Measurement of the Decay Rate for the Rare Process $K_L{}^0 \to \mu^+\mu^-$ [a]

M. J. Shochet, P. Linsay,[b] C. Grosso-Pilcher, H. J. Frisch, R. De Voe,[c] and J. W. Cronin
The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

and

D. R. Moffett
Argonne National Laboratory, Argonne, Illinois 60439
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We have measured the decay rate for $K_L{}^0 \to \mu^+\mu^-$ in a double-arm spectrometer at the Argonne zero-gradient synchrotron. Sixteen events were found, from which we calculate $\Gamma(K_L{}^0 \to \mu^+\mu^-)/\Gamma(K_L{}^0 \to \pi^+\pi^-) = 4.2^{+1.4}_{-0.9} \times 10^{-6}$.

In 1971 a Bevatron experiment[1] set an upper limit on the branching ratio $\Gamma(K_L{}^0 \to \mu^+\mu^-)/\Gamma(K_L{}^0 \to \mathrm{all}) < 1.8\times10^{-9}$ with 90% confidence level which was in sharp disagreement with a theoretical lower bound[2] ($>6\times10^{-9}$) based on unitarity considerations and the measured rate for $K_L{}^0 \to \gamma\gamma$. More recently Carithers *et al.*[3] observed nine events, giving a branching ratio $12^{+8}_{-4}\times10^{-9}$ (90% confidence level errors), in serious conflict with the Bevatron result. In addition, Fukushima *et al.*[4] found three events ($8.8^{+10.7}_{-5.5}\times10^{-9}$). We present here the results of an experiment with significantly higher sensitivity which resolves the discrepancy among the previous results.

The experiment was performed in a high-intensity K_L beam at the Argonne zero-gradient synchrotron (ZGS). The neutral beam, produced at an angle of 4° with respect to the primary proton beam, entered a vacuum decay tank 22 ft from the target. The 34-ft-long decay tank had a 30-in.-high×100-in.-wide thin window at the downstream end. For a typical pulse of 2.5×10^{11} protons on target, $\sim10^6$ $K_L{}^0$'s with momenta between 1 and 7 GeV/c decayed in the vacuum tank. The beam intensity was monitored with two scintillation counter telescopes, one viewing the target at an angle of 90° with respect to the beam, the other situated in the neutral beam at the entrance to the re-entrant beam dump.

The K_L charged decay products were analyzed in a double-arm magnetic spectrometer (Fig. 1). High acceptance was achieved by constructing large aperture (3 ft×3 ft) magnets which were set to bend particles from two-body K^0 decays approximately parallel to the beam line ($\int Bdl = 225$ MeV/c). The most serious potential background, $K_L{}^0 \to \pi\mu\nu$ in which the π decayed within the spectrometer, was suppressed by the requirement of track continuity through two successive magnetic deflections. The trajectory in each arm was measured with five double-gap capacitive readout[5] wire spark chambers, which were constructed with aluminum wire to minimize multiple scattering. The trigger elements consisted of scintillation counters and multiwire proportional chambers (MWPC) located at the rear of the spectrometer.

Particle identifiers for rejection of pions and electrons were placed at the downstream end of the apparatus. The electron detectors were lead liquid-scintillator counters 6 radiation lengths deep. The muon detectors consisted of four banks of scintillation counters separated by blocks of steel. The muon ranges at these banks corresponded to momenta of approximately 850, 1050, 1250, and 1450 MeV/c.

The $K_L \to \mu^+\mu^-$ trigger required that in each arm there be a "parallel" track through the downstream MWPC and horizontal hodoscope in coincidence with a count in the vertical hodoscope, the first muon-counter bank, and the second muon-counter bank. The "parallel" condition was established by a hardware coincidence matrix which required the track to bend toward the beam line

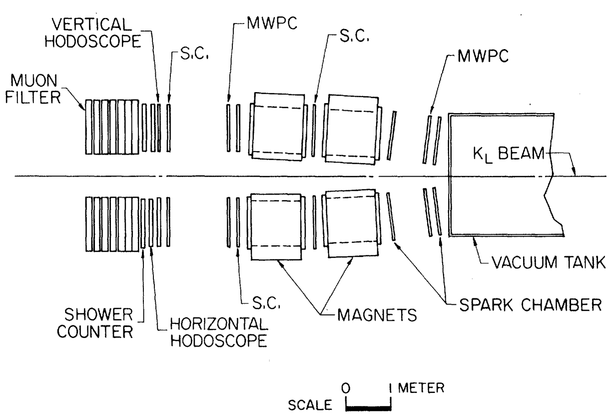

FIG. 1. Plan view of the apparatus.

with an angle less than 33 mrad or to bend away from the beam line with an angle less than 25 mrad.

The normalization for the $K_L \to \mu^+\mu^-$ events came from the kinematically similar $K_L \to \pi^+\pi^-$ events. Normalization data was taken every sixteenth accelerator pulse by removing the muon counters from the trigger. The beam monitors, which were gated along with the rest of the apparatus so that deadtime effects would be properly taken into account, recorded the relative exposures for the normalization and $\mu^+\mu^-$ data. The difference in the trigger hardware between the two data modes was a potential source of error. The electronic inefficiency of the additional muon-trigger requirement was measured to be $(2.5 \pm 1.0)\%$.

In order to detect discontinuities in a particle's trajectory, we calculated a χ^2 for each track. The χ^2 in the horizontal plane had two degrees of freedom: (1) the separation at the center of the spectrometer between the linearly extrapolated track segments from before and after the magnets, and (2) the difference between the measured position of the spark in the center chamber and the position predicted from track continuity. In the vertical plane, the χ^2 had a third degree of freedom because there was no magnetic deflection in this view. The additional parameter was the difference in angle between the two track segments at the center of the spectrometer. A sample of 20 000 $K_L \to \pi^+\pi^-$ decays was used to study the dependence of each χ^2 variable on the track momentum as well as vertical and horizontal track positions and to correct for systematic effects. Distributions of χ^2_x and χ^2_y for the sample of 20 000 $K_L \to \pi^+\pi^-$ events are shown in Fig. 2. Also shown are ideal χ^2 distributions for two and three degrees of freedom.

Events with two tracks coming from a common vertex inside the decay region were accepted. The momentum of a track was calculated from the measured angles in front of and behind the magnets, using a field integral parametrized as a function of the horizontal and vertical track positions in the center of the magnet. The apparent K^0 momentum, together with the two-particle invariant mass (M_K) and the angle between the beam and the reconstructed K^0 direction (α) were then computed.

Events were considered as $K_L^0 \to \mu^+\mu^-$ or $K_L^0 \to \pi^+\pi^-$ candidates if they satisfied the following criteria: (1) The decay vertex had to be within the beam fiducial volume. (2) The closest distance of approach of the two tracks at the vertex had to be within 3σ of zero. (3) The kaon momentum had to be less than 7 GeV/c. (4) The cosine of the center-of-mass polar angle of the decay, $\cos\theta_{\mathrm{c.m.}}$, had to be between -0.5 and $+0.5$. The efficiency for detection of two-body decays was zero outside this interval. (5) The decay vertex had to be at least 30 in. downstream of the last collimator. (6) In order to remove discontinuous tracks due to π decay in flight, the total χ^2 was required to be less than 20, while χ^2_x and χ^2_y were not permitted to exceed 14 and 18, respectively.

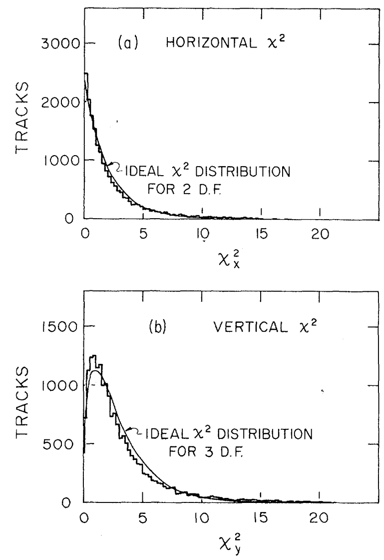

FIG. 2. χ^2 distributions in the (a) horizontal and (b) vertical views. Also shown are the ideal χ^2 distributions for the appropriate number of degrees of freedom.

The first four requirements eliminated approximately 0.5% of the $K_L^0 \to \pi^+\pi^-$ events from the normalization sample, while the fifth requirement eliminated 3.5%. The χ^2 requirement removed 5% of good tracks (thus 10% of the events), as determined from the $K_L^0 \to \pi^+\pi^-$ data. It is important to note that all of the above criteria were applied identically to the $K_L^0 \to \mu^+\mu^-$ candidates and to the $K_L^0 \to \pi^+\pi^-$ normalization data.

The only difference in the treatment of the two data samples was the muon-range requirement for the $K_L^0 \to \mu^+\mu^-$ data. The range measured by the muon identifier had to be consistent with the particle's momentum. This requirement was quite loose; the momentum interval for each counter bank was extended by $3\sigma_{\mathrm{straggling}}$ in each direction. In addition, the counters which fired had to be consistent with the horizontal and ver-

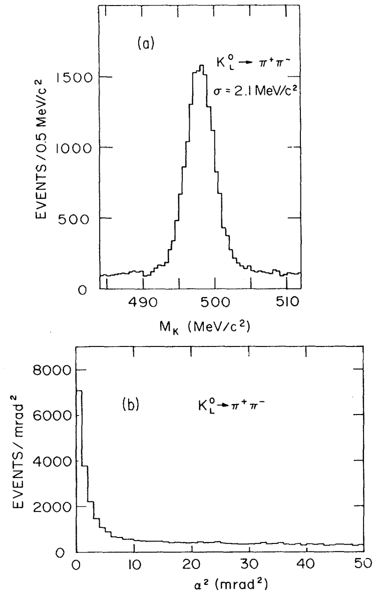

FIG. 3. A sample of the normalization data. (a) M_K distribution for events with $\alpha^2 < 7$ mrad^2. (b) α^2 distribution for events with $492 < M_K < 504$ MeV/c^2.

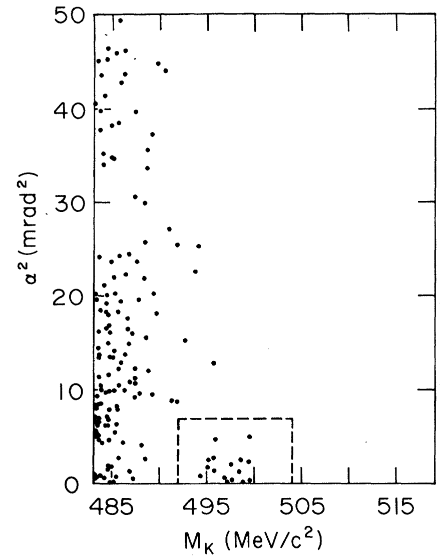

FIG. 4. Plot of M_K vs α^2 for the entire $K_L{}^0 \to \mu^+\mu^-$ data sample. The dotted line encloses the region which contains over 90% of the normalization data.

tical track coordinates. The effect of the range requirement was checked with a sample of muons from $K_L{}^0 \to \pi\mu\nu$ events. It was found that 3% of the muons were lost. Thus a 6% correction was included in the final result.

A sample of the $K_L{}^0 \to \pi^+\pi^-$ normalization data is shown in Fig. 3. After background subtraction, the number of $K_L{}^0 \to \pi^+\pi^-$ events with $492 < M_K < 504$ MeV/c^2 and $\alpha^2 < 7$ mrad^2 in the entire data sample was found to be $29\,470 \pm 525$. This number, after correction for π decay in flight (0.78), became $37\,780 \pm 670$. Finally, it was multiplied by 121.5, the ratio of the relative $\mu\mu$ to $\pi\pi$ exposure times as measured by the beam monitors. Thus the number of normalization events appropriate to the $\mu\mu$ mode exposure was $N_{2\pi} = (4.59 \pm 0.08) \times 10^6$.

The $K_L{}^0 \to \mu^+\mu^-$ data are shown in Fig. 4. In the region $492 < M_K < 504$ MeV/c^2, $\alpha^2 < 7$ mrad^2 there are sixteen events well separated from the nearest background. These events have M_K and α^2 distributions which agree well with those obtained for the $K_L{}^0 \to \pi^+\pi^-$ data. The mass distribution for events with $\alpha^2 < 7$ mrad^2 shows the background falling to zero well before the $K_L{}^0$ mass peak. In addition, the calculated background shape agrees with the data of Fig. 4 and indicates no background in the region of the $K_L{}^0$ peak. Thus, the number of $K_L{}^0 \to \mu^+\mu^-$ events is taken to be sixteen.

The $K_L{}^0 \to \mu^+\mu^-$ branching ratio is calculated from the equation

$$\frac{\Gamma(K_L{}^0 \to \mu^+\mu^-)}{\Gamma(K_L{}^0 \to \pi^+\pi^-)} = \frac{N_{2\mu}M}{N_{2\mu}C},$$

where M, the ratio of the $K_L \to 2\pi$ to $K_L \to 2\mu$ acceptances, was determined by Monte Carlo techniques to be 1.10 ± 0.02. C contains two factors: 0.975 due to the $\mu\mu$ trigger inefficiency and 0.94 due to the muon detector inefficiency. Thus $\Gamma(K_L{}^0 \to \mu^+\mu^-)/\Gamma(K_L{}^0 \to \pi^+\pi^-) = (4.2^{+1.4}_{-0.9}) \times 10^{-6}$, where the errors correspond to one standard deviation. The uncertainty includes a 7% systematic contribution calculated by moving the position of each cut 10% in each direction.

The $K_L{}^0 \to \pi^+\pi^-$ branching ratio was measured in a separate part of the experiment.[6] We found $\Gamma(K_L{}^0 \to \pi^+\pi^-)/\Gamma(K_L{}^0 \to \text{all}) = (2.01 \pm 0.09) \times 10^{-3}$ in agreement with other recent experiments.[7] Using this value we obtain $\Gamma(K_L{}^0 \to \mu^+\mu^-)/\Gamma(K_L{}^0 \to \text{all}) = (8.4^{+2.8}_{-1.8}) \times 10^{-9}$. This result is consistent with the unitarity limit and the two other recent determinations. It is inconsistent with the original Bevatron result.

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[b]Present address: Department of Physics, California Institute of Technology, Pasadena, Calif. 91125.

[c]Present address: Lawrence Berkeley Laboratory, Berkeley, Calif. 94720.

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Dilepton Production by Neutrinos in Neon[a]

C. Baltay, M. Hibbs, R. Hylton, M. Kalelkar, W. Orance, and E. Schmidt
Columbia University, New York, New York 10027

and

A.-M. Cnops, P. L. Connolly, S. A. Kahn, M. J. Murtagh, R. B. Palmer, N. P. Samios, and T. T. Tso
Brookhaven National Laboratory, Upton, New York 11973

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In an exposure of the Fermilab 15-ft bubble chamber filled with a heavy neon-hydrogen mixture to a broadband neutrino beam, we have observed 81 dilepton events of the type $\nu_\mu + \text{Ne}\to\mu^- + e^+ + \dots$. This corresponds to $(0.5\pm 0.15)\%$ of the total charged-current neutrino interactions. A total of fifteen neutral strange-particle decays ($K_s^0\to\pi^+\pi^-$, $\Lambda^0\to p\pi^-$) were found in these dilepton events. When corrected for detection efficiencies and unobservable strange particles, this is consistent with the production of approximately one strange particle per event.

The discovery of high-mass (3 GeV), narrow-width (keV) states, the J/ψ,[1] indicated the onset of a new phenomenon. The subsequent observation of bare charm[2] verified that this was indeed the uncovering of a new quantum number. The observed production of dilepton pairs ($\mu^-\mu^+$), (μ^-e^+) in high-energy neutrino interactions[3] could be a further manifestation of charm or something new. In this Letter, we report on 81 μ^-e^+ pairs produced by the interaction of high-energy neutrinos in neon, the rate and strange-particle content being consistent with charmed-particle production.

We present the results obtained in a run at the Fermi National Accelerator Laboratory consisting of 46 000 photographs in the 15-ft bubble chamber. The two-horn focused wide-band neutrino beam was used, with an average of 1×10^{13} 400-GeV protons per pulse indicent on a 12-in. long aluminum oxide target. The relative fluxes of the four kinds of neutrinos have been calculated to be of the order of $\nu_\mu:\bar{\nu}_\mu:\nu_e:\bar{\nu}_e\approx 100:3:1:0.2$. The ν_μ energy spectrum peaks near 25 GeV and extends to well over 100 GeV. The chamber was filled with a neon-hydrogen mix with the following properties: 64 at.% neon, 0.8-g/cm^2 density, 40-cm radiation length, and 125-cm interaction length. The chamber magnetic field was 30 kG. In this heavy mixture electrons are likely to radiate (the chamber is ~10 radiation lengths across), hadrons to interact visibly (the chamber is ~3 interaction lengths), and muons to escape without any visible interaction.

In a selective scan, all events with an e^+ or an e^- candidate were recorded, regardless of any other feature of the event. The $e^\pm$ was visually identified on the scan tables by the following cri-