PHYSICAL REVIEW D VOLUME 39, NUMBER 3 1 FEBRUARY 1989

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication should be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the accelerated schedule, publication is not delayed for receipt of corrections unless requested by the author or noted by the editor.

Limit on the decay $K_L^0 \to \mu e$

S. F. Schaffner, H. B. Greenlee, H. Kasha, E. B. Mannelli, M. Mannelli, K. E. Ohl, and M. P. Schmidt
Department of Physics, Yale University, New Haven, Connecticut 06511

E. Jastrzembski, R. C. Larsen, L. B. Leipuner, and W. M. Morse
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

(Received 8 August 1988)

We report on a search for the lepton-generation-number-violating decay $K_L^0 \to \mu e$. We find $B(K_L^0 \to \mu^\pm e^\pm) < 1.9 \times 10^{-9}$ (90% confidence level).

In the standard $SU(3) \times SU(2) \times U(1)$ model, flavor-changing neutral currents are highly suppressed; in particular, the decay $K_L^0 \to \mu^+\mu^-$ is suppressed by the Glashow-Iliopoulos-Maiani mechanism. The unitarity limit for this decay[1] is $B(K_L^0 \to \mu^+\mu^-) > (7.0 \pm 0.3) \times 10^{-9}$. The decay $K_L^0 \to \mu^\pm e^\mp$ is forbidden by lepton-generation-number conservation. However, the standard model provides no insight into the number of generations or the mechanism of lepton-generation-number conservation. Many models[2] that go beyond the standard model predict lepton-generation-number violation. Specifically, they predict decay modes such as $\mu \to e\gamma$ and $K_L^0 \to \mu e$. The latter decay mode conserves total (quark plus lepton) generation number. $K_L^0 \to \mu^\pm e^\mp$ requires pseudoscalar or axial-vector currents while the related decay $K^+ \to \pi^+\mu^\pm e^\mp$ requires scalar or vector currents.

The experiment was performed in the A3 line of the Brookhaven Alternating Gradient Synchrotron (AGS). A neutral beam was produced in the forward direction by the interactions of 24-GeV/c protons with a 5-mm-diameter, 23-cm-long copper target. Charged particles were swept away by a magnetic field of 8 Tm. γ's were attenuated by a 2.5-cm lead plug. The neutral beam had a divergence of 15 mrad vertical by 2.3 mrad horizontal. The 2.87-m evacuated decay region began 7.47 m downstream of the target. The mean kaon momentum was about 7 GeV/c. Events with secondary charged particles between 1 and 12 GeV/c were included in the analysis.

A schematic representation of the detector is shown in Fig. 1. The momenta of charged particles were measured with four sets of drift chambers placed upstream (A and B) and downstream (C and D) of a spectrometer magnet with a transverse momentum kick of 220 MeV/c. Each chamber had four sense planes: x, x', y, y', the x planes

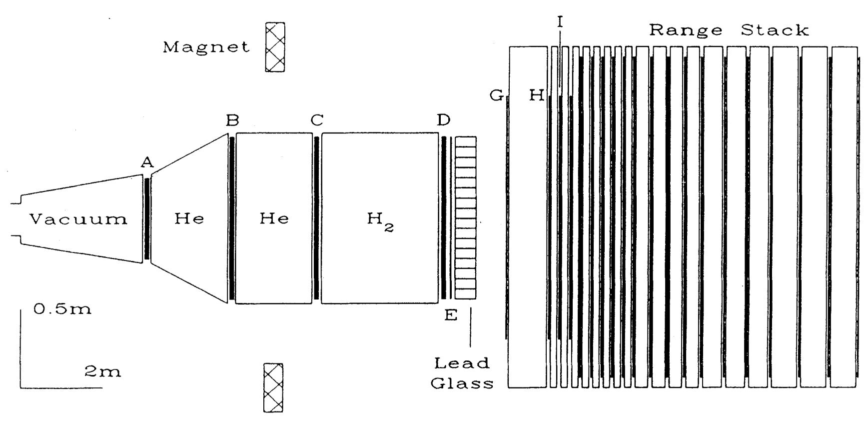

FIG. 1. Plan view of the detector.

 © 1989 The American Physical Society

measuring horizontal positions, the y planes vertical positions. The B chamber had an additional plane rotated 14° from the vertical to resolve track ambiguities. Electrons were identified by an atmospheric-pressure hydrogen Cherenkov counter located between the C and D drift chambers and a lead-glass array downstream of the D drift chamber. The detector represented only 0.008 radiation lengths of material upstream of the D chamber. Muons were identified by their passage through a steel filter and range stack instrumented with scintillation counters. We accepted about 8×10^{11} protons per AGS pulse, which generated approximately 10^7 counts/m^{2}s in the detector.

Four trigger types were collected: ee, μe, $\mu\mu$, and $\pi\pi$. The geometrical acceptances for these decay modes is 3.5%, 3.7%, 4.4%, and 5.3%, respectively. The $\pi\pi$ trigger was prescaled by 128. Electrons were required to activate the Cherenkov counter and to deposit at least 1.2 GeV in the lead glass. Muons were required to penetrate the lead-glass array and 1.05 m of steel ($E\cdot G\cdot H\cdot I$). Pions were required to penetrate the lead glass, but not to activate the H counters ($E\cdot G\cdot \overline{H}$). Numerous "minimum-bias" tapes requiring only two E counters were taken, which contained a large sample of unbiased K_{e3} and $K_{\mu3}$ events. From these it was determined that the Cherenkov counter was 93% efficient for electrons and the H and I scintillation planes were 95% efficient for muons. Further information on the detector and data acquisition system may be found in Ref. 3. Results of the analysis of the e^+e^- triggers can be found in Ref. 4.

The decay $K_L^0 \to \pi^+\pi^-$ served as a normalization and a measure of detector resolutions; we effectively collected 4×10^6 $\pi^+\pi^-$ decays. The events were required to pass requirements on track quality and distance of closest approach. The effective-mass distribution for in-bending $\pi\pi$ events is shown in Fig. 2(a). The mass resolution is $\sigma=2.3$ MeV/c^2 for in-bending events and $\sigma=4.0$ MeV/c^2 for out-bending events. Only in-bending events were used in this analysis. The distribution of the square of the angle between the reconstructed kaon momentum vector and the vector from the vertex to the target is shown in Fig. 2(b). The resolution in this angle is $\sigma=0.33$ mrad.

The constraints of kinematic reconstruction are important in searches for $K_L^0 \to \mu^+\mu^-$ and $\mu^\pm e^\mp$ to discriminate against backgrounds from $K_L^0 \to \pi\mu\nu$ and $\pi e\nu$ with the pion decaying to or being misidentified as a muon. For example, if the neutrino is produced with very little energy in the K rest frame and the muon from π decay is directed along the π trajectory, the dilepton effective mass equals 489 MeV/c^2. However, in this case, the transverse momentum with respect to the target for nearly transverse K decays will be unbalanced by approximately 9 MeV/c. If the π decays so as to affect the momentum measurement, the measured dilepton mass can even exceed the K mass. Then, however, the event will not have an acceptable θ^2. We expect similar background distributions in the $\mu^\pm e^\mp$ and $\mu^+\mu^-$ searches.

The decay $K_L^0 \to \mu^+\mu^-$ served to verify our estimation of the sensitivity of the experiment. Various cuts were applied to reduce backgrounds. The momentum asymmetry $A=(p_{\max}-p_{\min})/(p_{\max}+p_{\min})$ was required to be less than 0.45. 93% of the $\pi^+\pi^-$ events pass this cut. Monte Carlo calculations show that 95% of $\mu^\pm e^\mp$ decays would pass this cut. Muons were required to penetrate at least 1.05 m of steel to satisfy the trigger. Furthermore, if the muon stopped in the range stack, the energy obtained from the muon range was required to be at least 70% of the momentum as measured in the magnetic spectrometer. From our study of $K_{\mu3}$ events, only 3% of muons fail this

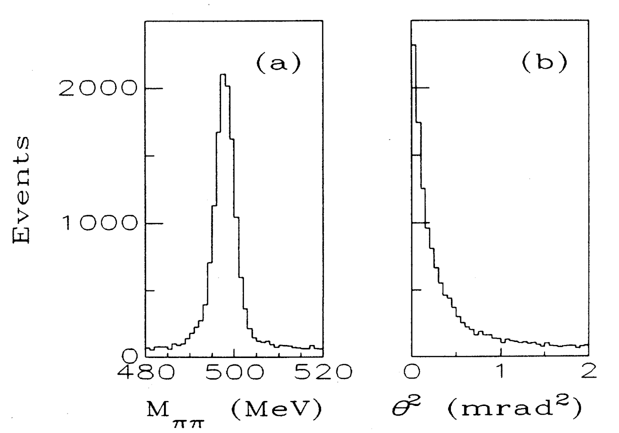

FIG. 2. (a) $\pi^+\pi^-$ effective-mass distribution for in-bending events with $\theta^2<1.5$ mrad^2. (b) Square of the angle between the reconstructed kaon momentum vector and the vector from the vertex to the target for events within 3σ of the K mass.

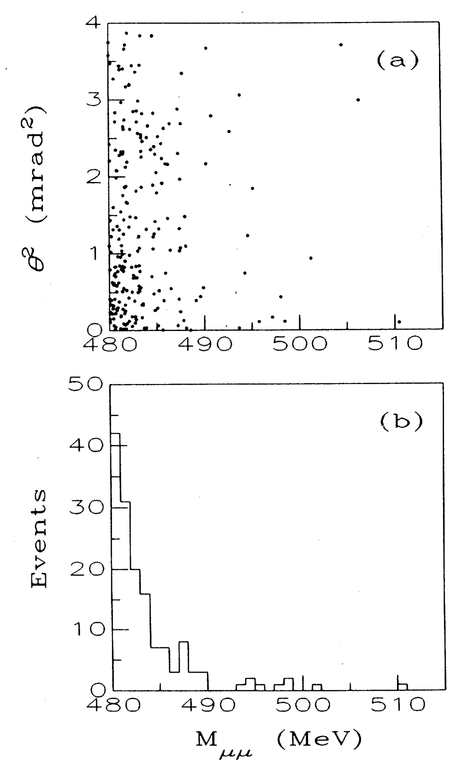

FIG. 3. (a) Scatter plot of $\mu^+\mu^-$ effective mass vs θ^2. (b) Distribution of $\mu^+\mu^-$ effective mass for events with $\theta^2<1.5$ mrad^2.

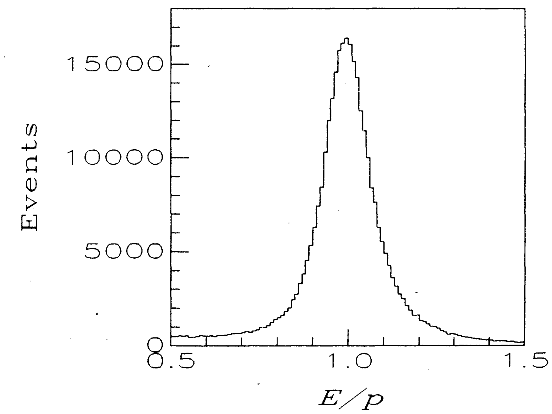

FIG. 4. Distribution of energy deposited in lead glass divided by momentum for electrons from K_{e3} events.

cut.

A scatter plot of $\mu^+\mu^-$ effective mass versus θ^2 is shown in Fig. 3(a). The distribution of $m(\mu^+\mu^-)$ for events which point back to the target to within 1.5 mrad^2 is shown in Fig. 3(b). There is a clear peak around the K mass. All eight events are within 1.8σ of the K mass. As stated above, we expect similar background distributions in the μe and $\mu\mu$ data. Since there are no events in the fiducial region in the μe sample (see below), we subtract no background from the number of $\mu\mu$ events in the fiducial region. The sensitivity of the experiment to the decay $K_L^0 \rightarrow \mu^+\mu^-$ was determined through an accounting of the kinematically similar decay $K_L^0 \rightarrow \pi^+\pi^-$. A correction of 15% was applied to the $\pi\pi$ event sample to account for background contributions in mass and θ^2. The background subtracted data was then fit as a function of K energy and decay position to determine the K_s^0 contamination. It was determined that effectively 78% of the $\pi\pi$ decays were due to K_L^0. Corrections were also made for the efficiency of the muon trigger counters. Using the known $\pi\pi$ branching ratio,[5] it was determined that the single-event sensitivity to $K_L^0 \rightarrow \mu^+\mu^-$ was 1.3×10^{-9}. Using the single-event sensitivity and the Particle Data Group world average $B(K_L^0 \rightarrow \mu^+\mu^-) = (9.1 \pm 1.9) \times 10^{-9}$, we would expect to observe 7.0 events, in good agreement with the eight events in the fiducial region.

The same kinematic and muon identification requirements were made on the μe triggers. Additional requirements were made on the electron track. The electron momentum was required to be less than the pion Cherenkov threshold of 8 GeV/c. Furthermore, the energy as measured in the lead glass divided by the momentum measured in the magnetic spectrometer was required to be greater than 0.75. The distribution of E/p from a sample of K_{e3} events is shown in Fig. 4. 96% of electrons satisfy this requirement. A scatter plot of $\mu^{\pm}e^{\mp}$ effective mass versus θ^2 is shown in Fig. 5(a). The distribution of $m(\mu e)$ for events which point back to the target to within 1.5 mrad^2 is shown in Fig. 5(b). There are no events close to the K mass. The closest event had an effective mass of 489.3 MeV/c^2. This is 3.7σ below the K mass. We then

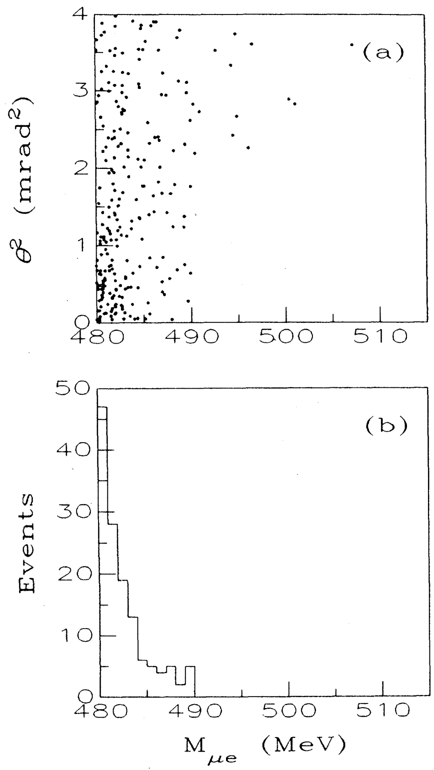

FIG. 5. (a) Scatter plot of $\mu^{\pm}e^{\mp}$ effective mass vs θ^2. (b) Distribution of $\mu^{\pm}e^{\mp}$ effective mass for events with $\theta^2 < 1.5$ mrad.^{2}

find no events consistent with the decay $K_L^0 \rightarrow \mu e$. The single-event sensitivity to the decay $K_L^0 \rightarrow \mu e$ was determined to 1.1×10^{-9}. The 90%-confidence-level limit is then $B(K_L^0 \rightarrow \mu e) < 2.6 \times 10^{-9}$. Combining this result with our previous limit[3] gives a final result $B(K_L^0 \rightarrow \mu e) < 1.9 \times 10^{-9}$. This limit places constraints on models with exotic gauge bosons: Assuming the boson couples to μe and sd with the universal weak-coupling constant, the mass of such a boson is related to the K_L^0 branching ratio by $B(K_L^0 \rightarrow \mu e) \approx 2.5 \times 10^{-3}\,(M_x/1\ \text{TeV})^{-4}$. Our result thus requires $M_x > 34$ TeV.

We thank the Brookhaven AGS accelerator department staff for their support. We gratefully acknowledge the timely loan of lead-glass blocks from M. Kreisler and colleagues at the University of Massachusetts, Amherst, and photomultipler tubes from Brookhaven National Laboratory experiment No. 734. We gratefully acknowledge the contributions of R. K. Adair who worked on the earlier stages of the experiment. We also wish to thank Michael Lenz and Joseph Yelk who made technical contributions to the experiment. This research is supported by the U.S. Department of Energy under Contracts No. De-AC02-76CH00016 and DE-AC02-76ER03075. Additional support for one of us (M.P.S.) is provided by the Alfred P. Sloan Foundation.

[1]L. M. Sehgal, Phys. Rev. **183**, 1511 (1969); M. Holder, Ann. N.Y. Acad. Sci. **518**, 140 (1987).

[2]E. Eichten, I. Hinchliffe, K. D. Lane, and C. Quigg, Phys. Rev. D **34**, 1547 (1986); J. C. Pati and H. Stremnitzer, Phys. Lett. B **172**, 441 (1986); I. I. Bigi, G. Köpp, and P. M. Zerwas, Phys. Lett. **166B**, 238 (1986); Wei-Shu Hou and A. Soni, Phys. Rev. Lett. **54**, 2083 (1985); L. J. Hall and L. J. Randall, Nucl. Phys. **B274**, 157 (1986).

[3]H. B. Greenlee *et al.*, Phys. Rev. Lett. **60**, 893 (1988).

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

[5]M. Aguilar-Benitez *et al.*, Phys. Lett. **170B**, 134 (1986). $B(K_L^0 \rightarrow \pi^+\pi^-) = 2.0 \times 10^{-3}$.