Measurement of the Ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi l \nu)$ for K_L with 65 GeV/c Laboratory Momentum

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We have measured the ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi l \nu)$ to be $(3.13 \pm 0.14) \times 10^{-3}$ for K_L with a mean laboratory momentum of 65 GeV/c. This value corresponds to the *CP*-nonconservation parameter $|\eta_{+-}| = (2.28 \pm 0.06) \times 10^{-3}$, and is consistent with the world average $|\eta_{+-}| = (2.274 \pm 0.022) \times 10^{-3}$ which is derived from measurements with K_L laboratory momenta less than 10 GeV/c. In this experiment we find no evidence for an energy dependence of $|\eta_{+-}|$.

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The discovery[1] of the decay mode $K_L \to \pi^+\pi^-$ stimulated many explanations for its existence. Among these was the suggestion that the effect was due to a long-range external vector field.[2,3] The decay rate $\Gamma(K_L \to \pi^+\pi^-)$ was predicted to vary as the square of the K_L laboratory energy. This hypothesis was eliminated when the ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi l \nu)$ measured for K_L of 10 GeV/c was equal, within experimental errors, to the same ratio measured at 1 GeV.[4]

Recently, however, there have been claims of a small energy dependence of the ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi\mu\nu)$.[5] We have investigated this possiblity, and report here a measurement of the ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi l \nu)$ for a mean K_L momentum of 65 GeV/c.[6] Here $\Gamma(K_L \to \pi l \nu)$ refers to the sum of the decay rates to the modes $K_L \to \pi\mu\nu$ and $K_L \to \pi e \nu$. The experiment was carried out at the Fermi National Accelerator Laboratory with an apparatus designed to measure the *CP*-nonconservation parameter $|\eta_{00}/\eta_{+-}|$.[7]

The K_L were produced by 400-GeV/c protons incident on a Be target. Two neutral beams were produced side by side by appropriate collimation. At the decay region each beam was 10.7 cm high by 8.5 cm wide; the horizontal separation of the centers was 12.6 cm. A spectrometer, located ~470 m from the target, accepted K_L decays over a momentum range from 30 to 150 GeV/c. These decays originated in a vacuum tank which was 14 m long, whose center was located 60 m upstream from the center of the spectrometer. A carbon regenerator was placed in one beam; the free decays of K_L, which are the subject of this experiment, were observed in the other beam. After each machine pulse the role of the two beams was interchanged. A detailed description of the apparatus is reported elsewhere.[6,7]

Briefly, the detector (see Fig. 1) consisted of a large-aperture magnetic spectrometer which recorded pairs of charged particles emerging from the decay region. The decay region began with a 1.6-mm-thick veto counter just upstream of the 0.21-mm-thick Al entrance window of the vacuum vessel. The decay region was terminated by a 0.0025-radiation-length-thick window of Mylar and sailcloth followed by a 4.5-mm-thick scintillation hodoscope. The particle trajectories were recorded by four drift chambers. The trigger required that at least one charged particle pass the hodoscope, and two charged particles pass through the magnetic spectrometer. A lead-glass array and a muon filter, required for the $|\eta_{00}/\eta_{+-}|$ measurement, were not directly used in this experiment.

The two-body decay mode $K_L \to \pi^+\pi^-$ was separated from the three-body K_L decays on the basis of kinematics alone; no particle identification was used in this measurement.

For each event two tracks were reconstructed and the vertex was determined. The vertex resolution was 30 cm (standard deviation) in the beam direction and 0.3 cm (standard deviation) in the transverse direction. The transverse position was used to remove events from the regenerated beam. The remaining contamination was negligible. An event was accepted if its vertex was contained with the vacuum chamber.

For each event the invariant mass ($m_{\pi\pi}$) was calculated on the assumption that each charged particle was a pion. In addition, the transverse momentum (P_T) of the event with respect to the beam direction was calculated. In a distribution of events the $K_L \to \pi^+\pi^-$ events exhibit a peak at $P_T = 0$ and $m_{\pi\pi} = 498$ MeV/c^2, the K_L mass. The background under this peak due to $K_L \to \pi l \nu$ must be subtracted. Contributions to the $K_L \to \pi^+\pi^-$ signal from regeneration in the veto counter and vacuum-tank window

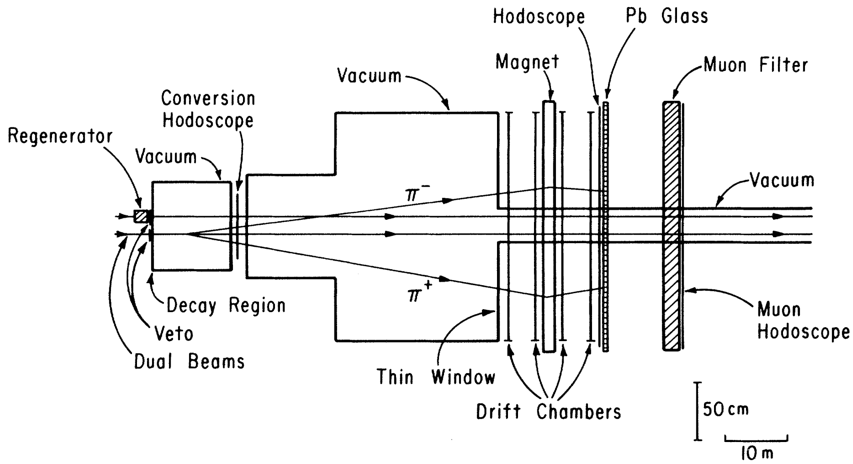

FIG. 1. Schematic diagram of the apparatus.

were negligible.

The $K_L \rightarrow \pi^+\pi^-$ events thus extracted were normalized to the $K_L \rightarrow \pi l \nu$ events, which were restricted to 380 GeV/$c^2 < m_{\pi\pi} <$ 630 MeV/c^2 and $P_T^2 < 5\times10^4$ (MeV/c)^2. This mass cut removed $K_L \rightarrow \pi^+\pi^-\pi^0$ events. Since the $K_L \rightarrow \pi l \nu$ events have fewer kinematic constraints (the neutrino is not observed), it is necessary to assure that these events originate from decays in the vacuum. For this reason cuts have been made 1 m distant from the windows of the vacuum vessel to eliminate events produced by interactions in the vacuum-chamber windows.

The success of this measurement depends on reliable Monte Carlo calculations for three purposes: (1) subtraction of $K_L \rightarrow \pi l \nu$ background from the $K_L \rightarrow \pi^+\pi^-$ signal; (2) demonstration that the $K_L \rightarrow \pi l \nu$ sample is free of background; and (3) calculation of the relative efficiency of the apparatus for $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi l \nu$.

A Monte Carlo program generated $K_L \rightarrow \pi l \nu$ events in the same form as the real data. These events were run through the same reconstruction programs as the real data. The program included the effect of multiple scattering, drift-chamber resolution, pion decay in flight, pion absorption in the material of the apparatus, electron bremsstrahlung in the apparatus, and radiative corrections to the $K_L \rightarrow \pi e \nu$ decay.[8] Many comparisons between the calculated and measured distributions confirmed the accuracy of the Monte Carlo program.

Figure 2 shows the distribution of events in the neighborhood of the $K_L \rightarrow \pi^+\pi^-$ peak as a function of $m_{\pi\pi}$ for $P_T^2 < 200$ (MeV/c)^2 and as a function of P_T^2 for $482.5 < m_{\pi\pi} < 512.5$ MeV/c^2. Also plotted are the corresponding $K_L \rightarrow \pi l \nu$ distributions calculated by Monte Carlo simulation. The Monte Carlo events are normalized to the total number of events contained in the two regions defined by $400 < m_{\pi\pi} < 470$ MeV/c^2 with $P_T^2 < 500$ (MeV/c)^2 and $525 < m_{\pi\pi} < 575$ MeV/c^2 with $P_T^2 < 500$ (MeV/c)^2. The total number of $K_L \rightarrow \pi^+\pi^-$ events in the region $482.5 < m_{\pi\pi} < 512.5$ MeV/c^2 and $P_T^2 < 200$ (MeV/c)^2 was found to be 1687 ± 63 after a background subtraction of 1612 ± 27.

A study of the background subtraction as a function of the range of $m_{\pi\pi}$ and P_T accepted for the $K_L \rightarrow \pi^+\pi^-$ events leads to an estimate of a 2% error in the number of $K_L \rightarrow \pi^+\pi^-$ events in addition to the statistical error of 3.7%.

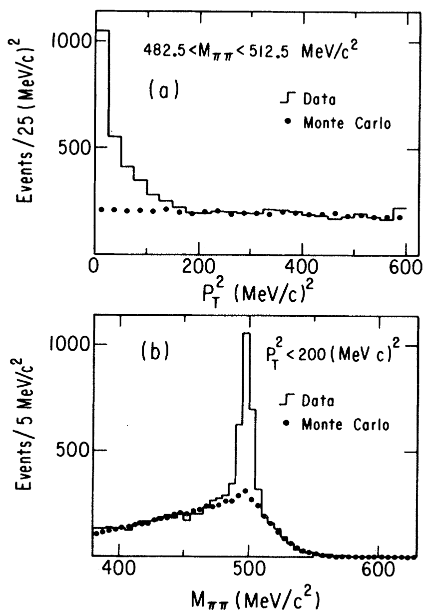

FIG. 2. (a) Plot of events vs P_T^2 for $482.5 < m_{\pi\pi} < 512.5$. (b) Plot of events vs $m_{\pi\pi}$ for $P_T^2 < 200$ (MeV/c)^2. The expected $K_L \rightarrow \pi l \nu$ background calculated by Monte Carlo methods is also plotted.

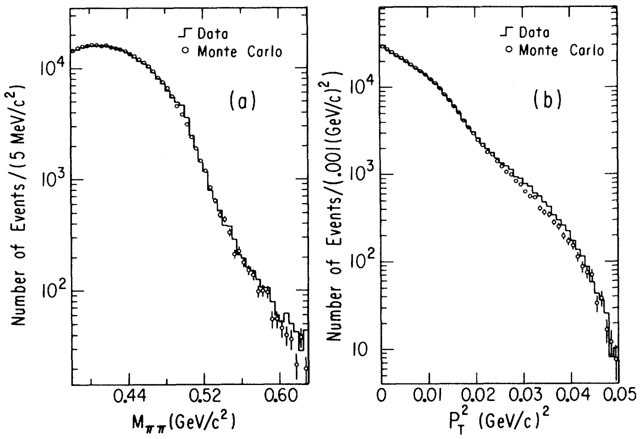

FIG. 3. (a) Plot of events vs $m_{\pi\pi}$ for $P_T^2 < 5.0\times 10^4$ $(\mathrm{MeV}/c)^2$. The Monte Carlo prediction is superimposed. (b) Plot of events vs P_T^2 for $380 < m_{\pi\pi} < 630\ \mathrm{MeV}/c^2$. The Monte Carlo prediction is superimposed.

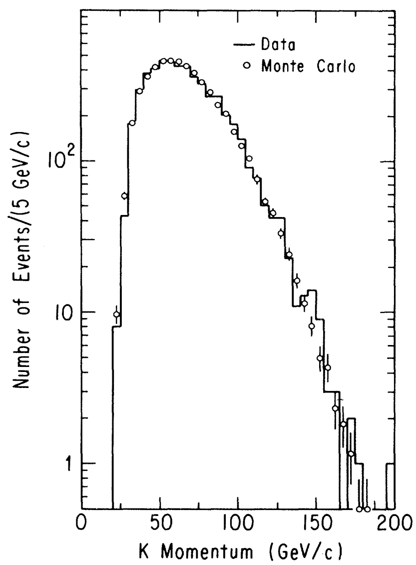

FIG. 4. Plot of $K_L \to \pi^+\pi^-$ vs the K_L momentum. The Monte Carlo prediction is superimposed.

Figure 3(a) shows the distribution of $m_{\pi\pi}$ for all the accepted events along with the corresponding Monte Carlo distribution. The small excess of events evident at $m_{\pi\pi} \sim 500\ \mathrm{MeV}/c^2$ is due to the $K_L \to \pi^+\pi^-$ events. Figure 3(b) shows the distribution in P_T^2 of the events, along with the corresponding Monte Carlo distribution.

The number of $K_L \to \pi l \nu$ events is found to be $(3.006 \pm 0.006)\times 10^5$. The ratio of acceptance for the $K_L \to \pi^+\pi^-$ events to that for $K_L \to \pi l \nu$ events was found by Monte Carlo calculation to be 1.792 ± 0.012. The sensitivity of this ratio to variations in the geometrical cuts applied to the data leads to an estimated systematic error of 1%. Figure 3(b) shows a slight deviation of the P_T distribution for the $K_L \to \pi l \nu$ events for the Monte Carlo prediction. This leads to an estimated 0.9% systematic error.

Figure 4 shows the momentum spectrum of the $K_L \to \pi^+\pi^-$ events along with the corresponding Monte Carlo distribution. The agreement between data and Monte Carlo calculation confirms that the proper K_L momentum spectrum has been used in the calculation.[9] The systematic error in the result due to uncertainty in the momentum spectrum is 0.1%.

A list of the systematic errors mentioned above along with those associated with pion attenuation, bremsstrahlung, and radiative corrections is given in Table I.

We find the ratio

$$\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi l \nu) = (3.14 \pm 0.14)\times 10^{-3}.$$

This leads to a value of

$$|\eta_{+-}| = [\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_s \to \pi^+\pi^-)]^{1/2} = (2.28 \pm 0.06)\times 10^{-3}$$

by use of appropriate branching ratios and lifetimes given by the G. Wohl *et al.* (Particle Data Group).[10]

Our value for $|\eta_{+-}|$, measured at a mean K_L momentum $\langle P_k\rangle$ of 65 GeV/c, does not agree with the value $(2.09 \pm 0.02)\times 10^{-3}$ at $\langle P_k\rangle$ of 70 GeV/c claimed in Ref. 5. Our value is in good agreement with the world average reported by the Particle Data Group $|\eta_{+-}| = (2.274 \pm 0.022)\times 10^{-3}$. Since this average is for values which have been determined for $\langle P_k\rangle \approx 5$ GeV/c, we find no evidence in this experi-

TABLE I. Systematic errors in the ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi l \nu)$.

Description	Error (%)
Radiative corrections to K_{e3} Dalitz plot	0.4
Energy loss of electrons	0.5
Pion absorption	0.2
Background subtraction	2.0
Semileptonic cut	0.9
Geometric cuts	1.0
Momentum spectrum	0.1
Total systematic error	2.5

ment to support the existence of an energy dependence in η_{+-}.

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[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).

[2]J. S. Bell and J. K. Perring, Phys. Rev. Lett. **13**, 348 (1964).

[3]J. Bernstein, N. Cabibbo, and T. D. Lee, Phys. Lett. **12**, 146 (1964).

[4]X. DeBouard *et al.,* Phys. Lett. **15**, 58 (1967).

[5]S. H. Aronson, G. J. Bock, H.-Y. Cheng, and E. Fischbach, Phys. Rev. Lett. **48**, 1306 (1982), and Phys. Rev. D **28**, 476 (1983).

[6]This experiment is reported in detail in David P. Coupal, Ph.D. thesis, University of Chicago, 1985 (unpublished).

[7]R. H. Bernstein *et al.,* Phys. Rev. Lett. **54**, 1631 (1985); Robert H. Bernstein, Ph.D. thesis, University of Chicago, 1985 (unpublished).

[8]E. S. Ginsberg, Phys. Rev. **171**, 1675 (1968), and **174**, 2169 (1968), and **187**, 2280 (1969).

[9]Extraction of the K_L momentum spectrum in this experiment is described in D. Carlsmith, Ph.D. thesis, University of Chicago, 1985 (unpublished).

[10]C. G. Wohl *et al.,* (Particle Data Group), Rev. Mod. Phys. **56**, S1 (1984).