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MEASUREMENT OF THE CHARGE ASYMMETRY IN THE DECAY $K_L^o \to \pi^{\pm}\mu^{\mp}\nu$ *

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The charge asymmetry in the decay $K_L^o \to \pi^{\pm}\mu^{\mp}\nu$ has been measured to be $(2.78 \pm 0.51) \times 10^{-3}$, leading to a value of Re ϵ in good agreement with the results from the $K_L^o \to 2\pi$ decay modes.

We present herewith a measurement of the CP violating charge asymmetry in the decay $K_L^o \to \pi\mu\nu$. This quantity can be directly related to the fundamental parameters describing the K^o-$\bar{K}^o$ system. Following standard phenomenology[1], if one defines

$$|K_L^o> = \left\{(1+\epsilon)|K^o> - (1-\epsilon)|\bar{K}^o>\right\}/\sqrt{2(1+|\epsilon|^2)} \quad ,$$

and the parameter x, which is the ratio of $\Delta S = -\Delta Q$ to $\Delta S = \Delta Q$ amplitudes, as

$$x = <\pi^-\mu^+\nu|H|\bar{K}^o>/<\pi^-\mu^+\nu|H|K^o> \quad ,$$

then the charge asymmetry δ, defined as $\delta = (\Gamma_+ - \Gamma_-)/(\Gamma_+ + \Gamma_-)$ with $\Gamma_{\pm} = \text{Rate}\ (K_L^o \to \pi^{\mp}\mu^{\pm}\nu)$, is given by

$$\delta = 2\ \text{Re}\ \epsilon \frac{1 - |x|^2}{|1 - x|^2} \quad .$$

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The parameter x, and hence δ, can in general be a function of the Dalitz plot position, and could be different for the $K^o_{\mu 3}$ and K^o_{e3} decay modes. Recent measurements, however, indicate that x is small[2].

The experiment was performed at the Stanford Linear Accelerator Center. The components of the experimental setup, as shown in Fig. 1, were:

(1) A neutral kaon beam was taken at an angle of 50 mrad to a beam of 19 GeV electrons incident on a 30 cm Be target. Photons were removed by 36 r.l. of lead, and charged particles by three sweeping magnets. At the center of the detector, 77 m from the target, the beam cross section was 64 cm wide by 28 cm high. We received 160 beam pulses per second, each of 1600 nsec duration. Each pulse was subdivided into buckets of < 20 psec duration, with 12.5 nsec between buckets. A signal induced in a coaxial cable placed immediately downstream of the target enabled us to determine the K^o_L production time. With this information and the time of the K^o_L decay products, we were able to determine the K^o_L momentum.

(2) The decay volume, filled with helium, was 6 m long.

(3) Five scintillation counter banks were used to identify events of interest. The V counter, operating as a veto, defined the upbeam side of the decay volume. The T counter bank, which defined the downbeam side of the decay volume, consisted of an upper bank and a lower bank of 20 counters each, covering a total area 100 cm wide by 120 cm high. The 12 A counters covered an area 180 cm wide by 120 cm high. Behind the first and second lead walls were 14 B and 16 C counters respectively. The trigger was $\overline{V}$.2T.A.B.C, in coincidence with a beam signal. Event times were recorded in the A, B and C counters.

(4) Two ten-gap wire spark chambers with capacitor-diode readout[3] were placed on opposite sides of the magnet. Each gap measured positions along one coordinate only, with 4 X, 4 Y and 2 UV planes in each chamber.

(5) The momentum-analyzing magnet had a gap which was 2.5 m wide by 1 m by 1 m, and imparted a momentum transfer of 377 MeV/c. The magnetic field, monitored by an NMR probe, remained constant to ± 0.1% throughout the experiment. A helium bag was placed in the magnet volume.

(6) The muon filter consisted of two lead walls, 75 cm and 30 cm thick respectively, for a total of 7.7 interaction lengths. The minimum muon energy loss in traversing the lead walls was 1.6 GeV.

(7) An on-line PDP-9 computer served to accumulate and monitor the data, which was written onto magnetic tape for later analysis on the SLAC IBM 360/91 computer. The PDP-9 also displayed histograms of wire chamber and scintillation counter data, and periodically tested the phototubes and the readout and trigger electronics.

Data runs lasted approximately two hours. After every other data run, the magnet polarity was reversed and diagnostic and calibration runs were made. Approximately 20 million triggers were taken. After removing data taken under inferior conditions and events with no identifiable muon, 15.1 million events remained. These were divided into groups as enumerated in Table 1. Only the 2 TRACK and 1.5 TRACK events were used in the charge asymmetry computation.

The following selection criteria, designed to reduce possible contamination, were then imposed on the data.

(1) Residual muon energy at the C bank as computed from track curvature measurement > 220 MeV.

(2) Muon transverse momentum $\leq$ 187 MeV/c.

(3) One and only one C counter triggered.

(4) Pion and muon triggered distinct T counters.

(5) Decay vertex > 25 cm upbeam of T bank.

(6) Kinematically fitted pion momentum > 500 MeV/c.

(7) $P_0'^2 < 0$, eliminating $K^o_{\pi 3}$ events. The variable $P_0'^2$ denotes the square of the K^o_L momentum in the frame in which the sum of the longitudinal momenta of the charged pair is zero when the event is analyzed as $K^o_{\pi 3}$ decay.

A total of 7.7 million events satisfied these criteria.

A great deal of attention was devoted to the study and correction of systematic biases. Geometric asymmetries were eliminated by averaging magnet polarity forward and reverse data. Reversing the magnetic field did not affect the wire chamber readout, and had an insignificant effect on the phototube pulse heights, which were recorded with each event.

Particle charge determination was totally unambiguous, but some uncertainty could enter into the muon identification. We have therefore excluded from the data all events in which there was any doubt as to which wire chamber track correlated with the muon counters behind the lead walls.

We have considered the possibility that accidental coincidences of tracks and scintillation counter signals might result in spurious events. However, a study of events in which a single muon track was merged with tracks from another totally uncorrelated event showed the probability of accidental vertices to be very small.

The level of regeneration was exceedingly small and readily calculable. Beam interaction biases were measured by placing a 2.5 cm thick carbon slab at several positions in the decay volume. From the number and asymmetry of the events verticizing at the slab, and from the helium/carbon slab mass ratio, we have determined the bias in the main data sample.

Potential muon biases were subject to direct measurement. We observed a large negative charge asymmetry for those muons which just barely penetrated the lead walls. This may be due to μ^- capture or to ionization differences which extend the μ^-

range[4]. We removed all such biases from the data by excluding events in which the computed muon energy after the second wall was < 220 MeV.

The pion absorbing material of the detector was divided into two equal sections: the decay volume helium, the T counters, and the upbeam chambers; and the magnet volume helium, a polyethylene sheet duplicating the T counter material, and the downbeam chambers. By measuring the absorption in the downbeam section, we could compute the overall bias. Using the muon and K_L^o information and only the upbeam pion direction, we kinematically selected those events in which the pion momentum must have been large enough for it to traverse the magnet and the downbeam chambers. The numbers of these events which did and did not have an observed downbeam pion segment determined the absorption level and asymmetry. However, since this procedure was not equally sensitive for all pion momenta, we have excluded from the data all events which could have had a pion with momentum < 500 MeV/c, and applied a momentum-dependent correction based on the 2 TRACK events.

Pion decay effects were computed by Monte Carlo simulations. Biases due to pion penetration of the lead walls were measured via the $K_{\pi 3}^o$ mode. As the charge asymmetry in this mode is identically zero, any asymmetry observed in the $K_{\pi 3}^o$ events must be due to the penetration process.

We have also searched for other possible biases by examining many subsamples of the data, on the assumption that sizable systematic biases would affect different distributions in different ways. We have thus examined the asymmetry as a function of many variables. Some of these results are shown in Fig. 2. We have found no evidence of extraneous biases in any of these distributions.

The systematic corrections and the final charge asymmetry are presented in Table 2. Our value of $\delta = (+2.78 \pm 0.51) \times 10^{-3}$ agrees well with previous determinations in both the $K_{\mu 3}^o$ and K_{e3}^o decay modes[5]. We have also examined the dependence of the uncorrected asymmetry on the center-of-mass energies of the pion, muon and neutrino, and have found no statistically significant variation. In the absence of $\Delta S = -\Delta Q$ amplitudes, our result gives Re $\epsilon = (1.39 \pm 0.25) \times 10^{-3}$, in excellent agreement with the CP violation results in the $K^{o}_{\pi 2}$ modes[2], which yield Re $\epsilon = (1.51 \pm 0.07) \times 10^{-3}$. If we assume the $K^{o}_{\pi 2}$ result for Re ϵ, we may compute limits on the $\Delta S = -\Delta Q$ amplitudes. The uncertainties in the imaginary part are large, but for the real part we find Re $x = -0.04 \pm 0.10$. Thus the results of this experiment are completely consistent with the class of theories assigning the CP violation entirely to the K^{o}-$\bar{K}^{o}$ mass matrix[6], and with the absence of $\Delta S = -\Delta Q$ amplitudes.

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FIGURE CAPTIONS

1. Plan view of experimental apparatus.

2. The uncorrected charge asymmetry, δ, is plotted with respect to several variables. (a), (b), and (c) show δ vs. the muon position in the A, B, and C counter banks. (d), (e), and (f) show δ vs. the kinetic energy of the μ, π and ν in the K_L^o rest frame. (g) and (h) show δ vs. the laboratory momentum of the μ and π. (j) shows δ vs. the residual energy of the muon after the 2nd wall; all events with muon energy < 220 MeV are included in the lowest bin, including those in which the muon was apparently below threshold. (k) shows δ vs. the horizontal distance between the projected muon wire chamber trajectory and the muon C counter position. (m) shows δ vs. the (π, μ) vertex position along the beam axis.

The upper left hand corner of each plot contains χ^2 and the number of degrees of freedom for a fit to the average δ from that plot.

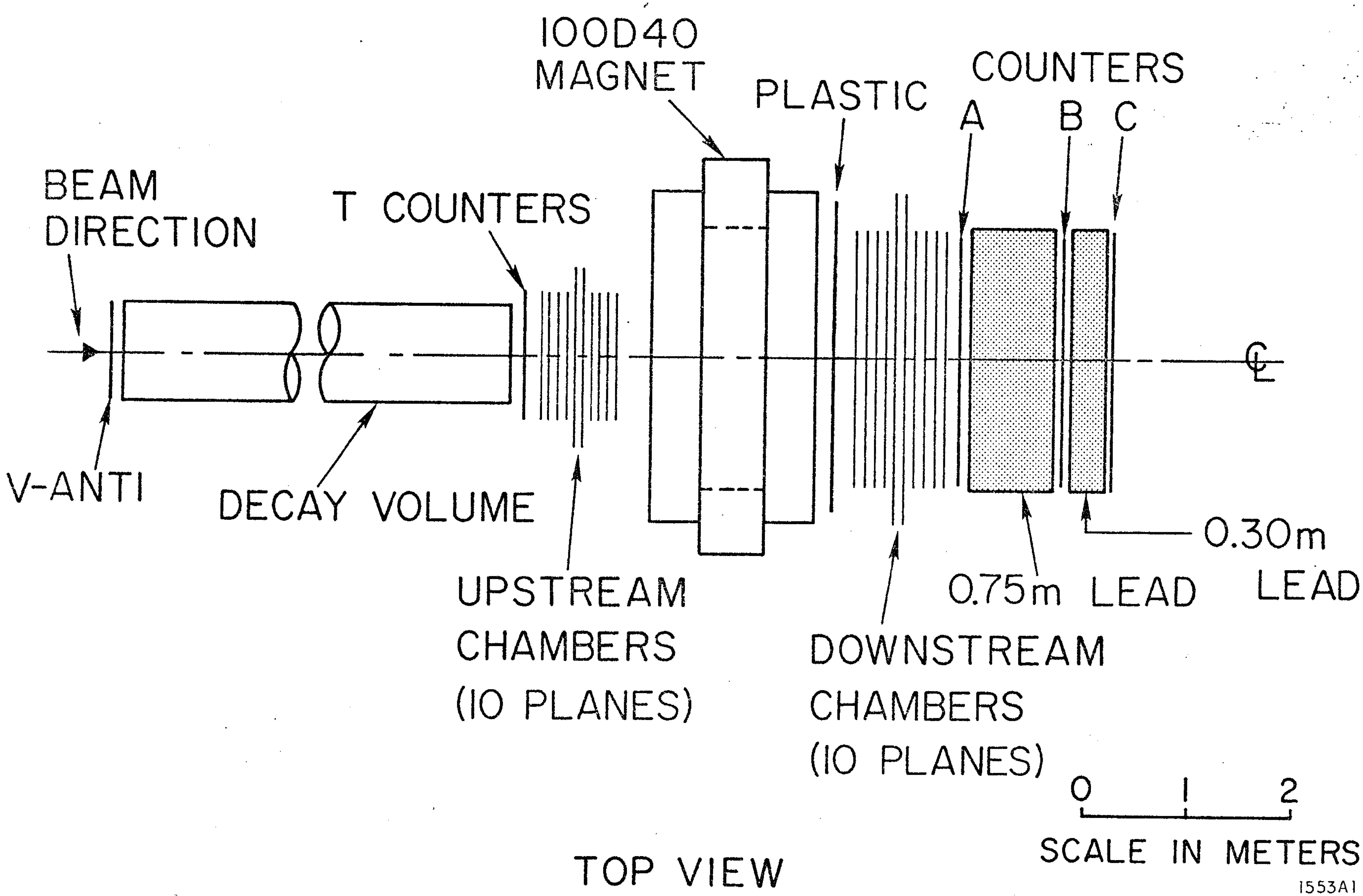
100D40
MAGNET
PLASTIC
COUNTERS
A
B
C
BEAM
DIRECTION
T COUNTERS
V-ANTI
DECAY VOLUME
UPSTREAM
CHAMBERS
(10 PLANES)
DOWNSTREAM
CHAMBERS
(10 PLANES)
0.75m LEAD
0.30m
LEAD
0
1
2
SCALE IN METERS
TOP VIEW
1553A1

Fig. 1

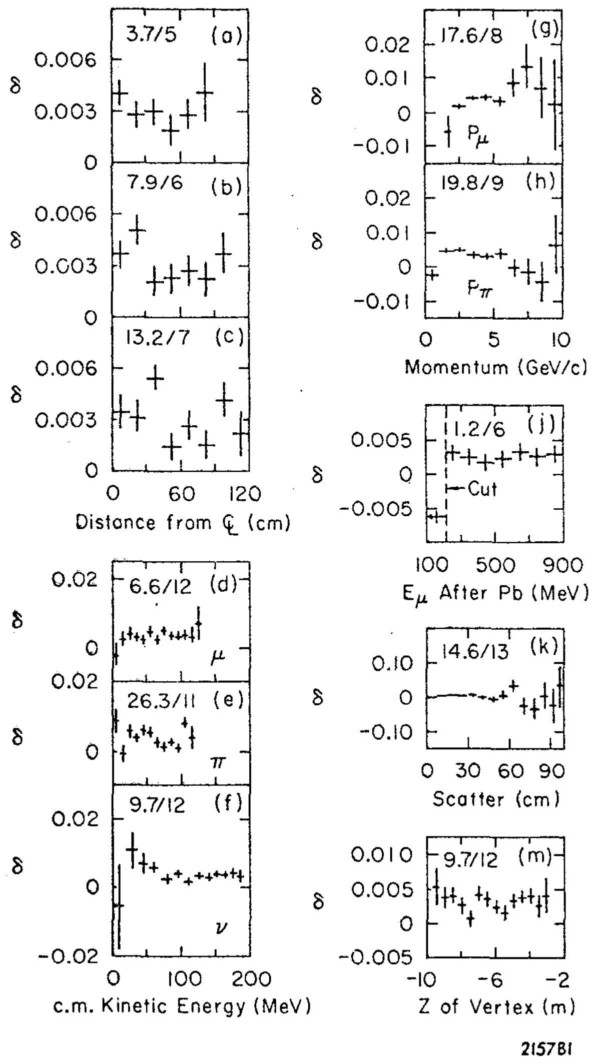
3.7/5 (a)
7.9/6 (b)
13.2/7 (c)
δ
0.006
0.003
0
0 60 120
Distance from ℄ (cm)
6.6/12 (d)
μ
26.3/11 (e)
π
9.7/12 (f)
ν
0.02
-0.02
0 100 200
c.m. Kinetic Energy (MeV)
17.6/8 (g)
P_μ
19.8/9 (h)
P_π
0.01
-0.01
0 5 10
Momentum (GeV/c)
11.2/6 (j)
Cut
0.005
-0.005
100 500 900
E_μ After Pb (MeV)
14.6/13 (k)
0.10
-0.10
0 30 60 90
Scatter (cm)
9.7/12 (m)
0.010
-10 -6 -2
Z of Vertex (m)
215781

Fig. 2

TABLE I

Event Categories

	Events ($\times 10^3$)
2 TRACK — Muon identification unambiguous; pion and muon seen in both chambers; vertex in decay volume.	8452
1.5 TRACK — Muon identification unambiguous; pion not seen in downbeam chambers; vertex in decay volume.	4701
NO PION — Muon identification unambiguous; no track verticizes with muon.	1235
AMBIGUOUS — Muon identification ambiguous; vertex in decay volume.	312
2 MUON — Two distinct muons present; muons come from common vertex in decay volume.	193
MULTIPRONG — Muon identification unambiguous; more than two tracks share same vertex.	244

TABLE II

Tabulation of Systematic Corrections

Description	Corrections in ppm
Events passing final cuts	+3010 ± 360
Pion absorption	- 290 ± 221
Pion decay	+ 431 ± 41
Pion penetration	- 394 ± 271
Beam Interactions	+ 8 ± 19
Pulse height variation	- 2 ± 2
Asymmetric contributions to AMBIGUOUS event group	- 25 ± 25
Asymmetric elimination of multiple C counter events	+ 65 ± 65
Regeneration	- 16 ± 6
Accidentals	- 8 ± 10
Final corrected Charge Asymmetry	+2779 ± 509