Measurement of the K_L Charge Asymmetry

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We present a measurement of the charge asymmetry δ_L in the mode $K_L \to \pi^{\pm}e^{\mp}\nu$ based on 298×10^6 analyzed decays. We measure a value of $\delta_L = [3322 \pm 58(\text{stat}) \pm 47(\text{syst})] \times 10^{-6}$, in good agreement with previous measurements and 2.4 times more precise than the current best published result. The result is used to place more stringent limits on *CPT* and $\Delta S = \Delta Q$ violation in the neutral kaon system.

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The charge asymmetry in K_L semileptonic decays is deeply related to *CP* violation through neutral kaon mixing. The K_L wave function is proportional to $(1 + \epsilon_L)K^0 - (1 - \epsilon_L)\overline{K}^0$, where ϵ_L parametrizes *CP* violation in mixing. This parameter can be determined in the decay modes $K_L \to \pi^{\pm}e^{\mp}\nu$ (Ke3) and $K_L \to \pi^{\pm}\mu^{\mp}\nu$ (Kμ3). The charge asymmetry (δ_L) is defined as

$$\delta_L = \frac{B(e^+\pi^-) - B(e^-\pi^+)}{B(e^+\pi^-) + B(e^-\pi^+)}.$$

Assuming $\Delta S = \Delta Q$ and no *CPT* violation in the decay $K^0(\overline{K}^0) \to e^+\pi^-\nu(e^-\pi^+\bar{\nu})$, δ_L is simply $2\,\mathrm{Re}\epsilon_L$. To first order in the parameters that violate *CP* and *CPT*,

$$\delta_L = 2\,\mathrm{Re}\epsilon_L - 2\,\mathrm{Re}Y - \mathrm{Re}(x - \bar{x}).$$

The terms Y and $\mathrm{Re}(x - \bar{x})$ parametrize *CPT* violation in the $\Delta S = \Delta Q$ and $\Delta S = -\Delta Q$ transitions, respectively [1,2]:

$$\frac{\langle e^+\pi^-\nu \,|\, K^0\rangle}{\langle e^-\pi^+\bar{\nu} \,|\, \overline{K}^0\rangle^*} = \frac{1 - Y}{1 + Y},$$

$$x = \frac{\langle e^+\pi^-\nu \,|\, \overline{K}^0\rangle}{\langle e^+\pi^-\nu \,|\, K^0\rangle} \qquad \bar{x} = \frac{\langle e^-\pi^+\bar{\nu} \,|\, K^0\rangle^*}{\langle e^-\pi^+\bar{\nu} \,|\, \overline{K}^0\rangle^*}.$$

In the standard model, the $\Delta S = \Delta Q$ violation is *CPT* conserving and occurs in second order weak decays. Estimates for $|x|$ are in the range 10^{-7} [3]. δ_L is modified to order $|x|^2$ and will not be considered in this Letter.

The measurement of δ_L can be compared to expectations derived from the $K_L \to 2\pi$ (Kπ2) amplitudes (η_{+-}, η_{00}) [2,4]:

$$\mathrm{Re}\left(Y + \frac{x - \bar{x}}{2} + a\right) = \mathrm{Re}\left(\frac{2}{3}\,\eta_{+-} + \frac{1}{3}\,\eta_{00}\right) - \frac{\delta_L}{2}. \tag{1}$$

This comparison is sensitive to *CPT* violation in Ke3 and Kπ2 decays, where the latter is parameterized by $\mathrm{Re}a$.

The current world average on δ_L comes mainly from a measurement by the CERN-Heidelberg Collaboration in 1974. Using 34×10^6 Ke3 decays, they find $\delta_L = [3409 \pm 171(\mathrm{stat}) \pm 50(\mathrm{syst})] \times 10^{-6}$ [5]. We describe in this Letter a measurement of δ_L in the Ke3 mode based on approximately 298×10^6 Ke3 decays.

The beam and KTeV detector [6] at Fermilab are designed to measure $\mathrm{Re}(\epsilon'/\epsilon)$ and to study rare kaon decays. These two programs use different detector configurations. For this analysis, the detector is configured for the measurement of $\mathrm{Re}(\epsilon'/\epsilon)$. As shown in Fig. 1, two approximately parallel neutral K_L beams enter a long vacuum tank, which defines the fiducial volume for accepted decays. One of the beams strikes an active absorber (regenerator), which tags the coherent regeneration of K_S. The regenerator moves to the other beam in between Tevatron spill cycles. Following the vacuum tank, there are four planar drift chambers and an analysis magnet that imparts a 411 MeV/c horizontal transverse kick to the charged particles. A high precision 3100-element pure cesium iodide calorimeter (CsI) is used primarily to measure the energy of $e^{\pm}$ and photons. Photon veto detectors surrounding the vacuum tank, drift chambers, and CsI serve to reject events with particles escaping the calorimeter.

Only Ke3 decays in the beam opposite the regenerator are used in this analysis. They are triggered by the presence of hits in the drift chambers and scintillators placed immediately upstream of the CsI and by the lack of activity in the regenerator or photon vetoes. To keep the event rate manageable, the trigger rejects beam muons and Kμ3 events by requiring no activity in the scintillation counters (muon veto) placed behind 4 m of Fe absorbers downstream of the CsI.

Selecting Ke3 events is relatively straightforward, as they are the most copious K_L decay mode [$B(\mathrm{Ke3}) \approx 0.39$]. We identify two-track vertices in the region between 90 and 160 m from the target with kinematics inconsistent with $K_L \to \pi^+\pi^-\pi^0$ (Kπ3) and $\Lambda(\bar{\Lambda}) \to p\pi^-(\bar{p}\pi^+)$. The tracks are required to extrapolate to CsI energy deposits while maintaining sufficient clearance from the inner and outer edges. A track is identified as an electron if its momentum exceeds 5 GeV/c and its CsI energy deposit divided by its momentum (E/P) exceeds 0.925. Pions are identified as having momentum exceeding 8 GeV/c and E/P less than 0.925. The tighter pion momentum requirement rejects Kμ3 background, since 8 GeV/c is the threshold for minimum-ionizing particles to penetrate through to the muon veto counters.

The K^0 (or $\overline{K}^0$) produced from the target evolve as a coherent superposition of K_S and K_L. To reduce the effect of $K_S - K_L$ interference, the event proper time (τ) has to exceed 10.5 K_S lifetimes (τ_S). The kaon momentum (P_K) reconstruction has ambiguities inherent to any three-body decay with one unobserved particle. The longitudinal component of the neutrino momentum in the kaon rest frame can be either parallel or antiparallel to the kaon flight direction in the lab frame. This introduces two possible solutions for P_K. We use the low P_K solution to calculate τ. Based on Monte Carlo (MC) simulations, this choice is at least 70% correct for $\tau < 22.5\tau_S$. A small correction, derived from MC, is made for errors in the P_K solution and the residual $K_S - K_L$ interference.

The measurement of δ_L requires a careful control of systematics. The most important of these is to ensure an equal acceptance and efficiency for oppositely charged particles. We combine data sets of opposite analysis magnet polarities, which are reversed about once per day, to ensure that the detector is exposed to oppositely charged particles in the same manner. We also use data collected during rare decay studies, which includes a transition radiation detector [7,8] used to study electron and pion identification.

There are eight possible configurations for Ke3 decays: $e^+\pi^-$ or $e^-\pi^+$, east (E) or west (W) K_L beams, and positive (+) or negative (−) magnet polarities. The number of Ke3 events in each configuration (N_i) depends on the branching ratio (B), the acceptance and efficiency (A), and

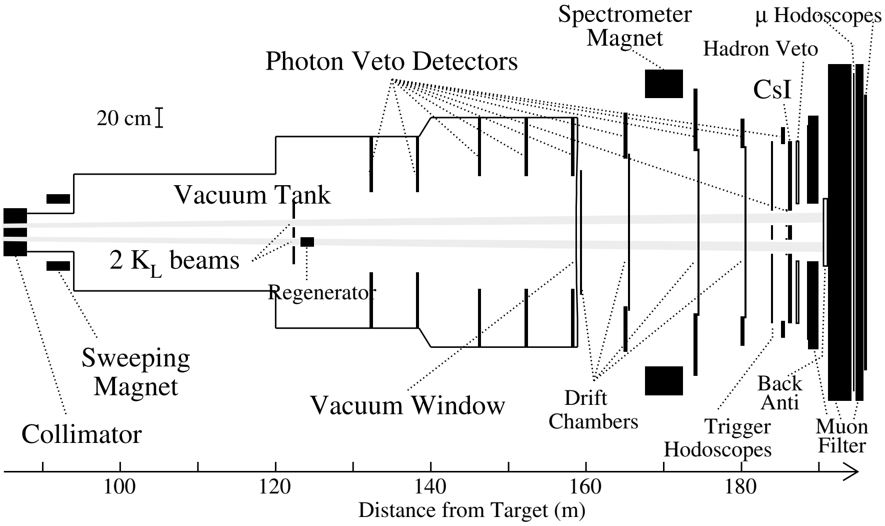

FIG. 1. The KTeV detector configured for measuring $\mathrm{Re}(\epsilon'/\epsilon)$.

the flux $N(K_L)$. We define R as

$$\begin{aligned} R^4 = {} & \frac{B(e^+\pi^-)A(e^+\pi^-,E,+)N(K_L,E,+)}{B(e^-\pi^+)A(e^-\pi^+,E,-)N(K_L,E,-)} \\ & \times \frac{B(e^+\pi^-)A(e^+\pi^-,E,-)N(K_L,E,-)}{B(e^-\pi^+)A(e^-\pi^+,E,+)N(K_L,E,+)} \\ & \times \frac{B(e^+\pi^-)A(e^+\pi^-,W,+)N(K_L,W,+)}{B(e^-\pi^+)A(e^-\pi^+,W,-)N(K_L,W,-)} \\ & \times \frac{B(e^+\pi^-)A(e^+\pi^-,W,-)N(K_L,W,-)}{B(e^-\pi^+)A(e^-\pi^+,W,+)N(K_L,W,+)}, \end{aligned} \tag{2}$$

where the four numerators and denominators represent N_i, $i = 1, 8$. Since the fluxes cancel and $A(e^\pm\pi^\mp) = A(e^\mp\pi^\pm)$ under magnetic field reversal, Eq. (2) reduces to

$$\text{raw } \delta_L = \frac{R-1}{R+1} \qquad \sigma(\text{raw } \delta_L) = \frac{1}{8}\sqrt{\Sigma_{i=1}^{8}\frac{1}{N_i}}. \tag{3}$$

Equation (3) defines the "raw" δ_L and does not take into account several effects discussed below. Our data yields raw $\delta_L = (3417 \pm 58) \times 10^{-6}$ (ppm). Figure 2 shows its dependence on the decay vertex distance from the target.

In principle, the same flux and acceptance/efficiency cancellation occurs in the pairing of the first and second (third and fourth) factors of Eq. (2), such that δ_L can be measured within the east and west beams. Equation (3) is the geometric mean of the two δ_L measurements.

Figure 3 shows the raw asymmetry in various data subsets. In particular, we see the importance of combining data from opposite polarity runs. The difference between measurements made with only one magnet setting, $\delta_L(+) - \delta_L(-)$, is significant and on the order of δ_L itself. This difference is due to very small offsets of the inner apertures and is well reproduced by our MC. The MC is not used to correct this large effect since Eq. (2) naturally accounts for such geometrical asymmetries. On the other hand, the values for δ_L agree between decays in the east and west beams. Other data divisions yield good agreement except for the sample with $8 < P_\pi < 15$ GeV/c (discussed below).

We account for the different behavior of particles and antiparticles in matter. For each cut that introduces a bias, we measure f^+ (f^-), the inefficiency in the $e^+\pi^-$ ($e^-\pi^+$) configuration. The correction to raw δ_L for the cut, summarized in Table I, is simply $(f^+ - f^-)/2$.

Many biases due to $\pi^\pm$ interaction differences are considered, and the data are used to measure most of the corrections. These include the $\pi^\pm$ energy deposition in the CsI, the loss of pions due to interactions in the trigger scintillators, and pion punchthrough past the Fe absorbers depositing energy in the muon veto. Events with E/P for pions exceeding 0.925 are removed since the analysis requires exactly one identified electron. This effect, studied using pions in Kπ3 events, removes ≈0.6% of the pions, with the probability being slightly larger for π^+ than π^-. The asymmetry between π^+ and π^- has a strong momentum dependence and explains the trend seen for the $8 < P_\pi < 15$ GeV/c data sample (see Fig. 3). The correction to δ_L is -156 ± 10 ppm.

A correction is estimated for possible biases due to the trigger muon veto requirement, which removes approximately 3% of pions due to decay in flight and punchthrough. Good events can also be lost if accompanied by accidental muons. Only pion punchthrough would cause a bias due to the neutron excess in the Fe absorbers. The estimate uses a Ke3 sample collected during rare decay studies, where the transition radiation detector gives additional electron purity. The sample is triggered by *requiring* muon counter hits, as these events are the ones that would be removed by the analysis trigger. This sample has a

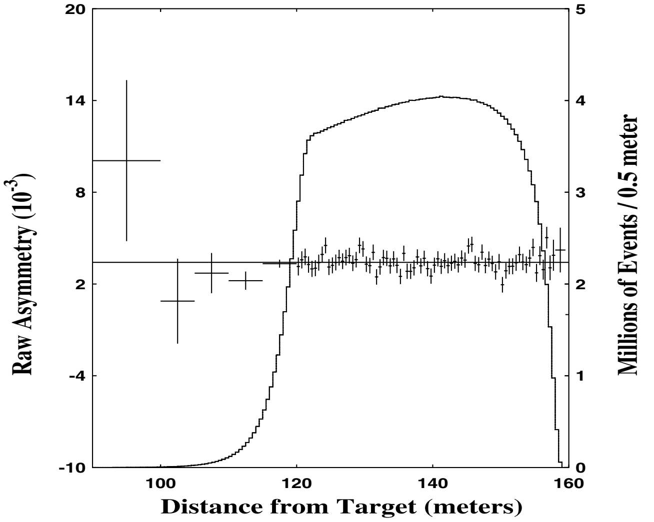

FIG. 2. Raw δ_L and number of events versus vertex distance from the target. A fit to a constant yields 3417 ± 58 ppm with a χ^2 of 81.53 for 81 degrees of freedom.

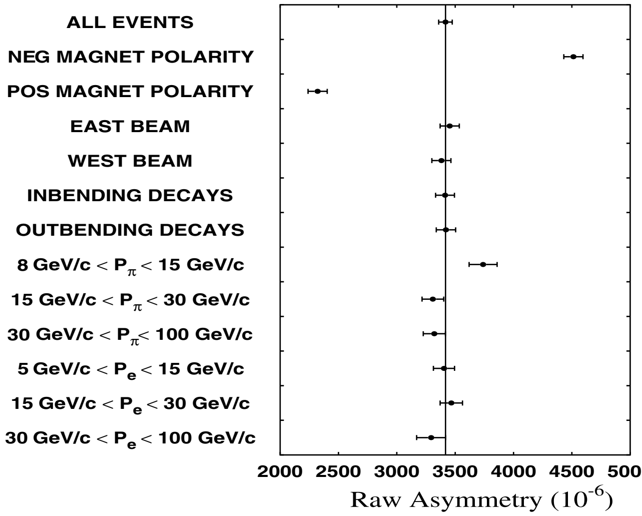

FIG. 3. Raw δ_L for all events and various data subsets. The line indicates the raw value of 3417 ppm.

TABLE I. Corrections in ppm for this analysis.

$\pi^{\pm}$ difference in CsI	-156 ± 10
$\pi^{\pm}$ interaction in trigger scintillator	$+54 \pm 10$
π decay and punchthrough	$+34 \pm 40$
e^+e^- difference in CsI	-19 ± 18
$K_S - K_L$ interference	-12 ± 1
e^+ annihilation in spectrometer	$+11 \pm 1$
δ-ray production	-8.5 ± 4.3
π absorption in spectrometer	$+5.0 \pm 3.2$
Inexact analysis magnet polarity reversal	-3.1 ± 1.6
Final collimator and regenerator scatters	-1.2 ± 2.3
Kπ3, Kμ3, $\Lambda_{p\pi}$, and Λ_β backgrounds	$+0.5 \pm 0.7$
Total correction	-95.3 ± 46.5

charge asymmetry of $(4.4 \pm 1.3) \times 10^{-3}$, which is consistent with the raw δ_L found in our main Ke3 sample. A correction of 34 ± 40 ppm accounts for any possible differences between these two Ke3 samples.

Pion interactions in the trigger scintillator can confuse the reconstruction so that the track fails to match to a CsI cluster. This effect, studied using Ke3 events with a relaxed track-cluster matching requirement, removes ≈0.42% of all pions and is slightly more probable for the π^- than π^+, leading to a correction of 54 ± 10 ppm.

Considering $e^{\pm}$ interaction differences, one has primarily e^+ annihilation and δ-ray production. An e^+ annihilation occurring near the upstream surface of the trigger scintillator would fail the trigger requirement due to the reduced energy deposition. δ rays more than 10 MeV and emitted from the vacuum window or tracking system can cause losses since the momentum transfer changes the event reconstruction. These losses cause a bias due to the small difference between the Bhabha (e^+e^-) and Moller (e^-e^-) scattering cross section. The annihilation and δ-ray corrections, derived by a GEANT simulation of the detector material, are of order ±10 ppm. They are small due to the high momentum of the tracks and the minimal material (2% X_0) upstream of the CsI.

Finally, a Ke3 sample is used to study potential biases of the E/P cut on electrons. This sample is selected by a relaxed E/P cut and by the tagging of a minimum-ionizing π in the CsI. The E/P cut removes approximately 0.233% of e^+ and e^-; the measured difference is -19 ± 18 ppm, consistent with no bias. This result is confirmed with a similar Ke3 sample collected during rare decay studies.

We apply a small correction to account for pions absorbed in the vacuum window, drift chambers, and helium bags. This is estimated assuming isospin conservation in strong interactions, and so the π^+ and π^- absorption differences depend on the excess protons, which are predominantly in the form of hydrogen. We account for a small bias due to π^- charge exchange near the upstream surface of the trigger scintillator (analogous to the case of e^+ trigger loss). For this, we use the measurements of [9,10] and extrapolate them to our π^- momentum range.

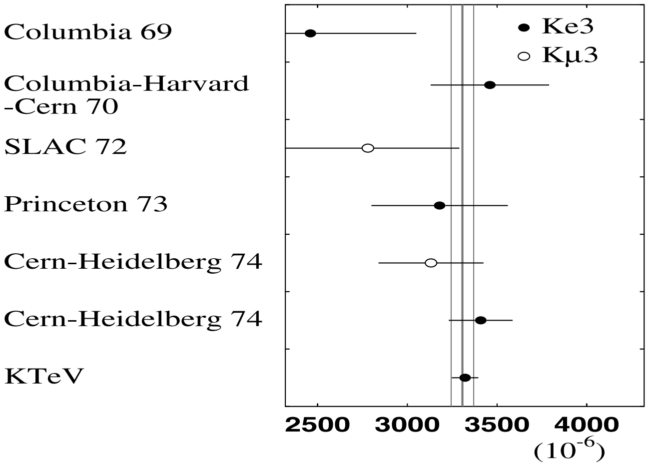

FIG. 4. Compilation of δ_L measurements including this result. Lines indicate the average and its uncertainty.

Other small corrections, derived from MC, account for the slight asymmetry in the magnetic field strength for the two polarities, the residual $K_S - K_L$ interference, and K_L scatters from the collimator and regenerator. A small correction is made for the Kπ3, Kμ3, $\Lambda_{p\pi}$, and Λ_β backgrounds. Table I shows the summary of all systematic corrections. The uncertainties are uncorrelated since they are mainly statistical errors of the Ke3 and Kπ3 control samples. Combining the corrections with raw δ_L, we find

$$\delta_L = 3322 \pm 58\ (\text{stat}) \pm 47\ (\text{syst})\ \text{ppm}$$
$$= 3322 \pm 74\ (\text{combined})\ \text{ppm}.$$

This result is in excellent agreement with previous measurements and 2.4 times more precise than the current best result (see Fig. 4). A combination of all results including ours yields

$$\delta_L = 3307 \pm 63\ \text{ppm} \qquad \chi^2 = 4.2/6\ \text{d.o.f.}$$

Substituting η_{+-} and η_{00} values from [11]and the combined δ_L into Eq. (1), we find

$$\text{Re}\left(Y + \frac{x - \bar{x}}{2} + a\right) = (1650 \pm 16) - (1653 \pm 32)$$
$$= -3 \pm 35\ \text{ppm}.$$

The result is consistent with no *CPT* violation and is limited by the charge asymmetry uncertainty. It limits $|\text{Re}[Y + (x - \bar{x})/2 + a]| < 61$ ppm at the 90% C.L. Barring fortuitous cancellations, this is thus far the most stringent limit on Y, x, and a.

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