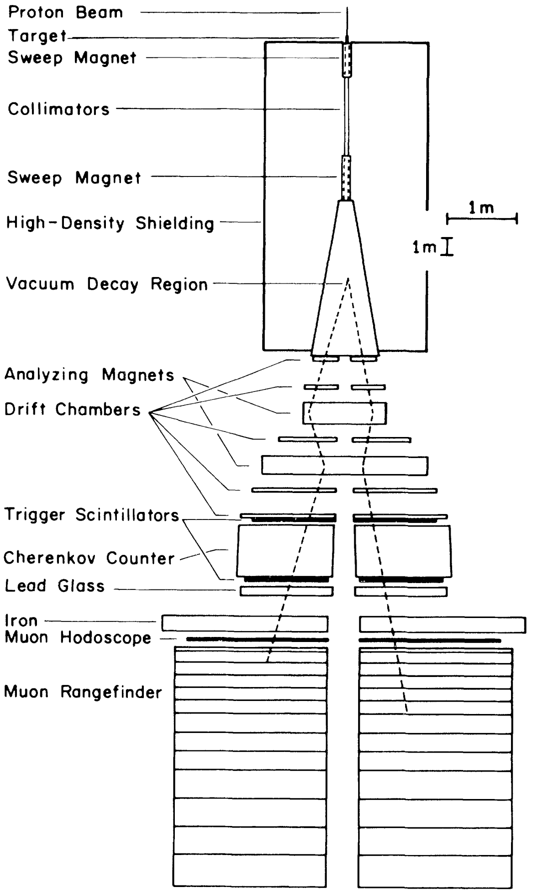

FIG. 1. Schematic plan view of the detector system, drawn with the indicated scales parallel and perpendicular to the beam direction.

tions. Two planes of x-y scintillation hodoscopes followed the spectrometer. Events were selected on line by requiring signals in each arm of the spectrometer in the drift chambers and hodoscopes, in time windows of 54 and 14 ns, respectively.

Two independent means were used to identify both electrons and muons. Electrons were identified using segmented gas Čerenkov counters and an electromagnetic shower counter array. Time and pulse-height information was recorded for all channels of both systems. The Čerenkov counters were filled with a helium-nitrogen mixture that yielded a pion threshold of 8.3 GeV/c. The shower counter consisted of 13.8 radiation lengths (r.l.) of lead glass, divided between converter blocks (3.3 r.l.) and absorber blocks (10.5 r.l.).

Muons were identified with detectors downstream of 91 cm of iron. Those above 1.4 GeV/c penetrated the lead glass and iron and induced signals in an x-y scintillation hodoscope that followed. Further identification was provided by a tracking muon rangefinder[5] consisting of marble and aluminum absorber plates instrumented at 13 depths with planes of proportional tubes. These were spaced to correspond to 10% momentum intervals. For each event, times in the muon scintillators and the state of all rangefinder tubes were recorded.

Independent on-line selection paths were provided for each particle-pair combination. The gas Čerenkov counter and muon scintillators were used to select μe, $\mu\mu$, and ee events. A large sample of $K_L^0 \rightarrow \pi^+\pi^-$ decays was provided for calibration purposes by selecting a fixed fraction of those events with no Čerenkov or muon scintillator signals. Also, a sample of "minimum-bias" events was selected without regard for lepton identification, to be used for efficiency studies and normalization of the result.

Time[6] and pulse-height information[7] for selected events was digitized and transferred[8] into one of a set of 3081/E computers;[9] the number used increased from 4 to 8 during the run. Additional event selection was performed in the 3081/E's by reconstructing tracks and doing kinematic calculations. Accepted events were recorded on magnetic tape for off-line analysis.

The kinematic analysis done in the 3081/E's calculated and imposed requirements on the two-body invariant mass (m_{12}) and the collinearity angle (θ_c) between the vector from the target to the decay vertex and the measured two-body momentum vector. The measurements used the first three drift-chamber planes and first magnet. For events with multiple-particle identification designations, all corresponding mass solutions were tested. Off line, a slightly tighter selection was made on these 3081/E-calculated quantities, requiring lepton-pair events to be restricted to $460 < m_{12} < 550$ MeV/c^2 and $\theta_c < 10$ mrad. No restrictions were placed on minimum-bias events, which were subsequently fully analyzed off line to monitor the 3081/E selection efficiency. It was 0.79 ± 0.02 for $K_L^0 \rightarrow \pi^+\pi^-$ decays.

In the first stage of off-line analysis, a pattern recognition algorithm used hits from all chamber planes to identify tracks originating from a common vertex. To save computing time, θ_c and m_{12} were recalculated and only events with $\theta_c < 3$ mrad and m_{12} above some value (between 450 and 475 MeV/c^2, depending on the event type) were retained for subsequent analysis.

These events were fitted to derive the particle momentum vectors.[10] Parameters for the particle trajectories in the upstream and downstream halves of the spectrometer were separately adjusted to require the trajectory to pass through the hit positions in the drift chambers. The K_L^0-decay vertex was determined from the two trajectories and the track parameters were redetermined, requiring that they originate from a common vertex.

Identification of a particle as an electron required that the trajectory pass close to a struck Čerenkov cell, that the time be within ~ 5 ns of the expected time, that the ratio of the particle energy measured using the lead glass to that determined using the spectrometer exceed 0.75, and that the fraction of the energy deposited in the converter blocks exceed 0.045. The efficiency of selection criteria for the Čerenkov counters was determined using well identified electrons from $K_L^0\to\pi e\nu$ decays. The average efficiency, weighted for electrons with kinematic distributions appropriate for $K_L^0\to\mu e$ decays, was 0.893 ± 0.010. About 1% of particles below threshold gave a signal in the counters because of knock-on electrons or accidental coincidences. The efficiency of the lead-glass selection criteria was determined in a similar way to be 0.942 ± 0.007 and the pion rejection efficiency was measured to be about 0.95.

Details of the muon identification using the muon scintillation hodoscope and the rangefinder are discussed in the following Letter.[10] The efficiency of the selection criteria was determined using muons from $K_L^0\to\pi\mu\nu$ decays. It was 0.976 ± 0.004 for the muon counters and 0.987 ± 0.001 for the rangefinder. Both numbers represent efficiencies weighted by the expected momentum distributions of muons from $K_L^0\to\mu e$ decays.

Additional requirements ensured that events were contained within the detector volume and that the kinematic measurements were of high quality. Events with reconstructed vertices closer than -9.5 m to the production target were eliminated to reject backgrounds from decays in the fringe field of the last sweeping magnet and from particles produced from interactions in the collimator. The K_L^0 direction (determined from the target and vertex positions) was required to be within ±10 mrad vertically and ±2.7 mrad horizontally of the central beam direction. Limits were imposed on the particle trajectories at the neutral-beam vacuum window and the spectrometer magnets to eliminate events with particles which scattered in these devices. Charged-particle momenta were required to be above 1.5 GeV/c to eliminate kinematic regions with very low acceptance. Most events with pion decays and badly scattered particles were eliminated by additional cuts on the quality of the track and vertex fits.[10]

After all cuts, a small sample of lepton-pair events remains. Figure 2 displays the events for $K_L^0\to\mu e$, $K_L^0\to\mu\mu$, and $K_L^0\to\pi^+\pi^-$ decay modes as scatter plots of θ_c^2 vs m_{12}. The corresponding plot for $K_L^0\to ee$ events is empty. The rms resolutions in $m_{\pi\pi}$ and θ_c are 1.5 MeV/c^2 and 0.3 mrad for $K_L^0\to\pi^+\pi^-$ decays. The resolution in m_{12} for decays to lepton pairs is calculated to be slightly worse due to the larger momentum transfer in these decays. Based on estimates from Monte Carlo simulations, 96.3% of $K_L^0\to\mu e$ and 98.0% of $K_L^0\to\pi^+\pi^-$ events are expected to be contained in a fiducial region with $493<m_{12}<503$ MeV/c^2 and $\theta_c<1.0$ mrad. Since potential backgrounds to the $K_L^0\to ee$ mode contribute only well below the K_L^0 mass, a fiducial volume of $483<m_{ee}<513$ MeV/c^2 and $\theta_c<2.0$ mrad was used; this region should contain 96.7% of the signal. No events in the fiducial regions satisfied all selection criteria for the processes $K_L^0\to\mu e$ or $K_L^0\to ee$. The following paper[10] reports the $K_L^0\to\mu\mu$ branching ratio measured using the 87 detected examples of the process $K_L^0\to\mu\mu$.

The number of $K_L^0\to\pi^+\pi^-$ events in the minimum-bias sample, $N_{\pi\pi}$, was determined by subtracting from the measured distribution in $m_{\pi\pi}$ the simulated spectrum due to semileptonic decays of the K_L^0, normalized to the data in the region away from the K_L^0 mass peak. The number of detected events was also corrected by a factor (0.979) to account for the effect of the small K_S^0 amplitude on the decay rate in the decay region. Corrected for these backgrounds, $N_{\pi\pi}=8226\pm148$.[10]

Since no $K_L^0\to\mu e$ events are observed, the 90%-confidence limit on the branching ratio is given by

$$B(K_L^0\to\mu e)<2.3\frac{B(K_L^0\to\pi^+\pi^-)}{6000N_{\pi\pi}}\frac{A_{\pi\pi}}{A_{\mu e}}\frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}}.$$

A similar expression is used to determine a limit on $B(K_L^0\to ee)$. Here $B(K_L^0\to\pi^+\pi^-)=(2.04\pm0.04)\times10^{-3}$ is the $K_L^0\to\pi^+\pi^-$ branching ratio[11,12] and 6000 is the minimum-bias prescale factor. $A_{\pi\pi}$ and $A_{\mu e}$ are the acceptances of the detector for $K_L^0\to\pi^+\pi^-$ and $K_L^0\to\mu e$ decays. They include factors for the loss of events due to pion decay and electron bremsstrahlung and the m_{12} and θ_c cuts. They were calculated with a Monte Carlo simulation; the ratios $A_{\pi\pi}/A_{\mu e}$ and $A_{\pi\pi}/A_{ee}$ are 1.47 ± 0.02 and 1.72 ± 0.02, respectively. The Monte Carlo calculation did not include the effects of

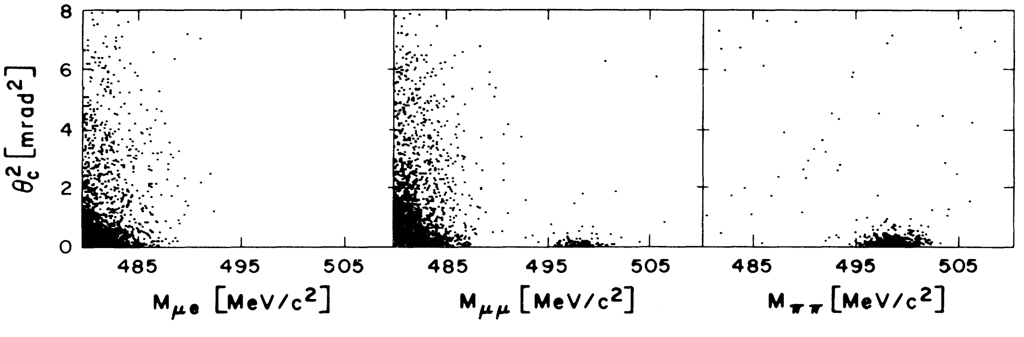

FIG. 2. Scatter plots of θ_c^2 vs m_{12} for $K_L^0\to\mu e$ events, $K_L^0\to\mu\mu$ events, and a representative sample of $K_L^0\to\pi^+\pi^-$ events.

initial-state bremsstrahlung; we estimate events with radiated photons below 4.5 MeV for $K_L^0 \rightarrow \mu e$ events and below 13.5 MeV for $K_L^0 \rightarrow ee$ events would be contained within the fiducial volume. The correction factor $\epsilon_{\pi\pi}$, 0.985 ± 0.002, is due to losses from pion interactions, while $\epsilon_{\mu e}$ (0.63 ± 0.02) and ϵ_{ee} (0.55 ± 0.02) include the lepton identification and trigger efficiencies quoted above and a factor (0.985 ± 0.015) to account for an inefficiency in the lepton-pair trigger circuit.

A check on the lepton identification efficiencies was performed by measuring the ratios $\Gamma(K_L^0 \rightarrow \pi^+\pi^-)/\Gamma(K_L^0 \rightarrow \pi\mu\nu)$ and $\Gamma(K_L^0 \rightarrow \pi^+\pi^-)/\Gamma(K_L^0 \rightarrow \pi e\nu)$ using the minimum-bias data. The values determined differed from accepted values[11] for the two ratios by $(+1.7 \pm 3.0)\%$ and $(-5.9 \pm 3.0)\%$, respectively, where the quoted uncertainty is the statistical uncertainty on our measurement.

The resulting 90%-confidence-level upper limit for the branching ratio for $K_L^0 \rightarrow \mu e$ is 2.2×10^{-10} and for $K_L^0 \rightarrow ee$ it is 3.2×10^{-10}. Based on uncertainties in the normalization and in the relative pion and lepton efficiencies quoted above, we estimate the total systematic uncertainty in the sensitivity to be 6%.

We greatly appreciate the support provided by the staff of the AGS Department, especially by H. Brown, G. Bunce, and J. Mills. Valuable technical assistance was rendered by J. Belz, M. Chronoviat, J. Cook, G. Daniel, V. Hart, M. Ierano, F. Mansell, C. Pierce, M. Roehrig, A. Tilghman, and C. Zhang. We also thank the BNL Computing and Communications Division for the timely processing of a large volume of data. We thank our colleagues G. Bonneaud, J. Frank, P. Guss, J. Martoff, and W. Wales for their substantial contributions to the first stages of this work, and J. Greenhalgh for his major contributions to the initiation and conception of the experiment. This research was supported by the U.S. Department of Energy and the National Science Foundation.

---

[a] Present address: Rockefeller University, New York, NY 10021.

[b] Present address: University of California, Los Angeles, CA 90024.

[c] Present address: Measurex Corporation, Cupertino, CA 95014.

[d] Present address: University of Texas, Austin, TX 78712.

[e] Present address: S-MOS Systems Inc., San Jose, CA 95131.

[f] Present address: University of California, San Diego, La Jolla, CA 92093.

[g] Present address: Continuous Electron Beam Accelerator Facility, Newport News, VA 23606.

[h] Present address: MCI Communications Corp., McLean, VA 22102.

[1] R. D. Cousins *et al.*, Phys. Rev. D **38**, 2914 (1988).

[2] H. B. Greenlee *et al.*, Phys. Rev. Lett. **60**, 893 (1988); S. F. Schaffner *et al.*, Phys. Rev. D **39**, 990 (1989).

[3] E. Jastrzembski *et al.*, Phys. Rev. Lett. **61**, 2300 (1988).

[4] T. Inagaki *et al.*, Phys. Rev. D **40**, 1712 (1989).

[5] J. Frank *et al.*, IEEE Trans. Nucl. Sci. **36**, 79 (1989); C. J. Kenney *et al.*, IEEE Trans. Nucl. Sci. **36**, 74 (1989); D. M. Lee *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **256**, 329 (1987).

[6] R. D. Cousins *et al.*, IEEE Trans. Nucl. Sci. **36**, 646 (1989).

[7] K. A. Biery *et al.*, IEEE Trans. Nucl. Sci. **36**, 650 (1989).

[8] R. D. Cousins *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **277**, 517 (1989).

[9] P. F. Kunz *et al.*, SLAC Report No. SLAC-PUB-3332, 1984 (unpublished).

[10] C. Mathiazhagan *et al.*, following Letter, Phys. Rev. Lett. **63**, 2185 (1989).

[11] G. P. Yost *et al.*, Phys. Lett. B **204**, 1 (1988).

[12] R. Messner *et al.*, Phys. Rev. Lett. **30**, 876 (1973); C. Geweniger *et al.*, Phys. Lett. **48B**, 487 (1974).