EXPERIMENTAL INVESTIGATION OF CP VIOLATION IN K_{e3}^0 DECAYS*

L. J. Verhey, B. M. K. Nefkens, A. Abashian, R. J. Abrams, D. W. Carpenter, R. E. Mischke, J. H. Smith, R. C. Thatcher, and A. Wattenberg
Department of Physics, University of Illinois, Urbana, Illinois
(Received 20 July 1966)

A spark-chamber experiment has been performed which measures the ratio $R=(K_L^0\to\pi^++e^-+\bar{\nu})/(K_L^0\to\pi^-+e^++\nu)$. On the basis of 1539 identified K_{e3}^0 decays, no variation of R is found over the Dalitz plot. The corrected integrated value is $R=0.93\pm0.05$.

Recent experiments[1-3] have shown that the long-lived neutral K meson (K_L^0) is not a pure eigenstate of CP, and can decay into either two or three pions. It is desirable to check for direct manifestations of CP violations in other decay modes. In this Letter, we report upon an experimental investigation of the K_{e3}^0 decay $[K_L^0\to\pi^\pm+e^\mp+\bar{\nu}(\nu)]$. We have measured the ratio $R=(K_L^0\to\pi^++e^-+\bar{\nu})/(K_L^0\to\pi^-+e^++\nu)$. A value of $R\neq1$ for the total rates or for any portion of the Dalitz plot would be a direct indication of CP nonconservation in K_L^0 decays. In the representation of Sachs,[4] the general expression for the asymmetry is $R=|(g^*-rf^*)/(f-rg)|^2$ where r is defined by $|K_L^0\rangle=(1+|r|^2)^{-1/2}\times(|K^0\rangle-r|\bar{K}^0\rangle)$ and f and g are the $\Delta S=+\Delta Q$ and $\Delta S=-\Delta Q$ leptonic decay amplitudes, respectively. Detailed analysis[5] of experiments on CP violation shows that the rough experimental upper limit on the deviation of r from unity is about 0.02. It is not difficult to obtain, within this constraint, a value of R which differs several percent from unity.

The experiment was performed in the 30° neutral beam at the Argonne zero-gradient synchroton (ZGS). The detector, which was 60 ft from the ZGS target, consisted of a thin-foil momentum-analyzing spark chamber inside a magnetic field of 10 kG, a vacuum pipe in which decays occurred, and associated scintillation counters. Following the magnet there was a spark chamber consisting of 115 $\frac{1}{8}$-in.-thick aluminum plates. A schematic drawing of the apparatus is shown in Fig. 1. The two sets of spark chambers were triggered on the coincidence $\bar{A}_\alpha\bar{A}_\beta M_1M_2\Omega_1\Omega_2$. This triggering mode favored the configuration of two charged particles which originated from the vacuum pipe and entered the range chamber. It required that no charged particles enter the system.

Since the experiment demands the symmetric detection of particles of each charge, we periodically reversed the direction of the magnetic field so that half of our data was obtained with each polarity. This should cancel out the effect of any counter asymmetries. The efficiency of each counter was greater than 98.5%. The performance of the counters was monitored during the runs as a further precaution against systematic effects.

All V's from the vacuum-pipe fiducial volume were measured by CHLOE, a flying-spot digitized measuring device developed by the Applied Mathematics Division of Argonne National Laboratory.[6] The CHLOE digitizations were analyzed[7,8] to determine the vector momenta of the charged decay products. The decay kinematics in the center-of-mass system were reconstructed on the assumption that the event was a decay of the K_L^0 meson.

Of the two ambiguous solutions for the K_L^0-meson energy, the lower was always assumed. An incorrect choice will not introduce an asymmetry.

Possible showers in the 115-plate aluminum spark chamber were selected by scanners; good K_{e3}^0 events were then identified by physicists on the basis of the quality of the shower and consistency with K_{e3}^0 decay kinematics.

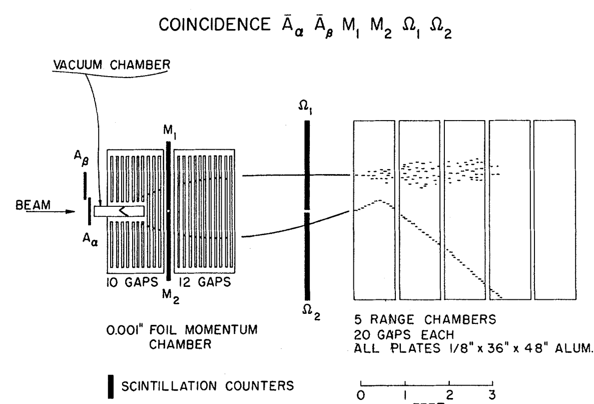

FIG. 1. Experimental arrangement. Counters A_α, A_β, M_1, and M_2 are $\frac{1}{8}$ in. thick; Ω_1 and Ω_2 are $\frac{3}{8}$ in. thick. The dashed lines represent the observed portions of the tracks.

In about 14 500 $K_L{}^0$ decays, we identified 746 electrons and 793 positrons which satisfied all criteria for $K_{e3}{}^0$ decays. We obtain an integrated ratio

$$R_{\text{observed}} \equiv \left(\frac{K_L{}^0 \to \pi^+ + e^- + \bar{\nu}}{K_L{}^0 \to \pi^- + e^+ + \nu}\right)_{\text{observed}}$$

$$= \frac{746}{793} = 0.94 \pm 0.05. \qquad (1)$$

The following possible corrections must be considered in treating the observed data.

(1) Differences in triggering efficiency due to pion absorption. —The only significant absorbing material before the final scintillation counters (Ω) was a $\frac{5}{8}$-in. aluminum wall. Zero-prong interactions arising from pi-meson absorption in this wall produced differences in the triggering efficiencies for electron and positron events. To determine the number of zero-prong events from π^+ and π^- interactions in aluminum, we placed a 3-in. copper regenerator in front of the vacuum pipe and observed the decays of $K_S{}^0$ into $\pi^+\pi^-$. From the observation of the absorption of these pions in the aluminum range chambers, we concluded that (1.6 ± 0.2 % of the π^+ mesons and (2.4 ± 0.2)% of the π^- mesons would produce zero-prong events in the $\frac{5}{8}$-in. wall. The corrected ratio is thus

$$R_{\text{corrected}} = \left(\frac{1.016}{1.024} \pm 0.003\right) R_{\text{observed}}$$

$$= 0.93 \pm 0.05. \qquad (2)$$

(2) Differences in showering properties of electrons and positrons. —In order to determine the efficiency of our shower identification, electron-positron pairs were produced by gamma rays in the beam. No differences were observed in the showering behavior of approximately 200 electrons and positrons. Experiments[9,10] show that differences between electron and positron bremsstrahlung are concentrated at the high-energy end of the photon spectra. Since we have over 4 radiation lengths of material in our range chambers, our ability to see showers produced by these high-energy (300-600 MeV) bremsstrahlung photons is very high and nearly independent of energy. At photon energies which are a small fraction of the energy of the showering particle, the electron and positron spectra appear to be the same.[9]

(3) Positron annihilation in flight. —Measurements of positron annihilation in flight[11,12] show that for 200-MeV positrons, about 0.2 % will annihilate in the first radiation length. For our average positron energy of 600 MeV, this number drops to 0.1 %.

(4) False identification of a pion as an electron. —While studying the pion interactions in aluminum, we looked for pions which simulated a shower. This could occur by a charge-exchange reaction producing a π^0 which decays into two photons, at least one of which goes forward the converts. We found that less than 1 % of all entering pions exhibited this behavior and could have been falsely identified as electrons.

Thus we estimate that the effect of 2, 3, and 4 above on our relative detection efficiencies for e^+ and e^- was less than 1 %.

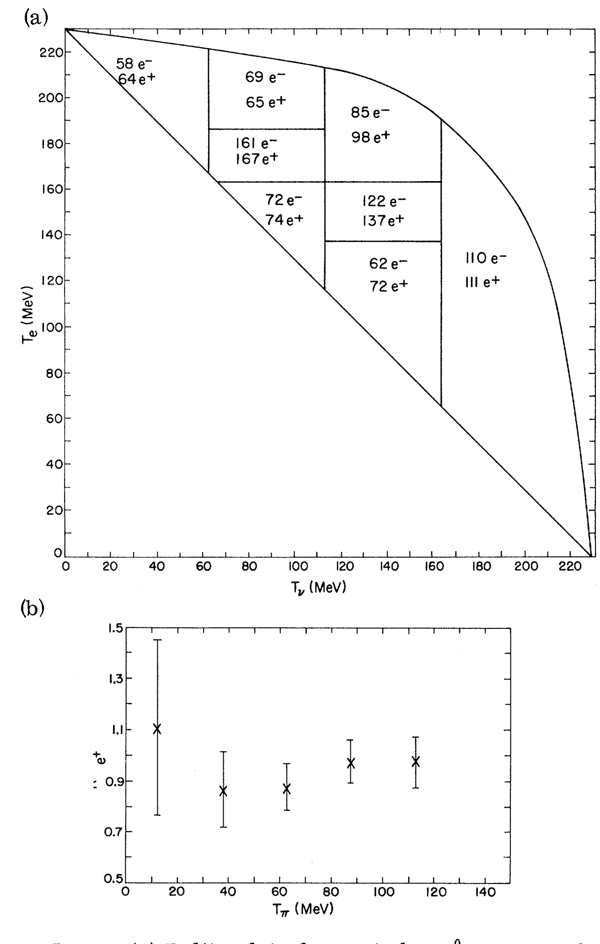

FIG. 2. (a) Dalitz plot of accepted $K_{e3}{}^0$ events. The upper number in each bin refers to the number of $\pi^+e^-\bar{\nu}$ events, the lower to the number of $\pi^-e^+\nu$ events. The reaction is $K_L{}^0 \to \pi^\pm + e^\mp + \bar{\nu}(\nu)$. (b) The ratio $R = (K_L{}^0 \to \pi^+ + e^- + \bar{\nu})/(K_L{}^0 \to \pi^- + e^+ + \nu)$ as a function of the center-of-mass pion kinetic energy in MeV. The indicated errors are statistical.

The corrected ratio (2) is to be compared with two results previously reported: $R=0.99 \pm 0.16$ based on 153 events in a bubble chamber[13] and $R=0.96\pm0.12$ based on 452 events in a one-meter cloud chamber.[14]

A CP violation might be expected to produce different Dalitz-plot distributions for e^+ and e^- final states. Figure 2(a) shows the Dalitz-plot distributions, while in Fig. 2(b), R is plotted as a function of the pion kinetic energy in the center-of-mass system. The data, compared with the assumption of $R=1$ at all pion energies, give χ^2 of 4.0 for 5 degrees of freedom. We conclude that there is no evidence for a variation of R over the Dalitz plot.

We would like to thank the staff of the ZGS at Argonne National Laboratory for their very helpful assistance. We would especially like to thank D. Hodges and R. Clark of the Applied Mathematics Division at Argonne for their help in the automatic measuring of our film. We would also like to express our appreciation to J. Frank and P. Mantsch for their help with scanning and identification of events.

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*This work was supported by the U. S. Atomic Energy Commission.

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BOUNDS ON THE RATIO f_-/f_+ IN K_{l3} DECAYS*

T. Das†
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania
(Received 17 June 1966)

Bounds on f_-/f_+ in K_{l3} decays are obtained under some general assumptions on the behavior of the divergence of the strangeness-changing vector current and the amplitude for s-wave $K\pi$ scattering, and its experimental implications are discussed.

In recent years there have been many experimental and theoretical investigations on the value of $\xi = f_-/f_+$ in K_{l3} decays. In the Cabibbo version[1] of the current-current theory of the leptonic decays, ξ is expected to be zero, since the strangeness-changing vector current $V_\mu^{(1)}$ is assumed to be conserved in the SU(3)-symmetric limit. In actual practice the current $V_\mu^{(1)}$ is not conserved; however, we may still expect ξ to be small if the symmetry-breaking effects are not too large. The other approaches which have been adopted to evaluate ξ consist in using dispersion theory[2] and, quite recently, the commutators of currents.[3] Most of these methods, however, use some specific models in the sense of assuming the dominance of some poles or some suitable single-particle intermediate states. In the following we shall show how some interesting bounds on ξ for K_{l3} decays can be obtained under some general assumptions. We emphasize that no explicit use of any symmetry considerations is made in this paper.

The divergence of the hadron current in K_{l3} decays has the most general form given by

$$\langle\pi|\partial_\mu V_\mu^{(1)}|K\rangle = (m_K^2 - m_\pi^2) f_+(q^2) + q^2 f_-(q^2) = F(q^2), \qquad (1)$$

where q is the four-momentum transfer, and m_K and m_π are the meson masses.

We now make our first assumption: