Measurement of the Branching Ratio for the Decay $K_L^0 \to \mu\mu$

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(Received 7 August 1989)

Concurrent with our search for the decays $K_L^0 \to \mu e$ and $K_L^0 \to ee$, we have observed 87 $K_L^0 \to \mu\mu$ events. Normalizing this sample to the simultaneous observation of the decay $K_L^0 \to \pi^+\pi^-$, we obtain the branching ratio $B(K_L^0 \to \mu\mu) = [5.8 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-9}$.

PACS numbers: 13.20.Eb

The study of particle decays that manifest flavor-changing neutral currents (FCNC's) has had a profound influence on the development of the standard model of the standard model of electroweak interactions. In this Letter, we report a new, more precise measurement of the branching ratio of one such decay, $K_L^0 \to \mu\mu$, made possible by a substantial increase in statistical sensitivity compared to earlier efforts.[1-3]

The observation that the $K_L^0 \to \mu\mu$ decay rate is much less than that for $K^+ \to \mu^+\nu_\mu$ helped to motivate the mechanism whereby Glashow, Iliopoulos, and Maiani[4] (GIM) explained the suppression of FCNC's in a four-quark model. Subsequent calculations,[5] which further illuminated the role of the GIM mechanism in rare kaon decays, have been extended to the six-quark standard model.[6] A more precise measurement of the rate for $K_L^0 \to \mu\mu$ should provide a motivation for improving these calculations, leading to possible constraints on parameters of the standard model.

A related theoretical investigation[7] was made of the contribution to the $K_L^0 \to \mu\mu$ rate by the intermediate process $K_L^0 \to \gamma\gamma$. If this were the only contribution, the branching ratio would be expected to be $B(K_L^0 \to \mu\mu) \approx 1.20 \times 10^{-5} B(K_L^0 \to \gamma\gamma)$. After an experiment[8] reported a value (later superseded by the measurements cited above) significantly below this, increased theoretical activity[9] emphasized that interference by other processes could decrease this branching ratio very little.

A preceeding Letter[10] describes the detector and reports the results of our search for the decays $K_L^0 \to \mu e$ and $K_L^0 \to ee$. Here we describe the collection and analysis of events from the kinematically similar decay modes $K_L^0 \to \mu\mu$ and $K_L^0 \to \pi^+\pi^-$. We emphasize the studies which are required in order to correct for differences in the response of the detector to events from the two modes. These studies benefit from many of the same features which aid the search for the μe and ee modes: a clean high-intensity neutral beam, a two-magnet high-resolution charged-particle spectrometer, timing measurements on most detector elements, redundant muon-identification systems, and a high-speed trigger and data-acquisition system.

At the end of the detector, two muon-detector systems followed a 91-cm-thick iron wall. Muons above 1.4 GeV/c reached the detectors, while e's and π's were mostly absorbed. First, a segmented x-y scintillation-counter hodoscope provided spatial and fast timing information for the trigger and for off-line analysis. Next, muons lost energy in a tracking rangefinder[11] consisting of marble and aluminum plates with planes of proportional tubes which measured x and y positions at 13 depths (gaps) within the plates. Struck groups of wires

19 cm wide were recorded in latches for use in the off-line analysis. The spacing of the gaps corresponded to intervals of 10% momentum loss. Muons with momentum > 6 GeV/c exited at the back.

Events written to tape satisfied a hardware trigger in commercial fast electronics and a software trigger in 3081/E processors.[10,12] Each trigger was the logical OR of requirements designed to isolate different classes of events. The "minimum-bias" trigger only required hits in scintillation counters and drift chambers to indicate the presence of two charged particles. The normalization sample of $K_L^0 \to \pi^+\pi^-$ events was selected from events passing this trigger, suitably prescaled. $K_L^0 \to \mu\mu$ events were selected from the class of minimum-bias events which also had hits in the muon hodoscope indicating that both particles were μ's. Further, the software part of the $\mu\mu$ trigger reconstructed a portion of each track and passed only those events consistent with a $K_L^0 \to \mu\mu$ hypothesis. Other trigger classes contained pulsed calibration data or other specific decay modes, which were used for calibration and resolution studies.[10]

We have investigated a number of possible effects of the trigger requirements on the relative yields of $K_L^0 \to \pi^+\pi^-$ and $K_L^0 \to \mu\mu$ events. The average efficiency of the 496-trigger scintillation counters was 0.993. The drift-chamber wires had a weighted mean efficiency of 0.994. The effect of the few relatively inefficient counters and wires was found to have an insignificant effect on the relative rates of $K_L^0 \to \pi^+\pi^-$ and $K_L^0 \to \mu\mu$. A correction to the relative yields is required because the efficiency in the electronic latching of a bit signifying a $\mu\mu$ trigger was 0.985 ± 0.015. Finally, the hardware prescale factor in the minimum-bias trigger was verified by scaling the input and output of the prescale circuit during the data collection.

On-line software requirements were imposed on the $\mu\mu$ candidates but not on the minimum-bias sample. The program performed a partial-event reconstruction and calculated the two-body invariant mass $m_{\mu\mu}$ and the collinearity angle θ_c between the direction from the target to the vertex and the direction of the total momentum of the two tracks. Events were selected using these 3081/E-calculated quantities, first on line and later off line with tighter cuts. All surviving $\mu\mu$ candidates had 460 MeV/$c^2 \le m_{\mu\mu} \le 550$ MeV/c^2 and $\theta_c < 10$ mrad. The efficiency of this selection was measured to be $(79 \pm 2)\%$ by using a subset of the minimum-bias data for which the trigger calculation was performed on line without rejecting events.

The track-finding algorithm required at least nine of the ten potential hits in each view of both tracks. Accepted events had tracks in the two spectrometer arms with a distance of closest approach less than 3 cm in the decay region. The two estimates of the momentum obtained from the bends in the two magnets were averaged to give a momentum for each track. These momenta, along with directions determined from the hits in the first two chambers, were used to compute a vertex position, collinearity angle, and two-body invariant masses (under mass hypotheses consistent with the on-line particle identification). These kinematic calculations were used to make a preliminary selection of events.[10]

The final kinematic fitting used magnetic field maps consisting of measured values of the major component of the field for most of the volume and calculations of the minor components of the field. The results of the track-finding algorithm were used to start a successive approximation calculation, separately in the upstream and downstream halves of the spectrometer, which precisely determined the track parameters. Track quality was tested by constructing appropriate χ^2 functions. The horizontal view χ_x^2 included the difference between the upstream and downstream measured momenta and the horizontal angles of intersection at the central drift-chamber plane. The vertical view χ_y^2 included the differences between the upstream and downstream track extrapolation to the central drift chamber and between the vertical angles. A third function, χ_v^2, characterized the distance of closest approach at the decay vertex. The experimental distributions are somewhat broader than distributions calculated by Monte Carlo simulation, possibly due to such effects such as differences between the magnetic field map used and the actual field. Data and Monte Carlo–generated events were retained only if $\chi_x^2 < 20$ and $\chi_y^2 < 20$ for each track, and if $\chi_v^2 < 10$. The cut eliminated approximately 2% more pion than muons. Pions selected to be nondecaying were cut with the same probability as muons. Varying the value of the track χ^2 cuts between 10 and 50 changed the measured value of $B(K_L^0 \to \mu\mu)$ by less than 2%. Finally, the fitting adjusted the track parameters to constrain the tracks to originate at a common vertex.

The reconstructed tracks of μ candidates were required to be consistent with the struck muon scintillation counters and rangefinder proportional tubes. The characteristics of these detectors were determined as a function of muon momentum from studies of well-identified $K_L^0 \to \pi\mu\nu$ decays. For the counters, a cut was made on a confidence level constructed from the transverse separation between the projected track and the nearest struck counter and the difference between the measured times in the struck muon scintillators and the time of the event trigger. For the rangefinder, the measured momentum was used to predict the track endpoint in the rangefinder. Muon candidates were required to approach within four gaps of, or to penetrate beyond, the predicted endpoint. The efficiencies per track of the scintillator and rangefinder requirements, weighted for the expected momentum spectrum of muons from $K_L^0 \to \mu\mu$ decays, were 0.976 ± 0.004 and 0.988 ± 0.007, respectively.

Additional selection criteria were applied to the $\mu\mu$ and $\pi\pi$ samples to eliminate events which had decay vertices outside the nominal beam or close to the beam defining magnets and collimators, or which had a track with momentum < 1.5 GeV/c. The small relative effect of these cuts on $K_L^0 \to \pi^+\pi^-$ and $K_L^0 \to \mu\mu$ decays was included in the Monte Carlo calculation.

Figure 1 shows the invariant-mass and collinearity distributions for the final $\mu\mu$ event sample. For comparison, the same distributions are shown for a representative sample of $K_L^0 \to \pi^+\pi^-$ events selected by requiring no signals in the electron and muon detectors.[10] The signal peaks are clearly separated from the background regions and have widths of 1.5 and 1.6 MeV/c^2 for the $\pi\pi$ and $\mu\mu$ peaks, respectively. On the basis of these distributions, $K_L^0 \to \mu\mu$ decays were selected by requiring 493 MeV/$c^2 < m_{\mu\mu} < 503$ MeV/c^2 and $\theta_c < 1$ mrad. The expected fraction of otherwise accepted events which fall within the acceptance region is large ($>99\%$ for $K_L^0 \to \mu\mu$ events and $>98\%$ for $K_L^0 \to \pi^+\pi^-$ events, from Monte Carlo calculations), and the relative acceptance changes by less than 1% for up to 50% variations in the spectrometer resolution. The number of $\mu\mu$ events in the signal region is $N_{\mu\mu}=87$. The expected number of background events in the signal region is 0.25, as estimated from uniformly distributed events outside the signal region and from the tail of events at lower masses.

The sample of $K_L^0 \to \pi^+\pi^-$ candidates used for normalization contains background events since no particle-identification requirements have been imposed. The expected shape of the background from $K_L^0 \to \pi\mu\nu$ and $K_L^0 \to \pi e\nu$ decays was calculated using the Monte Carlo method. Figure 2 shows the $\pi\pi$ mass distribution for those simulated events with collinearity angle $\theta_c < 1$ mrad, normalized to agree with the data sample in the region $m_{\pi\pi} < 488$ MeV/c^2 or $m_{\pi\pi} > 508$ MeV/c^2. After subtracting the simulated background, events were selected in the region 493 MeV/$c^2 < m_{\pi\pi} < 503$ MeV/c^2 and $\theta_c < 1$ mrad. The number of resulting events was corrected for an estimated 2.1% contribution from the K_S and interference terms in the neutral kaon state vector, yielding $N_{\pi\pi}=8226 \pm 148$ $K_L^0 \to \pi^+\pi^-$ events. The quoted error contains roughly equal contributions from statistical errors and uncertainty in the normalization of the background.

Pion interaction in the apparatus caused a loss of $\pi\pi$ events when an interaction resulted in poor track quality or missing hits in detectors. The loss of events was estimated using the total cross section for nuclear interactions and simulation of scattered pions. The correction, expressed as the contribution to the pion detection efficiency, is $\epsilon_{\pi\pi}=0.985 \pm 0.002$.

As a check on multiple aspects of μ and π reconstruction, identification, and simulation, we used the minimum-bias data set to measure the branching ratio $B(K_L^0 \to \pi\mu\nu)/B(K_L^0 \to \pi^+\pi^-)$. The result is 130 ± 4, in good agreement with the accepted value of 132.[13]

Because of slightly different kinematics, spectrometer resolution, and pion decay, the acceptance $A_{\pi\pi}$ for $K_L^0 \to \pi^+\pi^-$ is not equal to $A_{\mu\mu}$ for $K_L^0 \to \mu\mu$. Simulation of the detector response, event reconstruction, and kinematic fitting gives $A_{\pi\pi}/A_{\mu\mu} = 1.180 \pm 0.012$.

The $\mu\mu$ branching ratio is given by

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

Here 6000 is the minimum-bias prescale factor and the factor $\epsilon_{\mu\mu}=0.723$ contains the corrections cited above for trigger efficiency and muon identification. Using

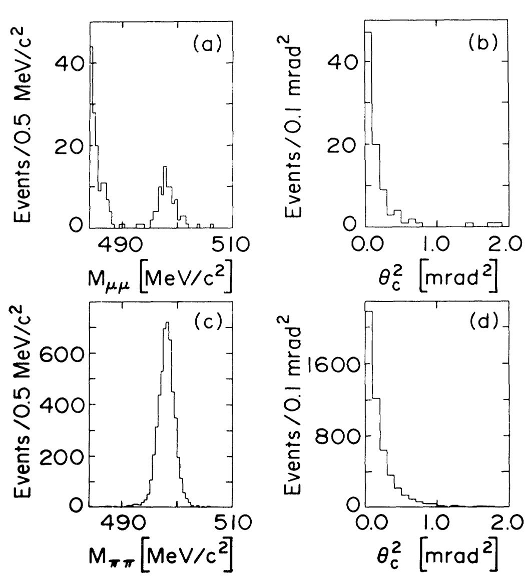

FIG. 1. For the final $K_L^0 \to \mu\mu$ event sample, (a) the $m_{\mu\mu}$ spectrum and (b) the θ_c^2 spectrum. For a representative sample of $K_L^0 \to \pi^+\pi^-$ events with lepton vetoes applied, (c) the $m_{\pi\pi}$ spectrum and (d) the θ_c^2 spectrum.

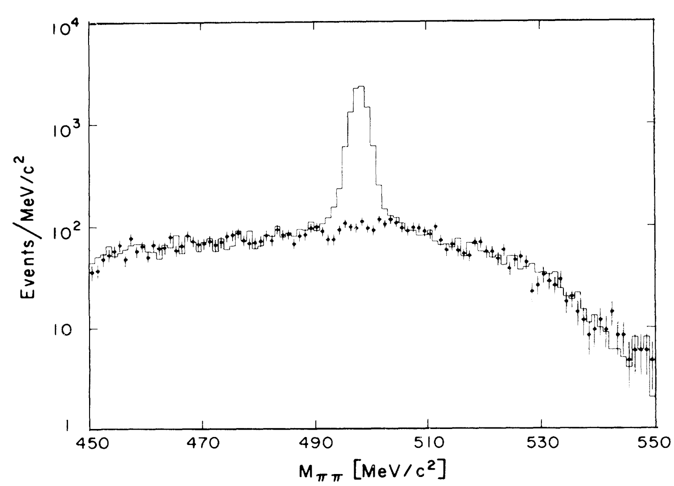

FIG. 2. The $m_{\pi\pi}$ spectrum for events in the final event sample with $\theta_c < 1$ mrad. The line is the minimum-bias data and the points are the Monte Carlo simulation of the background.

the current value[13,14] $B(K_L^0 \to \pi^+\pi^-) = (2.04 \pm 0.04) \times 10^{-3}$ yields

$$B(K_L^0 \to \mu^+\mu^-) = (5.8 \pm 0.6 \pm 0.4) \times 10^{-9}.$$

The errors are statistical and systematic, respectively. Our result, combined with the current value[13,15] for $K_L^0 \to \gamma\gamma$, yields

$$B(K_L^0 \to \mu\mu)/B(K_L^0 \to \gamma\gamma) = (1.01 \pm 0.13) \times 10^{-5}.$$

This result is 1.5 standard deviations below the theoretical calculation cited above.

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

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