Search for $K_L^0 \to \mu + e$ and $K_L^0 \to e + e$

H. B. Greenlee, H. Kasha, E. B. Mannelli, M. Mannelli, S. F. Schaffner, M. P. Schmidt, and C. B. Schwarz[(a)]

Department of Physics, Yale University, New Haven, Connecticut 06511

and

E. Jastrzembski, R. C. Larsen, L. B. Leipuner, W. M. Morse, and R. K. Adair

Brookhaven National Laboratory, Upton, New York 11973

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We report on a search for the flavor-changing neutral-current decays $K_L^0 \to \mu + e$ and $K_L^0 \to e + e$. Limits obtained for these processes are $B(K_L^0 \to \mu + e) < 6.7 \times 10^{-9}$ and $B(K_L^0 \to e + e) < 4.5 \times 10^{-9}$ (90% confidence level).

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In the standard model of the strong, electromagnetic, and weak interactions, flavor-changing neutral currents are forbidden or highly suppressed. In particular the decay $K_L^0 \to \mu + e$ is forbidden by lepton-number conservation. The decay $K_L^0 \to e + e$ is expected to be suppressed with respect to the rare, but observed,[1] decay $K_L^0 \to \mu + \mu$, since the mass of the electron is small compared with that of the muon. However, the standard model is incomplete; e.g., it does not predict the number of fermion flavors, nor does it specify the fermion masses or the mixing angles associated with the weak decays of quarks.

Lepton-number nonconservation and flavor-changing neutral currents are likely prospects in theories that go beyond the standard model. The details depend upon the model in question, be it a version of technicolor,[2] supersymmetry,[3] compositeness,[4] or one with horizontal gauge symmetry,[5] an extended scalar sector,[6] exotic leptoquarks,[7] or even superstrings.[8] In each case, present limits on transition rates for rare decays provide important constraints on the models. The decay $K_L^0 \to \mu + e$ requires an axial-vector or pseudoscalar coupling, so that this search is complementary to one[9] for the decay $K^+ \to \pi^+ + \mu^+ + e^-$, which requires a vector or scalar coupling. The mass (M_E) of an exotic gauge boson mediating the decay $K_L^0 \to \mu + e$ can be estimated by comparison with the weak decay $K^+ \to \mu^+ \nu$ mediated by the W; assuming equal coupling constants, one obtains $B(K_L^0 \to \mu + e) \approx 2.5 \times 10^{-3} (M_E / 1\ \text{TeV})^{-4}$. Similar statements can be made for the decay $K_L^0 \to e + e$ which is particularly sensitive to effective pseudoscalar interactions which may give rise to a branching fraction larger than the unitarity limit[10] of $B(K_L^0 \to e + e) > 2.5 \times 10^{-12}$.

The kinematics of the decays $K_L^0 \to \mu + e$ and $K_L^0 \to e + e$ are sufficiently similar so that a search for both decay modes with similar sensitivity can be made. We have performed a search for these processes and present the results below. The experiment was performed in the A3 beam line of the Brookhaven alternating gradient synchrocyclotron (AGS). A zero-degree beam was produced through the interactions of 28-GeV/c protons with a 9-in.-long, $\frac{3}{16}$-in.-diam copper target. The neutral beam was defined by a series of brass collimators and sweeping magnets and had a divergence of 15 mrad in the vertical and 2.3 mrad in the horizontal planes. The neutral-beam flux has been measured to be about one per 500 protons on target. γ rays from the target were attenuated by a 1-in. lead beam plug. The neutral beam passed through the detection apparatus shown in Fig. 1. Kaon decays occurring in an evacuated 120-in. drift space beginning 287 in. from the target were detected. The mean momentum of $K_L^0 \to \pi^+ + \pi^-$ events detected was 8.7 GeV/c.

Kinematic reconstruction was accomplished with a spectrometer consisting of four sets of drift chamber detectors placed upstream (A and B) and downstream (C and D) of a magnet which had a 22-in. gap and a field integral of $\Delta p = 220$ MeV/c. Mini-drift-chambers with small ($\frac{1}{8}$ in.) drift cells were employed. They provided efficient ($> 99\%$) and precise ($\approx 250\ \mu$m) determination of the coordinates of the particle trajectories through the spectrometer in the high-rate environment associated with the neutral beam. Each chamber had four sense planes: X, X', Y, and Y'. The "primed" sense wires were offset by one drift cell with respect to the "unprimed" sense wires. This configuration allows for the resolution of left-right ambiguities from a single sense wire. The B chamber had an additional sense plane oriented at 14° to the vertical (Y) to resolve track ambiguities. The chambers had an active area ranging from 20×20 in.^{2} for A to 40×40 in.^{2} for D. Multiple scattering in the spectrometer was minimized by the placement of the first scintillation trigger counter array (E) downstream of the last drift chamber (D) and by our filling the volume between the drift chambers with

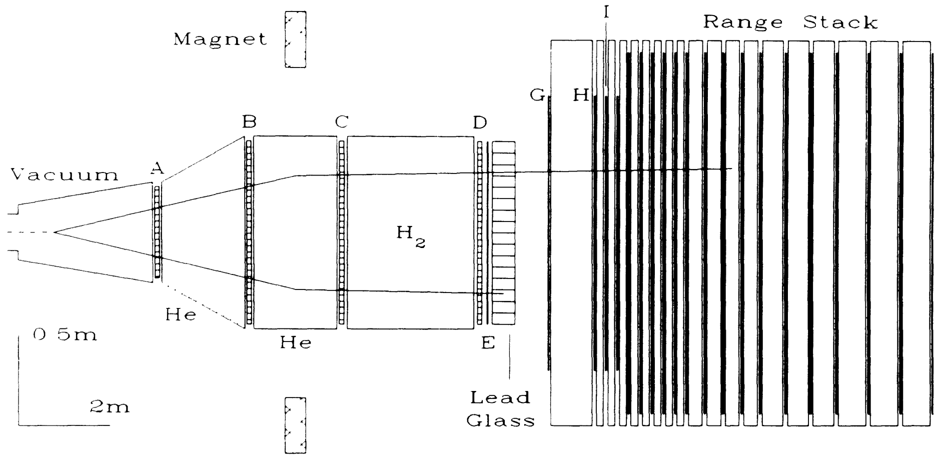

FIG. 1. Plan view of the E780 detector. Note the different horizontal and vertical scales.

helium.

The constraints of the kinematic reconstruction are particularly important in the $K_L^0 \to \mu + e$ search because of backgrounds that can arise from the decay $K_L^0 \to \pi + e + \nu$ with the pion either decaying to or being misidentified as a muon. Energy and momentum carried away by the neutrinos results in a low effective μe mass and an imbalance in the transverse momentum of the (pseudo) two-body decay with respect to the kaon direction of flight. In the absence of measurement errors the effective μe mass can approach within 8 MeV of the kaon mass.

The spectrometer had nearly equal acceptance ($\approx 6\%$) for $K_L^0 \to \mu + e$ and $K_L^0 \to e + e$ decays, as well as for the rare decay $K_L^0 \to \mu + \mu$ and the *CP*-invariance violating decay $K_L^0 \to \pi^+ + \pi^-$. Events were collected for all four modes. The $\mu\mu$ events served to test the signal isolation strategies for the rare-event search; the $K_{\mu 3}^0$ background for $K_L^0 \to \mu + \mu$ is similar to the K_{e3}^0 background for $K_L^0 \to \mu + e$. Events from $K_L^0 \to \pi^+ + \pi^-$ decays (taken with a prescaled trigger) were used to determine the kinematic resolution of the spectrometer and establish the number of kaon decays observed.

The spectrometer was augmented by an atmospheric-pressure hydrogen-gas Čerenkov counter, located between the *C* and *D* chambers, and a lead-glass array for electron identification. The lead-glass array was comprised of 244 blocks of Schott F2 glass, each of dimension 2.5×2.5×20 in. in length which were mounted in a 40×40-in.^{2} array with a central hole of 5×15 in.^{2} for passage of the neutral beam. Muons were identified by their passage through a steel filter and range stack interspersed with scintillator counters. The range stack was constructed of seventeen sections of steel increasing in thickness from 6 to 24 in. and arranged so that the mean incremental range per section traversed was $\approx 10\%$. The passage of a muon through the stack was determined by arrays of scintillation counters, each having eight elements and covering an area of 79×72 in.^{2}. The neutral beam passed through the range stack in a 6×18-in.^{2} hole.

For the purposes of triggering, the detector was physically and logically divided into quadrants about the neutral beam. In order to trigger the detector, electrons were required to register in one cell of the Čerenkov counter (>95% efficient) and to deposit at least 1.2 GeV in the appropriate quadrant of lead glass. Muons were required to penetrate a 42-in. steel filter to a scintillation counter array (*I*), while pions were required to penetrate the lead-glass array but not activate the *H* scintillation counters. These particle identification triggers were paired from quadrants on the left and right of the beam and placed in coincidence with bend-view information from the drift chambers to form the fast trigger.

The data were collected with the Brookhaven Fastbus[11] data-acquisition system. Typically about 2.5×10^{11} protons were incident on the target per pulse. The rate in the chambers was about 10 MHz/m^2. Wire address (not drift time) information from the chambers was used in the on-line analysis for the first stage of event rejections. Specifically, a search in the bend view was made for track candidates and a vertex within the fiducial volume. About 4000 triggers per pulse were processed, resulting in about twenty events per pulse recorded onto tape. The acquisition live time was better than 80%. About 10^7 events were collected in the course of two four-week running periods.

Particle identification was further established in the off-line analysis through use of the lead-glass array and the range stack. Electrons were identified with 99% efficiency by the requirement of $E/p > 0.75$, where E is the energy measured in the lead-glass array and p is the momentum measured in the spectrometer. A comparison of the muon energy as determined from the range stack with the momentum determined in the spectrome-

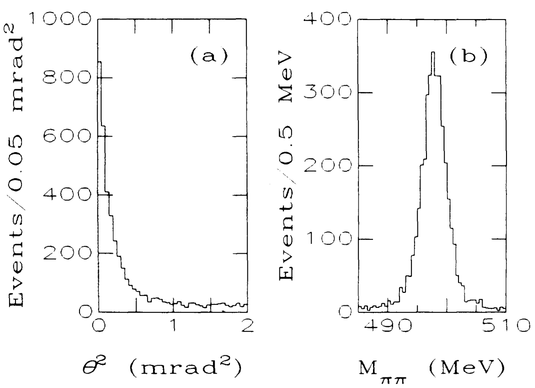

FIG. 2. Distributions of the square of (a) the target reconstruction angle and (b) the invariant mass for inbending $K_L^0 \rightarrow \pi^+ + \pi^-$ decays.

ter provides an important additional constraint for the backgrounds to $K_L^0 \rightarrow \mu + e$ from K_{e3}^0 decays and to $K_L^0 \rightarrow \mu + \mu$ from $K_{\mu 3}^0$ decays. In particular for K_{l3} events in which the pion decays in the spectrometer magnet so as to give a high effective "dilepton" mass, the resulting muon will have an energy lower than its apparent momentum by more than about 20%. The E/p resolution for the range stack has been determined to be about 8% from a study of muons from $K_{\mu 3}^0$ decays.

We present below results from off-line analyses of the data collected. Events were required to pass requirements on track quality and distance of closest approach at the vertex. Muons were required to have a pulse height in the lead glass consistent with a minimum ionizing particle and to travel at least 80% of their expected range in the stack. These criteria are met by $\approx 85\%$ of muons satisfying the trigger requirements. For the μe sample, the electron momentum was required to be less than 8 GeV/c, the threshold momentum for pions in the Čerenkov counter. The momentum asymmetry for the μe events, $A = (p_\mu - p_e)/(p_\mu + p_e)$, was restricted to be less than 0.6; for the $\pi\pi$ and $\mu\mu$ events the requirement was $|A| < 0.5$. From Monte Carlo calculations it is determined that $> 97\%$ of the two-body decays satisfy the momentum asymmetry constraint. Monte Carlo calculations, including the effects of particle-identification efficiency, were used to determine the relative acceptances for the four decay modes studied.

Figures 2 and 3 show the distributions for the mass and target reconstruction for the four event types. We note that the target reconstruction criteria are well characterized by an angle θ which defines the lack of collinearity between the directions of flight of the parent kaon as determined, one, from vector reconstruction of the secondary momenta, and two, from the direction of the reconstructed vertex from the target. The background is expected to be distributed uniformly in θ^2 for small θ.

From $K^0 \rightarrow \pi^+ + \pi^-$ events it is determined that reconstructed events point back to the target with a resolution of ≈ 0.33 mrad [Fig. 2(a)]. For $K^0 \rightarrow \pi^+ + \pi^-$ events from the target the mass resolution for inbending events is determined to be 2 MeV/c^2 [Fig. 2(b)]. A fiducial region in mass (± 7 MeV/c^2 for inbending events and ± 10 MeV/c^2 for the outbending events) and in θ^2 ($< 10^{-6}$ rad²) can be defined by the $K^0 \rightarrow \pi^+ + \pi^-$ events. There are no candidates in the fiducial region for the μe [Fig. 3(a)] and ee data samples [Fig. 3(b)]. There is also no background near the fiducial region; the ee distribution is especially clean.

There are two $K_L^0 \rightarrow \mu + \mu$ events within the fiducial region [Fig. 3(c)], one inbending and one outbending. This is statistically consistent with our sensitivity as determined from the $K_L^0 \rightarrow \pi^+ + \pi^-$ events and the known value[2,12] for $B(K_L^0 \rightarrow \mu + \mu) = (9.1 \pm 1.9) \times 10^{-9}$. Taking into account the prescaling factor and relative acceptance and efficiency for the $\pi\pi$ and "dilepton" events, we have effectively collected about 1.22×10^6 $K_L^0 \rightarrow \pi^+ + \pi^-$ events to obtain a single-event branching fraction sensitivity of 1.96, 2.92, and 4.59 times 10^{-9} for the ee, μe, and $\mu\mu$ events, respectively. Given this sensitivity and no event candidates one obtains a (90%

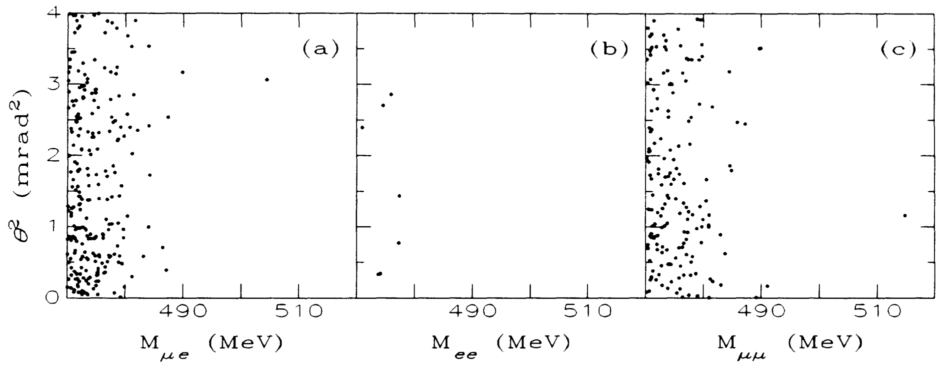

FIG. 3. Scatter plots for the reconstructed mass vs the square of the target reconstruction angle for the (a) μe, (b) ee, and (c) $\mu\mu$ event samples. Both inbending and outbending events are included.

confidence level) branching fraction limit of 6.7×10^{-9} for $K_L^0\rightarrow\mu+e$ and 4.5×10^{-9} for $K_L^0\rightarrow e+e$. This represents a considerable improvement over the present Particle Data Group values[12,13] of 6×10^{-6} and 2×10^{-7}, respectively. These results indicate that there is no new physics contributing to these processes with the weak-interaction coupling constant up to a mass scale of about 25 TeV.

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[a] Present address: Physics Department, Vassar College, Poughkeepsie, NY 12601.

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