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Test of the $\Delta S = \Delta Q$ Rule in K_{e_3} Decay*

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(Received 21 May 1973)

We report here the results of a test of the $\Delta S = \Delta Q$ rule in K_{e3} decay in which we observed ~ 1700 K_{e3} decays in the sensitive region of 0.25 to 4.8 $K_S{}^0$ mean lifetimes. We find, where X is the ratio of the $\Delta S/\Delta Q$ nonconserving to conserving amplitudes, $\mathrm{Re}X = -0.008 \pm 0.044$, $\mathrm{Im}X = -0.017 \pm 0.060$, and $|X| = 0.019$. The origin lies on the 0.65-standard-deviation likelihood contour; hence we find no evidence for a violation of the $\Delta S = \Delta Q$ rule in K_{e3} decay. $\Delta m = M_L - M_S$ and τ_S were also measured, giving $\Delta m = (0.557 \pm 0.038) \times 10^{10} \hbar$ sec^{-1} and $\tau_S = (0.867 \pm 0.024) \times 10^{-10}$ sec.
sec.

The $\Delta S = \Delta Q$ rule states that the change in strangeness must equal the change in electric charge for the hadrons in a weak decay. The K^0 decays show a CP nonconservation as yet unconnected with the rest of weak interactions, and a violation of the $\Delta S = \Delta Q$ rule could provide a link. While maximal $\Delta S/\Delta Q$ violation has already been ruled out, a violation at the limits of present experiments would impose a major constraint on theories of weak interactions. This rule has been most often studied in the decays $K^0, \bar{K}^0 \to \pi e \nu$ ("K_{e3}" decays), where a $\Delta S = -\Delta Q$ term would alter the temporal development of the amplitudes of the charge-conjugate channels, $\pi^- e^+ \nu$ and $\pi^+ e^- \bar{\nu}$. Assuming CPT invariance and neglecting terms of order ϵ, the CP-nonconserving amplitude, the temporal K_{e3} decay distribution $N^\pm(t)$ can be written

$$N^\pm(t) \propto |1+X|^2 \exp(-t/\tau_S) + |1-X|^2 \exp(-t/\tau_L) + [\pm 2(1-|X|^2)\cos(\Delta m t) - 4\,\mathrm{Im}X \sin(\Delta m t)] \exp[-\tfrac{1}{2}t(1/\tau_S + 1/\tau_L)],$$

where $\pm$ refers to the lepton's charge, $\Delta m \equiv M_L - M_S$, τ_S and τ_L are the lifetimes of the $K_S{}^0$ and $K_L{}^0$, and X is the complex ratio of the $\Delta S/\Delta Q$ nonconserving to conserving amplitudes. A violation would be most evident in the early $\pi^+ e^- \bar{\nu}$ decays of an initially pure K^0 beam.

Previous experimental results[1] are scattered around the origin in the X plane, but no single published experiment sets $|X| < 0.15$ to better than about 1 standard deviation. This experiment obtained some 1700 K_{e3}'s in the decay region 0.25 to 4.8 $K_S{}^0$ mean lifetimes. At the 1-standard-deviation level we conclude $|X| < 0.075$, and we believe our systematic errors in $|X|$ are no larger than 0.01.

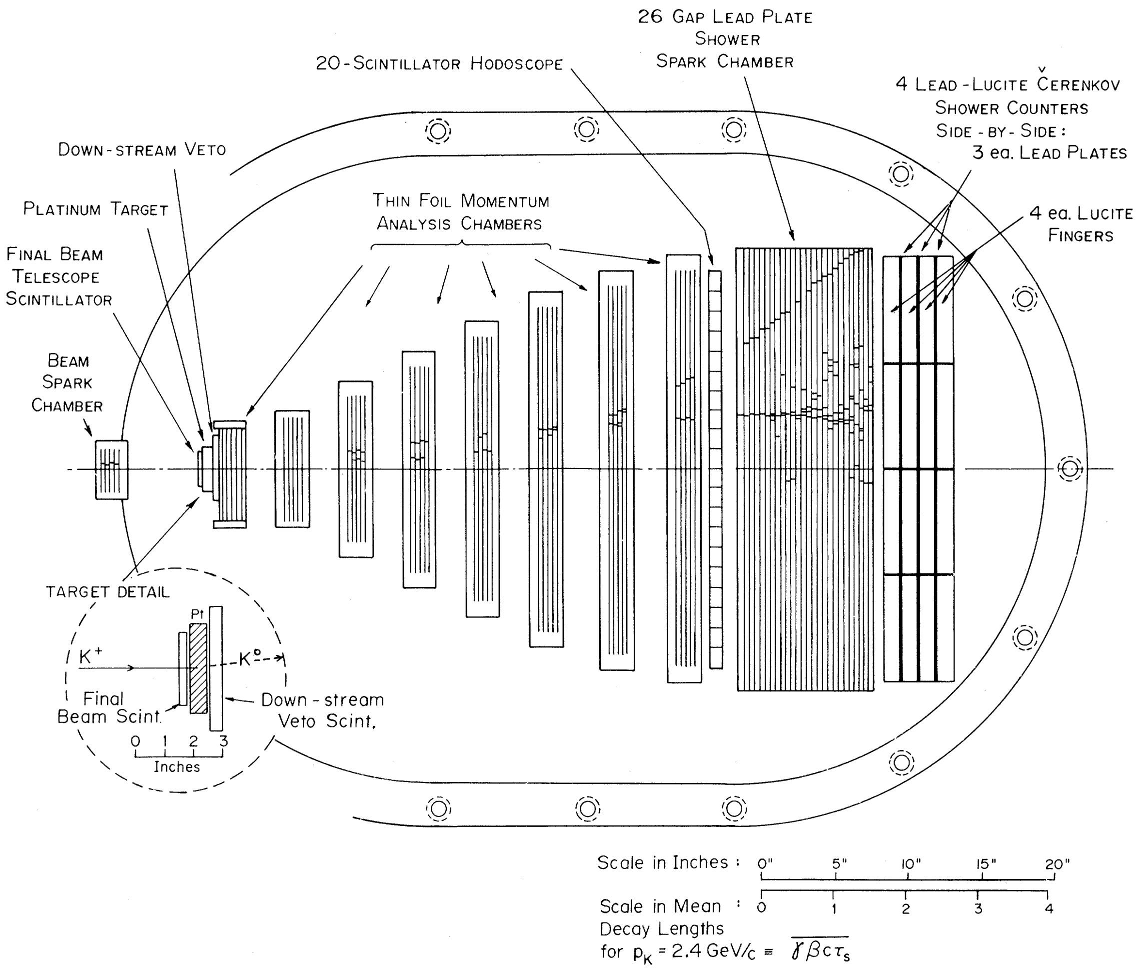

FIG. 1. Schematic plan view of the spark chamber and detector array. The detector array was inside the Argo magnet, whose field was perpendicular to the plane of the drawing. The sparks shown are dubbed in from a real event, but for clarity the side-view mirrors and the images of the sparks in them are not shown.

A partly separated, Cherenkov-tagged, 2.93-GeV/c K^+ beam[2] at the Brookhaven alternating-gradient synchrotron was incident on a 0.787-in.-thick platinum target. This produced an initially pure K^0 beam whose early decays were detected in a spark chamber and counter array[3,4] (Fig. 1) contained in a nearly uniform 14.5-kG magnetic field. To produce K^0's of definite strangeness the beam was chosen to be K's rather than π's, and K^+'s rather than K^-'s to minimize hyperon production. We expect and indeed find no evidence for any $\bar{K}^0$ or hyperon contamination.

The kaons were identified by a CO_2 differential Cherenkov counter[5] and the beam was defined by a scintillation counter telescope. The line of possible production points within the platinum target was determined by the K^+'s location in a four-gap beam-entrance chamber. A $\frac{3}{8}$-in.-thick anti counter just downstream of the platinum target vetoed events with charged particles emerging downstream of the target.

The K^0 decays were detected in a thin-aluminum-foil optical spark-chamber array of eight chamber modules each having four gaps. Next, a twenty-counter picket-fence hodoscope gave a trigger from the two charged K^0-decay products. A 2.8-radiation-length 26-gap lead-plate spark chamber downstream of the hodoscope gave a visual discrimination between π's and e's. The K_{e3} trigger was completed by summing the outputs from four lead-Lucite Cherenkov counters situated downstream of the lead-plate spark chamber and requiring an amplitude more than 3 times that of a single relativistic particle.

The K^0 momentum and production angular distributions were determined by measuring $K_S{}^0$

$\to \pi^+\pi^-$ decays with a very loose K^0 trigger, in which we required that only neutrals emerge downstream from the target. The K^0 production spectrum[6] is strongly peaked toward high energy and is so well known that when we fit to the radial decay distribution neither the spread of the spectrum nor the thickness of the target degrades substantially the sensitivity to a nonconservation amplitude. Thus we have an effectively monochromatic, compact, and intense source of K^0's.

With about 4.7×10^9 incident K^+'s, some 2.2×10^6 pictures were taken, of which 0.4×10^6 were calibration and background studies and 1.8×10^6 contained data candidates. About 1.2×10^6 of these were $K_S^0\to\pi^+\pi^-$ and 0.6×10^6 appeared to be the expected electromagnetic products of $K_S^0\to\pi^0\pi^0$. As expected, only some 2×10^4 appeared to be minor K^0 decay modes, of which we estimate about 1×10^4 were K_{e3}'s.

Scanners selected about 5×10^4 K_{e3} pictures with a good V and one leg showering, and physicists confirmed about 1.8×10^4 as candidates for encoding. Events in the final sample were encoded at least twice, and the two best measurements agreed closely in decay radius and in effective dipion mass (calculated assuming both legs were pions), just as expected from studies of Monte Carlo events generated using the observed spark jitter as a function of track angle.

The backgrounds were reduced further using the following kinematic cuts. The V's effective masses, $M_{\pi\pi}$ (M_{ee}), were found for each event assuming both legs were π's (e's). $M_{\pi\pi}<480$ MeV/c^2 was required for events with small decay radii, and $M_{ee}>100.0$ MeV/c^2 was required for all events. We calculate that the $M_{\pi\pi}$ cut lost 6.1%, and the M_{ee} cut lost 3.3% of the K_{e3}'s in the data. The $M_{\pi\pi}$ cut was removed for events with large decay radii, where the $\pi\pi$ background was relatively small, in order to guard against unknown kinematic losses resulting from any spark-jitter uncertainty. (The spark-jitter distribution could not be determined as accurately for the most-downstream module as for the others.) The main geometric cuts were that the π was required to reach the twenty-counter hodoscope, and the e was required to reach the shower-counter array.

Surviving events were examined by two physicists and finally grouped as π interactions or good showers. Scans of π and e beam pictures using the same criteria predicted that less than $\frac{1}{750}$ of the $K^0\to\pi^+\pi^-$'s and about $\frac{1}{2}$ of the K_{e3}'s were called good showers.

The only significant background is $K_S^0\to\pi^+\pi^-$. We estimate that all other backgrounds contribute less than four events to the final sample. To evaluate the $K_S^0\to\pi^+\pi^-$ background, events from the data (K_{e3} trigger) selected to be $K^0\to\pi^+\pi^-$ decays on the basis of nonshowering tracks in the lead-plate spark chamber and events selected from the very loose K^0 trigger were analyzed and subjected to the same kinematic and geometric requirements as the K_{e3}'s. Both gave a 45:1 kinematic rejection of $K^0\to\pi^+\pi^-$, averaged over decay radii, using the $M_{\pi\pi}$ cut. Combining the kinematic and visual rejections, we get the background curves shown in Fig. 2, containing 55 ± 28 events. The jump at 14 in. is from the removal of the $M_{\pi\pi}$ cut beyond this radius.

As a check on the $\pi\pi$ background, the data were fitted using an additional cut that required that the angle between the V's momentum vector and the K^0's direction of flight be greater than 0.03 rad. This reduced the data to 1402 and the background to 17 ± 9 events, but $|X|$ changed by less than 0.008 and $|\Delta\vec{X}|$ was less than 0.025—both changes small compared with statistical errors.

The K_{e3} detection efficiency and expected secondary distributions were determined by generating Monte Carlo K_{e3} decay events and subjecting them to the same analysis and selection requirements.

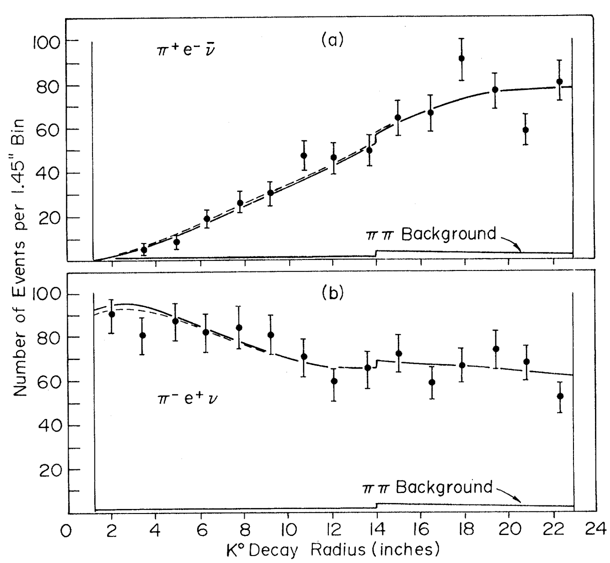

FIG. 2. Radial distributions of (a) $\pi^+e^-\bar{\nu}$, and (b) $\pi^-e^+\nu$ decays. Points, data; dashed lines, best fit; solid lines, $\Delta S=+\Delta Q$ curves. The solid lines at the bottom are the estimated $K_{\pi\pi}$ background events accepted as K_{e3}'s; they have been included in the likelihood fits shown.

Studies of the effects of magnetic field reversals and of various geometric and kinematic cuts, and comparisons with the expected distributions of the many secondary kinematic quantities (e.g., leg momenta, V opening angles), showed no evidence of apparatus asymmetry, with all distributions as expected. Our upper limits on the systematic errors are 0.03 in $|\Delta\vec{X}|$ and 0.01 in $|X|$.

2173 $K_S^0 \to \pi^+\pi^-$ events from the very loose K^0 trigger were analyzed to determine the K_S^0 lifetime. The maximum-likelihood fit gives $\tau_S = 0.867 \pm 0.024 \times 10^{-10}$ sec, consistent with the 1972 world average (0.862×10^{-10} sec) and also with recent higher values. In any case, the $\Delta S/\Delta Q$ parameters are very insensitive to τ_S; changing τ_S from 0.862×10^{-10} sec to 0.882×10^{-10} sec makes only a 0.005 change in $|X|$.

Figure 2 shows the observed K_{e3} radial decay distributions for 1757 events along with the best $\Delta S/\Delta Q$ fit and the no-violation ($\Delta S = \Delta Q$) curves calculated using $\tau_S = 0.862 \times 10^{-10}$ sec, $\tau_L = 5.172 \times 10^{-10}$ sec and $\Delta m = 0.540 \times 10^{10}\hbar$ sec^{-1}. The maximum likelihood fit to the data gives $\mathrm{Re}X = -0.008 \pm 0.040$ and $\mathrm{Im}X = -0.017^{+0.058}_{-0.055}$. The correlation coefficient ρ is -0.64. The χ^2 for the best fit is 24.9 for 27 degrees of freedom. The simultaneous best fit to ReX, ImX, and Δm gives $\mathrm{Re}X = -0.008^{+0.036}_{-0.038}$, $\mathrm{Im}X = -0.014^{+0.062}_{-0.052}$, and $\Delta m = 0.557^{+0.031}_{-0.033} \times 10^{10}\hbar$ sec^{-1}.

Taking the final errors to be the square root of the sum of the squares of the statistical and the maximum estimated systematic errors, and using the accepted Δm, we get finally $\mathrm{Re}X = -0.008 \pm 0.044$, $\mathrm{Im}X = -0.017 \pm 0.060$, and $|X| = 0.019$. The maximum value reached by $|X|$ on the 1-standard-deviation elliptical likelihood contour is 0.074, the origin lies on the 0.65-standard-deviation likelihood contour, and $|X| \leq 0.075$ on the 1-standard-deviation circle about the origin. For the best fit where Δm is variable we find $\Delta m = (0.557 \pm 0.038) \times 10^{10}\hbar$ sec^{-1}, $\mathrm{Re}X = -0.008 \pm 0.042$, $\mathrm{Im}X = -0.014 \pm 0.064$, and $|X| = 0.016$.

We thank most gratefully for all their excellent work the Brookhaven National Laboratory alternating-gradient synchrotron staff, especially H. Foelsche, J. Sanford, and W. Walker; our scanning staff, especially E. Bonis and E. Rosso; and our technicians and engineers, E. Druek, J. Bavineau, L. Stinson, and C. Strumski. We also thank P. Demos and R. Cool for most patient administrative support.

*Work supported in part by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-3069.

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[5]We thank Dr. T. Kycia for use of the CO_2 Cherenkov counter.

[6]G. Smoot, O. Fackler, D. Frisch, J. Martin, and L. Sompayrac, to be published.