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Rapid Communications

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Search for the decays $K_L^0 \to \mu e$ and $K_L^0 \to ee$

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We have obtained upper limits for the decays $K_L^0 \to \mu e$ and $K_L^0 \to ee$. The limits on the branching ratios are $B(K_L^0 \to \mu e) < 1.1 \times 10^{-8}$ and $B(K_L^0 \to ee) < 1.1 \times 10^{-8}$ (90% C.L.). In a simultaneous search for the previously observed decay $K_L^0 \to \mu\mu$, we have identified two events.

We have carried out a search for the decays $K_L^0 \to \mu e$ and $K_L^0 \to ee$, and have observed no examples of either process. The sensitivity of these searches is normalized to the branching ratio for the decay $K_L^0 \to \pi^+\pi^-$ (Ref. 1) using our simultaneous observation of the equivalent of approximately 10^6 of these decays. We also observed two events from the decay $K_L^0 \to \mu\mu$,[2] consistent with the known branching ratio.

The search for the decay $K_L^0 \to \mu e$ is motivated by the lack of a fundamental understanding of the fact that processes which violate the conservation of lepton flavor have not been observed, despite sensitive searches. Limits have been set in charged- and neutral-kaon-decay experiments,[3] muon-decay experiments,[4] and experiments searching for muon-to-electron conversion in the field of heavy nuclei.[5] In the standard model of strong and electroweak interactions, lepton flavor is conserved. Observation of this decay would require an extension of the model. The decay $K_L^0 \to ee$ is not forbidden, but is expected to be suppressed with respect to the decay $K_L^0 \to \mu\mu$ by a factor of 2000, due to a dependence on the lepton mass.[6] The goal of this experiment is a significant improvement in the sensitivity of these searches in the neutral-kaon system. The results presented here are a first report and we expect to substantially improve upon this work in the future.

We carried out the experiment with a new high-intensity neutral-particle beam (designated B5) at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS). A 28.5-GeV proton beam was focused on a $190 \times 3 \times 3$ mm^3 copper target. Charged particles from the beam, and those produced by interactions in the target, and by conversion of photons in lead foils downstream of the target, were swept away by a magnetic field. The resulting neutral beam was defined by a series of precision collimators centered at 2.75° from the incident-proton-beam direction. The final collimator was contained in a magnet in order to sweep charged particles produced in the collimators out of the region viewed by the detector. The neutral-beam solid angle realized during this initial run was 3.9 mrad × 15.6 mrad. The beam-defining elements were followed by an 8.3-m-long evacuated decay region beginning 9.5 m from the target.

The decay region was followed by a two-arm spectrometer capable of measuring each particle momentum twice and containing detectors for muon and electron identification. Figure 1 shows a schematic view of the system. The neutral beam passed between the two arms of the spectrometer, minimizing counting rates from beam interactions in the detectors. Except for the helium-filled region between the first two planes of drift chambers, the beam and decay particles propagated in air.

We measured the trajectories of charged decay products in low-mass high-resolution drift chambers arranged in five modules around two analyzing magnets. The spectrometer magnets imparted opposite and nearly equal momentum impulses of approximately 300 MeV/c. Each module of drift chambers contained four planes of sense wires, measuring the horizontal and the vertical coordinate twice. We measured the intrinsic resolution of each drift chamber, using the data reported here, to be < 120 μm, with an additional contribution due to wire position uncertainties of less than 25 μm. Two sequential analyzing magnets were used to increase the accuracy of the momentum determination, to permit identification of events with a pion decay in the spectrometer, and, in the future, to simplify on-line event selection by restoring the initial particle directions downstream of the second magnet.

The measurement accuracy of the spectrometer is characterized by the resolution in the two-particle invariant mass m and in the colinearity angle Θ_c between the vector from the target to the decay vertex and the measured momentum vector of the reconstructed decay. We use one standard deviation of the experimental distributions determined from reconstructed $K_L^0 \to \pi^+\pi^-$ decays to describe the resolution. The resolution in m varied with K_L^0 momentum from 1.4 MeV/c^2 at 5 GeV/c to 1.8 MeV/c^2 at 10 GeV/c. The resolution in Θ_c varied with K_L^0 momentum from 0.31 mrad at 5 GeV/c, to 0.25 mrad at 12 GeV/c. The resolution in m for $K_L^0 \to \mu e$ decays is estimated, with a Monte Carlo simulation, to be slightly worse due to kinematic differences. These resolutions define the ability to reject events from the principal background process, $K_L^0 \to \pi e \nu$, in which this decay is followed by the decay of the pion into a muon and neutrino, or by misidentification of the pion, mimicking the decay $K_L^0 \to \mu e$.

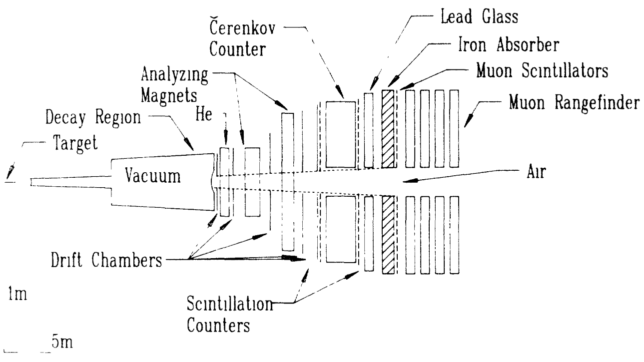

FIG. 1. Schematic view of the detector system. The diagram shows the plan view and is drawn with the indicated horizontal and vertical scales. The lead-glass counter array was installed to measure electron and photon energies. The array was not yet active, and was not used in the analysis presented here. The muon range finder (a marble absorber and drift-tube calorimeter) was not fully operational. We did not use it to analyze the data presented here.

The drift-chamber spectrometer was followed by scintillation-counter hodoscopes. Two planes of segmented counters were used, each with a horizontal and a vertical array of segments.

We identified electrons using a segmented Čerenkov counter, filled with a nitrogen-helium mixture at atmospheric pressure, with a velocity threshold of 0.999 86c. We measured the efficiency to be 94%.

Muons with momentum above approximately 1.4 GeV/c penetrated through 14 radiation lengths of lead glass and a 91-cm iron absorber and were detected in two planes of scintillation counters (the muon scintillators), while electrons, pions, and lower-energy muons were strongly attenuated. The efficiency for detecting muons was 80%.

The on-line event selection was performed with programmable logic. This logic triggered the data-acquistion electronics. Signals from the drift chambers and scintillation counters were used to establish the presence of a charged particle in each arm of the spectrometer. The gas Čerenkov counter and muon scintillators indicated the presence of one or more leptons in the event. Independent trigger paths were allowed for each logical combination, with the option of selecting events in a particular path with a preset frequency, determined by a prescaler. Events passing the first-level selection were digitized and transferred into computers which emulated the instruction set of the IBM 3081 computer.[7] All digitizations occurred within 200 ns, and all data were transferred to the computer within 5 μs. The transfer was made through a parallel connection from each crate of digitizing electronics. The crates contained time- and pulse-height digitization and latch modules. An additional software selection was performed in the emulators, using kinematic calculations based on reconstructed track parameters derived from the drift-chamber spectrometer. Data were then transferred to a host computer and recorded on magnetic tape for off-line analysis.

We collected the data in an exposure at two different beam intensities. A data set taken with a proton beam intensity of approximately 3×10^{11} protons per pulse yielded 8×10^7 recorded events. We selected these events in one of three categories, using only the first-level hardware selection criteria. Events with a lepton identified on both sides of the spectrometer were selected without prescaling. One event in ten with no lepton identified on either side (the $\pi\pi$ sample) was selected to provide a large sample of such events for calibration purposes. Finally, one event in forty was selected without regard for lepton identification (the minimum-bias sample) in order to provide a sample for efficiency studies and normalization of the result.

A second data set, taken with a proton beam intensity of approximately 1.3×10^{12} protons per pulse yielded 2×10^7 events. This sample was recorded using both levels of event selection described above. The software event selection was performed in two emulators, which were the first available in a system consisting of eight units. Minimum-bias and $\pi\pi$ events were prescaled by factors of 256 and 100, respectively. The kinematic selection performed in the emulators required the two-body invariant mass m of the reconstructed tracks to lie between 450 and 600 MeV/c^2 for lepton-pair events. We monitored the efficiency of the selection process with $\pi\pi$ events, for which we performed the reconstruction and kinematic analysis, but no on-line event selection. The efficiency was measured to be 80%. To ensure that no biases are introduced by this software event selection, the sample of $\pi\pi$ events which were used to monitor the efficiency were fully analyzed off-line. The results of this analysis were compared to the results produced in the emulators, demonstrating that no significant biases were introduced. After including corrections for pion decays and interactions, we found the sensitivities of the two exposures to be equivalent to 3.3×10^5 and 5.1×10^5 accepted $K_L^0 \to \pi^+\pi^-$ decays.

Analysis of the data proceeded in four steps: association of hits in the drift chambers with particles traversing the spectrometer (pattern recognition), fitting of the tracks to calculate particle momenta and select well-measured events, classification of decay modes by use of information from the particle identification counters, and imposition of final event-selection cuts to eliminate backgrounds.

We used a pattern-recognition algorithm to search for all possible groupings of hits on each side of the spectrometer, and in each coordinate view, consistent with a single particle traversing the spectrometer. We allowed only one hit (of ten) to be missing in each view. The algorithm used the fact that particle directions should be the same before the first and after the second magnet. We correlated the two views to form three-dimensional tracks, and required tracks in the two sides of the spectrometer to be consistent with an origin at a common vertex. We retained events with m above 460 MeV/c^2 and Θ_c less than 5 mrad.

Two procedures were used to calculate precise kinematic information. In the first, we determined the track parameters independently in the front and back halves of the spectrometer, and fit the tracks using the extracted upstream and downstream momenta, the positions and angles in the central plane, and the requirement of a common vertex. In the second procedure, we made use of the complete error matrix of the spectrometer, determined using Monte Carlo methods, to fit full tracks. In both procedures, we used the fit tracks to calculate all kinematic quantities of the decay. The results of the two procedures agreed well. The first procedure was used to derive the results reported here.

Following the kinematic fit, we projected the particle trajectories from the spectrometer to the gas Čerenkov counter and the muon hodoscope. Our identification of a particle as a muon or electron was based on the proximity of the struck counter to the projected trajectory and on the quality of the time coincidence of the signal in the counter.

Finally, we made selections to eliminate kinematic regions which were particularly susceptible to background, as determined from Monte Carlo studies and from the data. In particular, we required the ratio of the higher track momentum to the lower momentum to be below 2.75. We eliminated events with reconstructed vertices closer than 9.5 m to the production target to minimize backgrounds from decays in the fringe field of the last sweeping magnet and from particles produced from interactions in the collimator. We also used the transverse vertex position to reject events outside the nominal beam divergence. We required each track momentum to be below 9.0 GeV/c, to reduce the number of events with misidentified particles and tracks with poor kinematic resolution.

A small sample of lepton-pair events remained. Figure 2 displays the events for three of the four decay modes as

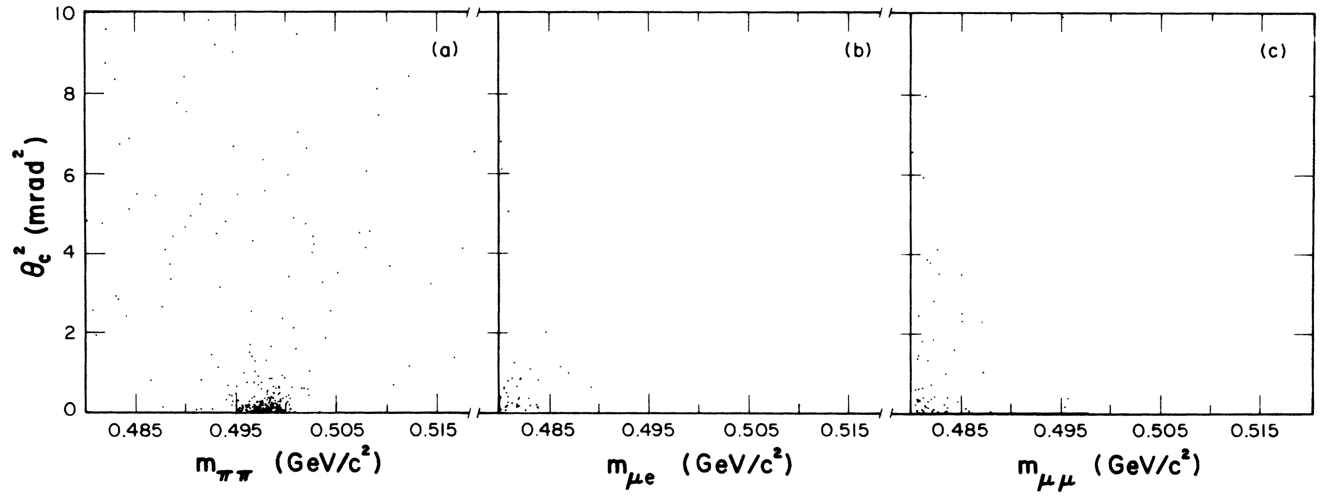

FIG. 2. Scatter plots of the reconstructed invariant mass m vs the square of the colinearity angle Θ_c for the (a) $K_L^0 \to \pi^+\pi^-$, (b) $K_L^0 \to \mu e$, and (c) $K_L^0 \to \mu\mu$ event samples. The scatter plot for the $K_L^0 \to ee$ sample is not shown, as it contains no events. The $K_L^0 \to \pi^+\pi^-$ plot contains only a representative sample of 500 events.

scatter plots of m vs Θ_c^2. The plot for $K_L^0 \rightarrow ee$ events is not displayed since it is empty. The quoted resolutions in m and Θ_c are obtained from the sample of $K_L^0 \rightarrow \pi^+\pi^-$ events. Our final selection of candidate rare-decay events retained events within 2.5 standard deviations of the kaon mass and with Θ_c less than 1.0 mrad.

No events satisfy all of the selection criteria for the processes $K_L^0 \rightarrow \mu e$ or $K_L^0 \rightarrow ee$. Two events from the known process $K_L^0 \rightarrow \mu\mu$ pass all the selection criteria.

The $K_L^0 \rightarrow \pi^+\pi^-$ events correspond to a branching ratio for this process of 2.4×10^{-9} for a single event. Our sensitivity to the decays $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow ee$ is different, due to variations in the spectrometer acceptance and particle-identification efficiencies for these decays. For K_L^0 momenta above 4 GeV/c, the acceptance for the decay $K_L^0 \rightarrow \pi^+\pi^-$ is 6.8%, for $K_L^0 \rightarrow \mu\mu$ it is 5.3%, for $K_L^0 \rightarrow \mu e$ it is 4.8%, and for $K_L^0 \rightarrow ee$ it is 3.8%. The resulting 90%-confidence-level upper limit for the branching ratio for $K_L^0 \rightarrow \mu e$ is 1.1×10^{-8} and for $K_L^0 \rightarrow ee$ it is 1.1×10^{-8}. Our observation of two $K_L^0 \rightarrow \mu\mu$ decays corresponds to a branching ratio of 1.0×10^{-8}, which is consistent with the previous world average.[8]

The previous best published limit on $B(K_L^0 \rightarrow \mu e)$ (Clark *et al.*[3]) has been called into question, the Particle Data Group[8] recommending 6×10^{-6}. Our results agree with a recent report[9] in setting new limits well below this value.

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[9] H. B. Greenlee *et al.*, Phys. Rev. Lett. **60**, 893 (1988). These authors have published limits $B(K_L^0 \rightarrow \mu e) < 6.7 \times 10^{-9}$ and $B(K_L^0 \rightarrow ee) < 4.5 \times 10^{-9}$ (90% confidence level). In the future, we expect substantial improvement in sensitivity from these authors, from our own experimental work, and from an experiment (E137) being carried out at the National Laboratory for High Energy Physics (KEK), Tsukuba, Japan.