Measurement of the $\Delta S = -\Delta Q$ Amplitude from $K_{e3}^{\ 0}$ Decay*

F. J. Sciulli, J. D. Gallivan,† D. M. Binnie,‡ R. Gomez, M. L. Mallary, C. W. Peck, B. A. Sherwood, § A. V. Tollestrup, and J. D. van Putten‖
California Institute of Technology, Pasadena, California 91109
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We have measured the time distribution of the $\pi^+e^-\nu$ and $\pi^-e^+\nu$ modes from initial K^0's in a spark-chamber experiment performed at the Bevatron. From 1079 events between 0.2 and 7 $K_S^{\ 0}$ lifetime, we find $\mathrm{Re}X = -0.069 \pm 0.036$, $\mathrm{Im}X = +0.108^{+0.092}_{-0.074}$. This result is consistent with $X=0$ (relative probability = 0.25), but more than 4 standard deviations from the existing world average, $+0.14 - 0.13i$.

In 1958,[1] the $\Delta S = \Delta Q$ rule was proposed to describe the the leptonic transitions of hadrons. This rule has been the subject of intense experimental testing,[2] especially in the leptonic decays $(K_{l3}^{\ 0})$ of the K^0 system, $K^0(\overline{K}^0) \to \pi^\pm + l^\mp + (\overline{\nu})\nu$. The time distributions of these modes are especially useful because interference effects permit measurements of both the real and imaginary part of the ratio X of the $\Delta S = -\Delta Q$ amplitude to the $\Delta S = +\Delta Q$ amplitude.

$\mathrm{Im}X \neq 0$ requires a time reversal violation in the leptonic decay. Assuming CPT invariance, this is equivalent to CP violation. It is known,[3] on the other hand, that the physical eigenstates $(K_S^{\ 0}, K_L^{\ 0})$ of the neutral kaon complex are not eigenstates of CP. It has been suggested by Sachs[4] that the origins of this violation lie in the $K_{l3}^{\ 0}$ decays with $|\mathrm{Im}X|$ of order unity. At the same time, experimental determinations of X congregate in the fourth quadrant; a weighted average of all previous experiments[2] gives $\mathrm{Re}X = +0.14 \pm 0.05$ and $\mathrm{Im}X = -0.13 \pm 0.04$.

We have made a measurement of X by producing K^0 mesons at $t=0$ and observing the time distributions of the $\pi^+e^-\overline{\nu}$ and $\pi^-e^+\nu$ modes. Under normal assumptions, including CPT invariance, these distributions are given by

$$N^\pm(t) = C\left\{|1+X|^2 \exp\left(-\frac{t}{\tau_S}\right) + |1-X|^2 \exp\left(-\frac{t}{\tau_L}\right) + \exp\left[-\frac{t}{2}\left(\frac{1}{\tau_S}+\frac{1}{\tau_L}\right)\right][\pm 2(1-|X|^2)\cos\omega t - 4\,\mathrm{Im}X \sin\omega t]\right\}$$

for the positive and negative electrons, respectively, where $\omega = M(K_L^{\ 0}) - M(K_S^{\ 0})$ in $\sec^{-1}$ and τ_S, τ_L = total lifetimes of $K_S^{\ 0}$, $K_L^{\ 0}$, respectively.

Figure 1 shows the experimental apparatus. Negative pions (2.85 BeV/c) from the Lawrence Radiation Laboratory Bevatron impinged on two brass targets. A typical K_{e3} event had a π^- interacting in one target, with no charged particle traversing the veto counter. A neutral kaon decayed downstream of the target, with both prongs of the vee entering the magnet, and at least one particle passing through the S5 counter located immediately downstream of the decay region. The electron in the decay triggered the gas Cherenkov counter located inside the magnet. The two particles traversed two different MH counters, separated by at least one counter, and triggered two different RH counters located at the rear of the magnet. Approximately half the data was taken at each field polarity.

One very important property of this apparatus is that it accepts K^0 decays from within a small forward cone ($\lesssim$15 deg) and of preferentially high momentum ($\gtrsim$1.2 GeV/c). The point was to utilize primarily K^0's of high momentum in the forward peripheral peak.

In order to reduce the 0.24×10^6 K_{e3} event pictures to our final sample of 1079 events, the scanning was performed in the following phases:

Phase I. –The computer tapes were interrogated for K_{e3} triggers whose shower-counter pulse heights were consistent with a minimum-ionizing pion and a showering electron. This selection reduced the total number of candidates to 67 205 event pictures.

Phase II: Shower scan. –The shower chamber pictures belonging to events passing phase I were subsequently examined by scanners and retained if they satisfied "πe" criteria (i.e., one shower and one nonshower). The total number of pictures left after this stage was 14 613.

Phase III: Vee scan. –The remaining candidiates were subjected to a scan of the production- and decay-region picture for a decaying vee. This scan was the most crucial, since position-dependent scanning efficiency would have resulted in a biased time distribution. For this reason, the scan was performed twice. For the events eventually retained as πe, the average

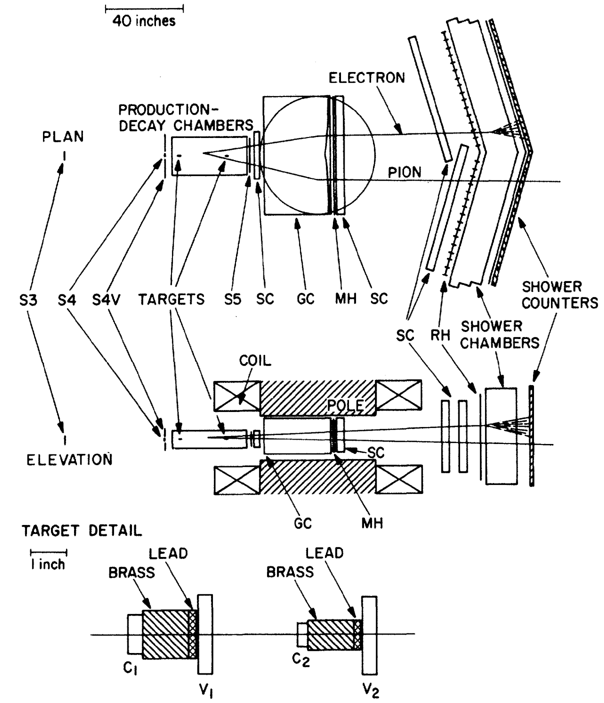

FIG. 1. Experimental apparatus: S3, S4, beam counters; S4V, beam veto counter; S5, $18\times7\times\frac{1}{8}$-in. scintillator defining end of decay region; SC, thin-plate spark chamber; GC, 1-atm. Freon-12 Cherenkov counter which had two mirrors, each with a set of phototubes; MH, hodoscope, fifteen 50×1-in. scintillators arranged horizontally; RH, hodoscope, 32 42×4-in. scintillators arranged vertically; shower chambers, spark chambers containing three radiation lengths of lead distributed over eighteen gaps; fourteen shower counters, each consisting of two $50\times10\times\frac{3}{8}$-in. scintillators with two radiation lengths of lead between scintillators; C_i, counter detecting beam particle entering target; V_i, veto counter demanding neutrals out of target. The πe trigger was $(S3.S4.\overline{S4V})*(C_i\overline{V}_i$ from either target)*S5*(two MH counters fire with one counter separation)*(two RH counters fire)*(pulse in GC, set at very low bias).

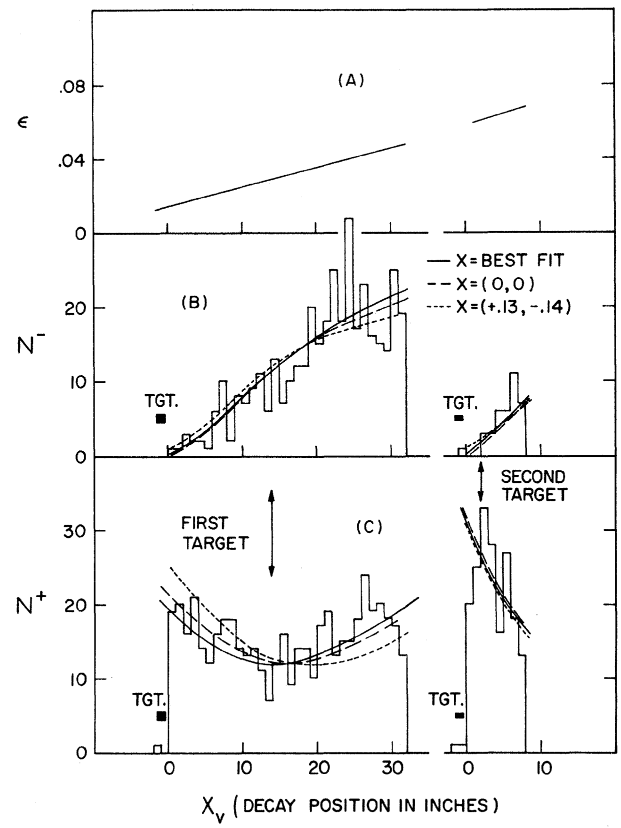

FIG. 2. (a) Efficiency for K_{e3} detection as a function of distance for both targets, (b) position distribution of $\pi^+e^-\overline{\nu}$ events for both targets, (c) same for $\pi^-e^+\nu$ events. N^- and N^+ are shown with calculated curves for three different values of $X=(\mathrm{Re}X, i\ \mathrm{Im}X)$. Distance is measured from the beginning of the fiducial volume.

individual scanning efficiency was 97.2%. It was determined that the few percent of the final events that were missed by a single scanner showed no bias relative to the rest of the events.

The 3395 πe candidates that survived the scanning phases were measured in the spark chambers. These measurements allowed us to determine whether the event consisted of two continuous tracks through the magnet. The 1691 remaining candidates were further subjected to a final scan in the shower and production-decay chambers by a physicist. There were 1337 events left after this scan.

In the Monte Carlo calculation of the K_{e3} efficiency, the distribution in K^0 production angle and momentum obtained from $K^0\to\pi^++\pi^-$ events was used. The distributions in pion momentum, electron momentum, and invariant mass from the πe data agreed well with those predicted by the Monte Carlo program. The distributions in decay position of $K^0\to\pi^++\pi^-$ events for calibration data and Monte Carlo were also in good agreement. Figure 2(a) shows the calculated efficiency for accepting a K_{e3} event as a function of decay position. The Cherenkov counter efficiency for detection of K_{e3} as a function of position has also been investigated. From Cherenkov counter pulse-height distributions, we find that the difference in efficiency between the extremes of decay position was less than 1.2%.

The background processes which we have considered are (1) neutron stars; (2) $K^0\to\pi^++\pi^-$, $\Lambda^0\to p+\pi^-$; (3) e^+e^- pairs; (4) $\Lambda^0\to p+e^-+\overline{\nu}$; (5) $\overline{K}^0$ production in the targets. As an experimental check that neutron stars were not a background in the final sample, we determined the excess of accepted πe vees, produced in the first target, that appeared to decay inside the second target. After extrapolating to the spark-chamber volume and correcting for relative densities and solid angles, we estimate a background from neutron stars from the spark-chamber plates of about 0.5 ± 2.0 events in the final sample.

The $K^0 \to \pi^+ + \pi^-$, $\Lambda^0 \to p + \pi^-$ decay modes, without discrimination, constitute a noise/signal background near $t=0$ of order $10^3/1$. We were able to isolate these events using Cherenkov pulse height information and the invariant mass of the charged prongs. We estimate that there are 7.8 ± 10.0 such background events in the sample of 1337 events. This background estimate is without any cuts in either Cherenkov counter pulse height or invariant mass. Such cuts can reduce the background even further in order to demonstrate insensitivity of our result to it.

The e^+e^- background falls into two categories: $\gamma + Z \to e^+ + e^- + Z$ (external conversions), and $K^0 \to \pi^0 + \pi^0$ followed by $\pi^0 \to \gamma + e^+ + e^-$ (Dalitz pairs). In either case, the expected invariant-mass distribution of the electrons peaks at very low mass. The invariant-mass distribution of our πe sample under the hypothesis that both charged particles are electrons shows no evidence of a low-mass peak. We require $M_{e^+e^-} > 30$ MeV and estimate from the data that there are fewer than 0.3 external conversions in our final sample. Using the known K^0 momentum and angular distributions, we have calculated from our Monte Carlo program that after applying our measured shower rejection, and with the 30 MeV cut, the total number of Dalitz events is <12. To check sensitivity of the experimental result, this background may be cut further by a factor of 4.8 by moving the cut on $M_{e^+e^-}$ to 60 MeV. Dalitz decays from $\Lambda^0 \to n\pi^0$ are lower by more than a factor of 10.

The $\Lambda^0 \to p + e^- + \bar{\nu}$ decay would appear in our sample as π^+e^- combination. We estimate that there were 16 ± 8 such Λ^0 decays in our uncut sample. To rid outselves of this background we require that $M_{pe} > 1115$ MeV; this is the maximum mass possible.

We estimate, using bubble-chamber data,[5] that the total cross section for $\bar{K}^0$ production is less than 10% of the K^0 production at our beam energy. The momentum distribution of these $\bar{K}_0$ will peak somewhat lower than the K^0, and their angular distribution will be less peripheral. We calculate that the relative acceptance of $\bar{K}^0$ to K^0 into our apparatus is less than $\frac{1}{10}$. We find, therefore, that less than 1% of our K_{e3} data come from pion production of $\bar{K}^0$. Similarly, from measurement of beam K^- and from K^-p charge-exchange data, we estimate less than 0.5% $\bar{K}^0$ from this source. These numbers are in agreement with the number of $\bar{K}^0$ estimated from the data.

In summary, we have applied the following additional cuts to the data: (1) at least one spark-chamber plate gap visible upstream of the decay: (2) $M_{ee} > 30$ MeV; (3) $M_{pe} > 1115$ MeV. The total number of events after these cuts was 1137, with an estimated contamination of less than about 20 events.

The best value for the $\Delta S/\Delta Q$ violation parameter X was determined in a maximum-likelihood program. When calculating the proper time of decay for an individual event it was assumed that each event had the mean momentum ($\simeq 2.3$ GeV/c) for accepted K_{e3} events, as determined by the Monte Carlo calculation. The standard deviation for the momentum distribution of accepted K_{e3} was 0.38 GeV/c. In addition, the production point was taken at the center of the appropriate target. We have fitted the data with corrections for the finite widths of the production point distribution and the momentum distribution. Without these corrections, $|X|$ would change by less than 0.01. We have calculated the effect of higher moments, and they are negligible.

In making our fits, we assume the following numbers from the literature[6]: $\tau_S = 0.862 \times 10^{-10}$ sec, $\tau_L = 53.8 \times 10^{-9}$ sec, and $\Delta m \tau_S = 0.469$. Our best result is $\mathrm{Re}X = -0.069 \pm 0.036$, $\mathrm{Im}X = +0.108^{+0.092}_{-0.074}$, on 1079 events inside our fiducial volume. Figures 2(b) and 2(c) show the position distributions of our data together with predictions for various values of X. We have investigated the stability of our result with respect to changes in our fiducial volume and find no significant trends when the fiducial volume is further restricted.

We have allowed the mass difference Δm to vary as a free parameter. We obtained $\mathrm{Re}X = -0.081^{+0.034}_{-0.036}$, $\mathrm{Im}X = +0.101^{+0.094}_{-0.088}$, $\Delta m \tau = 0.424^{+0.052}_{-0.048}$. The last is in good agreement with the accepted value.

As an independent check that produced $\bar{K}^0$'s were not significant, we allowed the fraction of $\bar{K}^0$ at $t=0$ to vary as a free parameter. We obtained $\mathrm{Re}X = -0.056^{+0.036}_{-0.038}$, $\mathrm{Im}X = +0.116^{+.082}_{-.080}$, $\bar{K}^0$ fraction $= +0.006^{+0.019}_{-0.006}$, in agreement with the estimated fraction. This result is independent of the mean $\bar{K}^0$ momentum.

To determine our sensitivity to other assumptions, we changed the assumed mean momentum by ±50 MeV/c, corresponding to more than one standard deviation on the mean momentum as calculated from the Monte Carlo calculation, and changed the assumed target center by 0.20 in. In neither case were we able to get a change of more than 0.015 in either ReX or ImX.

A number of additional fits have been made in an attempt to demonstrate the presence of background or some systematic position bias brought about by the apparatus. In particular, the data give consistent results if we analyze the sum only (independent of charge), and asymmetry only (independent of efficiency). When we reduce the $K\to\pi\pi$, $\Lambda\to p\pi$ background by 3.0 or reduce the Dalitz pair background by 4.8, the result does not change significantly. We divided the data into the following divisions and fitted each separately: magnetic field up, down; Cherenkov pulse height greater than or less than the mean pulse height; first target data, second target data; positive electrons only, negative electrons only. In none of these cases did we get a statistical inconsistency between divisions.

Sensitivity of the result to the efficiency function has been investigated by varying the parameters of the distribution in kaon momentum and angle input to the Monte Carlo program. The parameters were varied within the statistical limits of the $K^0\to\pi^++\pi^-$ calibration data. Also the $K^0\to\pi^++\pi^-$ data from a single target was used to generate the input distribution to the Monte Carlo program. The largest change in X we could effect was 0.005 in ReX, 0.024 in ImX.

In conclusion, this experiment finds as a best result

$$\mathrm{Re}X=-0.069\pm0.036,$$

$$\mathrm{Im}X=+0.108^{+0.092}_{-0.074}.$$

Figure 3 shows the contours corresponding to 1, 2, 3, and 4 standard deviations. The relative probability that $X=0$ is correct is $P(0)=e^{-1.38}=0.25$. We conclude that these data are consistent with $X=0$.

The figure also shows the prior world average for comparison. This number is more than 4 standard deviations from our best value. The relative probability that $X=0.14-0.13i$ is correct is less than $e^{-16/2}=3.3\times10^{-4}$. We conclude that our data are inconsistent with the world average.

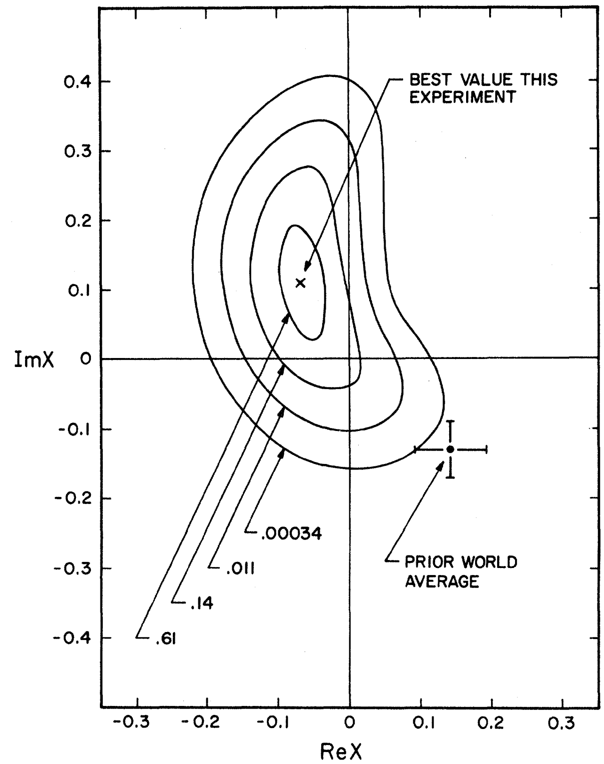

FIG. 3. The best value for X from this experiment. Also shown are the contours corresponding to the 1-, 2-, 3-, and 4-standard-deviation limits. The previous world average is shown for comparison.

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‡On leave from Imperial College, London, England.

§Present address: Department of Physics, University of Illinois, Urbana, Ill.

‖Present address: Department of Physics, Hope College, Holland, Mich.

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Compton Scattering from Hydrogen Between 5 and 17 GeV†

R. L. Anderson, D. Gustavson, J. Johnson, I. Overman, D. Ritson, and B. H. Wiik
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

R. Talman
Cornell University, Ithaca, New York 14850

and

J. K. Walker
National Accelerator Laboratory, Batavia, Illinois 60510

and

D. Worcester
Harvard University, Cambridge, Massachusetts 02138
(Received 7 August 1970)

Measurements have been made on Compton scattering for photon energies between 5 and 17 GeV and t values from -0.06 to -1.1 $(\mathrm{GeV}/c)^2$. The data were obtained by performing a coincidence between the Stanford Linear Accelerator Center 1.6-GeV/c spectrometer and a Lucite shower counter. The scattering appears diffractive out to high t values, but the cross sections seem not to be in good agreement with the prediction of a strict vector-meson-dominance model.

Compton scattering is interesting as one of the basic reactions involving photons and protons. It is expected to be predominantly diffractive at low t values but possibly to become nondiffractive at larger momentum transfers. Previous to this experiment, data were available only up to incident photon energies of 1.5 GeV.[1] We report here our measurement of the differential cross sections for incident photon energies between 5 and 17 GeV and for squares of four-momentum transfer between -0.06 and -1.1 $(\mathrm{GeV}/c)^2$.

The results of this experiment are particularly useful within the context of the vector meson dominance model (VMDM).[2] In this model the Compton cross section is directly related to the known cross sections[3] for photoproduction of vector mesons. Knowledge of the Compton cross section at high energies therefore makes possible a direct test of the model.

A comparison between the total photoabsorption cross section σ_T and the forward Compton cross section at $t=0$ is also important. Such a comparison serves as a check on the forward dispersion relations.[4] These relations have been well established in elastic πN scattering. However, in the case of photons additional terms,[5] which are absent in πN scattering, may be added to the real part of the diffractive amplitude. The limits[6] on such terms previous to this experiment were rather poor.

The layout of the experiment is shown in Fig. 1. A well-collimated photon beam passed through a