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MEASUREMENT OF THE CHARGE ASYMMETRY IN THE DECAY $K_L^0 \to \pi^\pm + e^\mp + \nu$ †

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The charge asymmetry $\delta = (\Gamma_+ - \Gamma_-)/(\Gamma_+ + \Gamma_-)$ for the electron in the decay of the long-lived neutral kaon to pion, electron, and neutrino has been measured. We find asymmetry $\delta = (+2.24 \pm 0.36) \times 10^{-3}$. The result shows that CP symmetry is not conserved in this process.

Charge asymmetry in the decay of a neutral boson is possible only if CP symmetry is not conserved. The magnitude of this asymmetry in K_L^0 decay is an important parameter in the phenomenology of CP nonconservation in K decay. We report here a measurement for the processes $K_L^0 \to e^\pm + \pi^\mp + \nu$.

Let Γ_+ and Γ_- be the partial decay rates of the long-lived neutral kaon to positrons and electrons, and define the charge asymmetry δ as

$$\delta = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}.$$

$|\delta|$ can be expected to be no greater than $\sim 4 \times 10^{-3}$ on the basis of existing measurements of CP nonconservation in K decay.[1] Measurements with sufficient sensitivity for the detection of such a small asymmetry have not been previously reported.

The experiment is performed by means of a neutral beam produced at an internal target in the Brookhaven alternating-gradient synchrotron. The beam is defined by a series of three collimators at 20° to the circulating proton beam and located, respectively, 4, 9, and 19 m from the target. Each collimator has a tapered rectangular aperture such that all internal faces are generated by a common pyramid with its apex at the target. The exit opening is 13.6 cm wide and 20.8 cm high. Before the beam enters the collimators, it traverses 10 radiation lengths of lead to attenuate the γ rays. Between the first two collimators a sweeping magnet bends charged particles aside. The beam traverses a vacuum from the entrance port of the first collimator to the forward end of a 3.75-m-long helium-filled decay region which is flanked on both the right- and left-hand sides by six scintillation counters (see Fig. 1). The decay particles then traverse a helium-filled region and enter a magnet with aperture 150 cm wide and 45 cm high. The faces of the magnet are protected with scintillation counters in anticoincidence.

The magnet is followed on each side in turn by a four-counter hodoscope, a 2-m-long threshold Cherenkov counter filled with 1 atm of ethylene, and a six-counter hodoscope (see Fig. 1). The Cherenkov counters have angular acceptances of ±12° horizontally and ±7.5° vertically. For electrons the average number of photoelectrons collected is 10, corresponding to an efficiency of 99.99 %. The threshold for pions is 3.8 BeV/c, and for muons it is 2.7 BeV/c. None of the pions and ~0.3 % of the muons from K_{L_3} in this experiment (average kaon momentum is ~2.2 BeV/c) exceed these thresholds according to our calculations.

Events are recorded on magnetic tape provided that there are signals from each of the six hodoscopes and from at least one Cherenkov counter. All counters are recorded, as

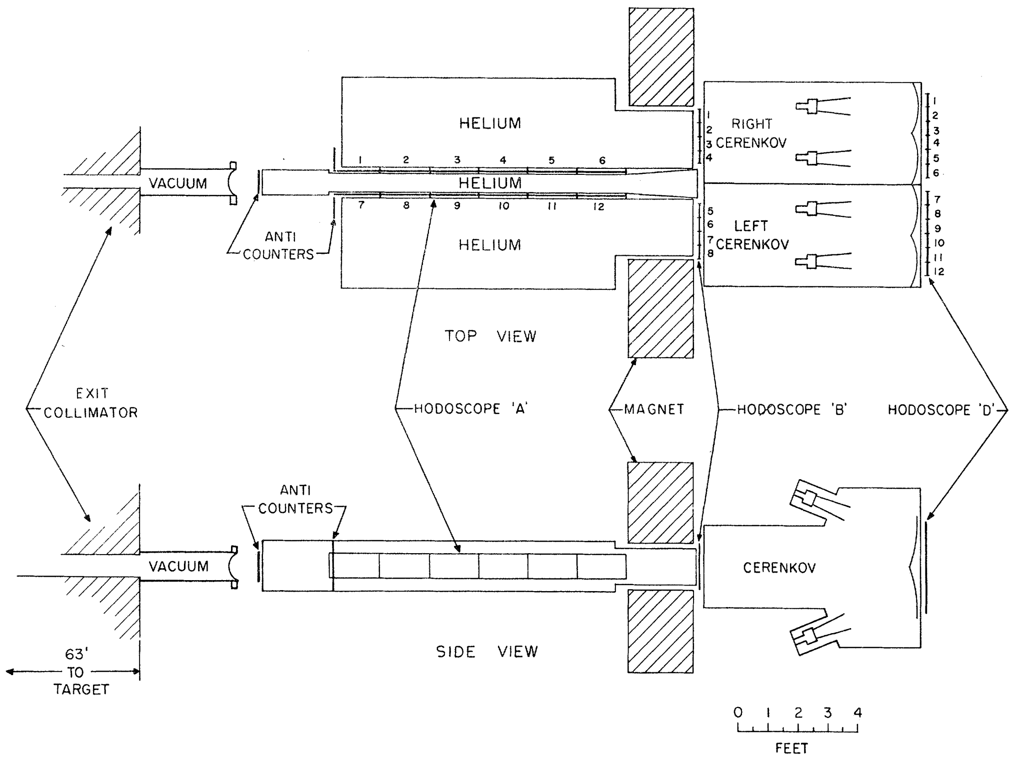

FIG. 1. Vertical and horizontal views of the detection apparatus.

well as the Cherenkov pulse height. The events are also entered into an on-line computer which checks the stability of the counters by comparing the rates in the contemporary run with averages obtained from previous similar runs.

For the computation of the asymmetry, additional selection criteria may be applied. The asymmetry has been computed with four different selection criteria to check the sensitivity of the result with respect to such variation. Two conditions which were always required were: (a) no veto counter pulse, and (b) the "angular condition" on the lepton side. The angular condition associates only three of the six D counters with any particular B counter in such a way as to select an angular region symmetric with respect to a vertical plane parallel to the beam. This eliminates from consideration those electrons which traverse the Cherenkov counters at angles larger than the acceptance of its optics.

Figure 2 shows observed rates as a function of the magnetic field, in comparison with Monte Carlo calculations for K_{e3} decay. Figure 3 shows the distributions of rates in the various hodoscopes, compared with corresponding expectations for K_{e3} decay. In comparing experimental and calculated distributions it must be kept in mind that the calculations suffer from uncertainties in the kaon-momentum distribu-

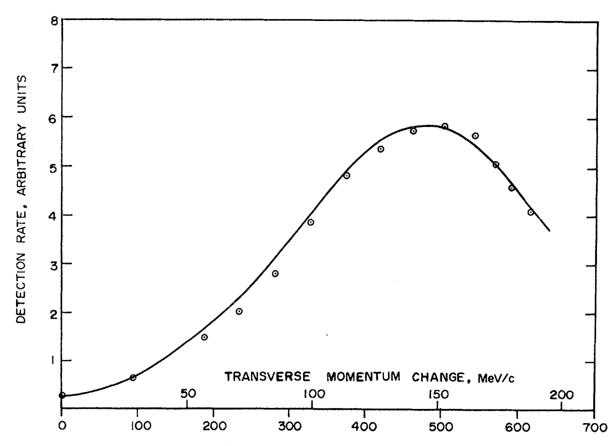

FIG. 2. Event rate as a function of the magnetic field in the analyzing magnet. The abscissa is labeled by the transverse momentum change produced by this field. The Monte Carlo predictions for K_{e3} (full curve) are shown as well as the experimental results (points with error flags).

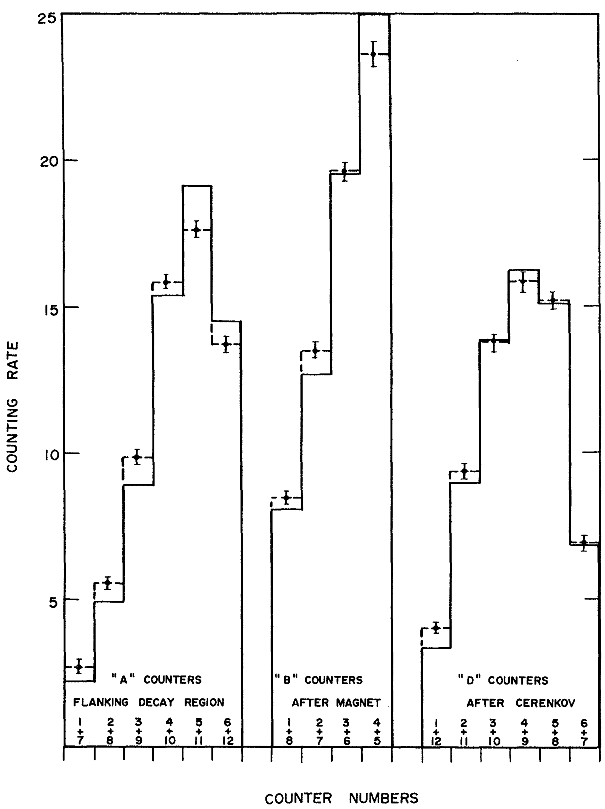

FIG. 3. Distribution of events in the hodoscope counters. The rates in symmetrically placed counters are combined. The experimental results (full line) are compared with the Monte Carlo predictions (dashed).

tion. We are content that the results of Figs. 2 and 3 support the premise that we are counting K mesons. This can be checked further by observing the fraction of these coincidences which are associated with electrons, that is, are detected in the Cherenkov counter. For K decay we expect the fraction

$$F_{\text{theo}} = \left[1 + \frac{\Gamma_{\mu 3} \times (K_{\mu 3} \text{ detection efficiency})}{\Gamma_{e3} \times (K_{e3} \text{ detection efficiency})}\right]^{-1}$$

$$= 0.52 \pm 0.02.$$

Experimentally, we find

$$F_{\text{exp}} = \frac{\text{sixfold coincidences} + \text{Cherenkov}}{\text{sixfold coincidences}} = 0.50.$$

Only kaon decays are detected with substantial efficiency in the Cherenkov counter, and comparison of F_{theo} with F_{exp} permits the conclusion that not more than a small fraction of the sixfold coincidences without Cherenkov requirement are due to extraneous events such as neutron interactions and accidental coincidences. This fraction is substantially reduced by the Cherenkov requirement. The possible asymmetries produced by the remaining contaminants will be discussed later. The accidental rate for events with Cherenkov requirement is 5 %. Of these 5 %, approximately one-fifth are events in which the Cherenkov pulse is uncorrelated; the remainder are events in which some pulse in the scintillation hodoscope is uncorrelated. The veto counters reject approximately 6 % of all events. Two-thirds of these are rejected by the counters protecting the magnet surface. Most of these rejections are due to uncorrelated events in the veto counters. The asymmetry inherent in these accidental events has been investigated and found to be negligible. With a target intensity of 10^{12} protons/burst we observe 50 000 events/h.

With magnetic field pointing down, the left-hand branch counts positrons and the right-hand branch counts electrons. The experiment consists of repeated (to the present, ~500) paired rate observations with magnetic field first up and then down. In this way we find $N_L^{\uparrow}$, $N_R^{\uparrow}$, and $N_L^{\downarrow}$, $N_R^{\downarrow}$ with obvious notation. The asymmetry we seek is

$$\delta = \frac{1}{2}\left[\frac{N_L^{\downarrow} - N_R^{\downarrow}}{N_L^{\downarrow} + N_R^{\downarrow}} - \frac{N_L^{\uparrow} - N_R^{\uparrow}}{N_L^{\uparrow} + N_R^{\uparrow}}\right].$$

The technique of reversing the field makes the result independent of geometrical inaccuracies; it is, however, imperative that counter efficiencies and, in particular, the phototubes of the Cherenkov counters are independent of field reversal. The Cherenkov pulse heights are recorded for each event, and we find that the average pulse heights do not change by more than 0.2 % on field reversal. An asymmetry of this magnitude coupled with the large Cherenkov detection efficiency results in a negligible contribution to δ.

We report here the rates and asymmetry for those events which satisfy selection criterion given above:

$$N_L^{\downarrow} = 4\,320\,870, \quad N_L^{\uparrow} = 4\,275\,699,$$

$$N_R^{\downarrow} = 4\,263\,411, \quad N_R^{\uparrow} = 4\,244\,595,$$

$$\delta_{\text{raw}} = (1.61 \pm 0.24) \times 10^{-3}.$$

Table I. Materials in the detector and asymmetry corrections.

Detector element	H (g/cm^2)	C (g/cm^2)	Al (g/cm^2)	He (g/cm^2)	Correction applied (in parts per thousand)	Basis
A counters[a]	0.008	0.05	0.025	···	+0.26 ± 0.11	Table II Entry 1
He bag	···	···	···	0.045	+0.025 ± 0.01	Table II Entry 1
B counters	0.016	0.09	0.030	···	+0.06 ± 0.08	Table II Entry 2
Cherenkov, gas	0.034	0.205	···	···	+0.11 ± 0.15	Table II Entry 2
Cherenkov, mirror and windows	0.015	0.19	0.070	···	+0.32 ± 0.21	Table II Entry 3
Beam tube	···	···	···	0.035	−0.01 ± 0.06	Table II Entry 4
Total correction					0.76 ± 0.34	

[a]The particles go through these counters at an average angle of 10°, so that the amount of material traversed is ~6 times as great as that shown.

δ_{raw} includes a factor 1/0.95 to account for the accidental rate.

Results with further conditions, such as no multiple events in the *B* and *D* hodoscopes, and the "angular condition" on the pion side, have also been computed and are in agreement.

The raw asymmetry must be corrected for asymmetries which result from the interaction of the leptons and pions in the detector. The thicknesses of the various elements of the detector are given in Table I. Small but non-negligible asymmetries result from positron annihilation, differential π^+ and π^- absorption in hydrogen, and differential detection of secondaries from pion interactions in all nuclei. The correction can be performed on the basis of known cross sections, or we can choose an experimental approach, and in this way we hope to avoid subtle questions of the propagation of secondaries from these interactions in the apparatus. We have performed auxiliary asymmetry measurements with additional material inserted in the region near the various counters, as shown in Table II.

The corrections which follow from these measurements are shown in Table I. They are small and rather poorly established statistically. Taken all together they amount to a substantial correction with large error:

$$\delta_{\text{correction}} = (+0.76 \pm 0.34) \times 10^{-3}.$$

Using this experimental correction, we find

$$\delta = (+2.37 \pm 0.42) \times 10^{-3} \text{ (measured correction).}$$

The positron decay is favored. The indicated

Table II. Results of auxiliary asymmetry measurements after insertion of material in various locations.

Entry	Location	Material	Asymmetry (in parts per thousand)
1a	Behind counters "*A*"	$\frac{1}{4}$ in. Lucite (0.65 g/cm^2 CH)	−0.49 ± 0.88
1b	Behind counters "*A*"	$\frac{1}{8}$ in. Lucite (0.33 g/cm^2 CH)	−0.70 ± 1.06
2	In front of counters "*B*"	$\frac{1}{2}$ in. Lucite (1.3 g/cm^2 CH)	+0.94 ± 0.82
3	Behind Cherenkov counters	$\frac{1}{4}$ in. Lucite (0.65 g/cm^2 CH)	+0.79 ± 0.48
4	Beam tube[a]	1 atm SF_6 (1.3 g/cm^2)	1.9 ± 2.3

[a]Comparing the runs with SF_6 in the decay volume to those with helium, we find an increase in the ratio of coincidences without Cherenkov counts to those with. The excess events without Cherenkov counts are to be attributed to interactions in the gas and amount to 0.2 events per observed K_{e3} decay. From this we deduce that these interactions contribute 0.005 events to the rate without Cherenkov counter, per observed K_{e3} decay. The contribution to the rate with Cherenkov counter is expected to be smaller by a factor of about 100, so that the contamination of our events by gas interactions is $\sim 5 \times 10^{-5}$.

error is statistical. This does not imply that there are no other errors; it is only a reflection of the fact that we are ignorant of any substantial systematic errors.

If instead we correct using known annihilation[2] and pion cross sections[3] and some auxiliary measurements performed on secondaries from π^+ and π^- interactions in Freon-filled bubble chambers,[4] we find corrections of $(+0.25 \pm 0.05)\times 10^{-3}$ for positron annihilation, and $+(0.25 \pm 0.15)\times 10^{-3}$ for differential pion interactions, for a total correction

$$\delta_{\text{correction}} = (+0.5 \pm 0.16)\times 10^{-3}$$

and

$$\delta = (+2.11 \pm 0.3)\times 10^{-3} \quad \text{(computed correction)}.$$

We combine these results to report what we believe to be the best value at this time:

$$\delta = (+2.24 \pm 0.36)\times 10^{-3} \quad \text{(average correction)}.$$

We wish to thank Dr. J. Hornbostel and Dr. C. Rubbia for very useful suggestions, Mr. W. Sippach for the design and construction of beautiful register and logic circuits, Mr. Y. Au and Mr. J. Walker for assistance in the mechanical design, Dr. J. Sanford, Mr. W. Walker, and Mr. G. Tanguay for their assistance in preparing the experiment on the alternating-gradient-synchrotron floor, and Dr. Lindenbaum and Dr. Ozaki for their generosity in making the Brookhaven National Laboratory on-line data facility available and for their help in the adaptation of this facility to this experiment. Finally, we wish to thank Mr. D. Koppel and Mr. J. Marx for their help in the conduct of the experiment.

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[4]We wish to thank Professor D. H. Perkins and Professor H. H. Bingham for making these heavy-liquid bubble-chamber photographs of π^+ and π^- interactions available to us.

NONORTHOGONALITY OF THE LONG- AND SHORT-LIVED NEUTRAL KAON STATES AND PHENOMENOLOGICAL ANALYSIS OF EXPERIMENTS ON CP NONCONSERVATION IN K^0 DECAY*

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It is noted that the nonzero charge asymmetry in the $(K_L)_{e3}$ decay demonstrates the nonorthogonality of the $K_L{}^0$ and $K_S{}^0$ states. The result of the foregoing Letter on the charge asymmetry, combined with other measurements relevant to CP nonconservation in K decay, are found to be consistent with a phenomenological analysis, which yields a pion-pion scattering phase shift consistent with other indirect observations only if the mass difference $m_L - m_S$ is negative.

The result on the charge asymmetry reported in the preceding Letter can be related to other properties of neutral kaon decay.[1] Here we wish to call attention to two essentially separate connections, one to the nonorthogonality of the long- and short-lived K^0 states, the other to the CP-nonconserving amplitudes in the two-pion decay.

We assume CPT symmetry in the absence of any evidence to the contrary. It was shown by Lee, Oehme, and Yang[2] that the long- and short-lived states can then be written in terms of the eigenstates of hypercharge, K and $\bar{K}$:

$$|L\rangle = p\,|K\rangle + q\,|\bar{K}\rangle, \tag{1a}$$

$$|S\rangle = p\,|K\rangle - q\,|\bar{K}\rangle, \tag{1b}$$

$$|p|^2 + |q|^2 = 1,$$

where p and q are as yet undetermined coefficients, which are equal in the case of CP con-