TEST OF THE $\Delta S = \Delta Q$ RULE IN LEPTONIC DECAY OF NEUTRAL K MESONS*

D. G. Hill, D. Lüers, D. K. Robinson,† M. Sakitt, and O. Skjeggestad
Brookhaven National Laboratory, Upton New York

and

J. Canter, Y. Cho, A. Dralle, A. Engler, H. E. Fisk, R. W. Kraemer, and C. M. Meltzer
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 15 June 1967)

The time distribution of 335 leptonic decays of K^0's produced by $K^+ + d \to K^0 + p + p$ has been analyzed. The likelihood estimate for $xe^{i\varphi}$, the ratio between the $\Delta S = \Delta Q$ violating and nonviolating amplitudes, yields $x = 0.26_{-0.11}^{+0.08}$ and a phase $\varphi = 50° {}_{-27°}^{+25°}$.

In recent years, a number of experiments[1-6] have been performed which test the validity of the $\Delta S = \Delta Q$ rule in the leptonic decay of neutral K mesons. Several of these experiments were suggestive of a violation of the rule but were limited by low statistics or uncertain systematic effects. In view of the possibility of CP nonconservation, a more careful study seemed necessary. In the experiment reported in this Letter, we examine the time distribution of 335 leptonic decays of the neutral K.

The leptonic decays analyzed here were obtained from two exposures of the 30-in. Brookhaven National Laboratory bubble chamber, filled with deuterium, to a 600-MeV/c K^+ beam at the alternating-gradient synchrotron. The first exposure of approximately 250 000 pictures had an average flux of 13 K^+ per picture and an equal number of background tracks; the second exposure of 100 000 pictures had a flux of 25 K^+ per picture and less than 10% background tracks. These exposures represent approximately $\frac{1}{2}$ of the total experiment. The neutral K mesons were produced in the reaction

$$K^+ + d \to K^0 + p + p. \quad (1)$$

The pictures were scanned for V's and production vertices. All events were required to be within a suitably chosen fiducial volume. The bulk of the pictures were scanned twice, giving an over-all efficiency of 98% For all V's, the following criteria were imposed: (a) The dip angles of both the neutral and charged tracks were less than 70°, and (b) the distance of a V from the production origin was greater than 3 mm. Monte Carlo calculations show a 7% loss of leptonic events and a 9% loss of two-body events due to the dip-angle cut for charged tracks.

All V candidates were fitted to the decay mode $K_S \to \pi^+\pi^-$ (two body) under the hypotheses that (a) the V was not associated with any production origin (one-constraint fit), and (b) the V was associated with all likely production origins (three-constraint fit). The χ^2 distributions for both the one- and three-constraint two-body fits are in excellent agreement with those expected. Events for which the χ^2 probability was greater than 0.01% for either fit were classified as two-body decays. We expect 7% of the leptonic events to satisfy this two-body criterion. For events which did not fit the two-body hypothesis, fits were tried with all possible productions, under the assumptions that the V's were the three-body decays $\pi e \nu$, $\pi \mu \nu$, $\pi\pi\gamma$, and $\pi^+\pi^-\pi^0$. If the spectator proton is invisible (about one-half the events), the over-all fit for these three-body events is still overdetermined (one constraint). The association of the K^0 decay and a production origin was unique for all events, and the fitted K^0 momentum was known to better than 15%. The decays $K^0 \to \pi^+\pi^-\pi^0$ were kinematically unique and will be treated in a separate communication. In addition to kinematic fitting, all three-body candidates were checked by a physicist for ionization consistency. The charge of the lepton was determined for 44% of the sample; the remaining 56% were ambiguous among $\pi^+ l^- \bar{\nu}$, $\pi^- l^+$, and $\pi^+\pi^-\gamma$. Since the decay rate $K_L{}^0 \to \pi^+\pi^-\gamma$ has been shown to be small,[7] we assume the decay into $\pi^+\pi^-\gamma$ is only due to internal bremsstrahlung of the K_S and we correct the ambiguous events.[8] The test of $\Delta S = \Delta Q$ is dominated by the information obtained from the events for which the charge of the lepton is known, so that our result is insensitive to this correction. In order to eliminate Dalitz pairs with nonzero opening angles from $K_S \to \pi^0 + \pi^0$, we calculated the effective mass of the V assuming both tracks were electrons. Events for which the effective mass was less than 85 MeV were rejected, thus reducing the expected Dalitz pair contamination[9] to less than one event and causing a loss of less than 2% of the total leptonic sample.

It should be noted that the losses due to these cuts are independent of time and the charge of the lepton and thus cannot effect the test of $\Delta S = \Delta Q$. The corrections from the Monte Carlo calculation are used only in estimating the total leptonic rate.

After imposing these cuts, we obtain 335 leptonic decays with decay times less than $12\tau_S$ [$\tau_S = \tau(K_S)$]. The sign of the lepton is known for 143 of these events. The time distributions of the events are shown in Fig. 1. Since we produced the neutral K by K^+ charge exchange at time $t=0$, we have a pure K^0 state which after several K_S lifetimes evolves into an equal mixture of K^0 and $\bar{K}^0$. At short times, positive leptons arise mainly from the $\Delta S = \Delta Q$ amplitude f for $K^0 \to \pi^- + l^+ + \nu$, while negative leptons would arise mainly from the $\Delta S = -\Delta Q$ amplitude g for $K^0 \to \pi^+ + l^- + \nu$. The time distribution of the leptons as a function of x and φ, where $xe^{i\varphi} = g^*/f$, is given by

$$N^{\pm}(t) = \tfrac{1}{4}|f|^2[(1+x^2+2x\cos\varphi)\exp(-\lambda_S t) + (1+x^2-2x\cos\varphi)\exp(-\lambda_L t) \pm 2\cos\delta t(1-x^2)e^{-\Lambda t} + 4x\sin\delta t\sin\varphi e^{-\Lambda t}], \quad (2)$$

where the ± refers to the charge of the lepton, $\delta = M(K_S) - M(K_L)$, and $\Lambda = \frac{1}{2}(\lambda_S + \lambda_L)$, where λ_S and λ_L are the K_S and K_L decay rates.[10] If $x=0$, $\Delta S = \Delta Q$ is implied. It should be noted that the nonconserving amplitude g produces a change of $\frac{3}{2}$ in the z component of isospin and therefore also violates the $\Delta T = \frac{1}{2}$ rule. If $\Delta S = -\Delta Q$ amplitudes exist, then CP conservation implies that g^*/f must be real or, equivalently, that φ must equal 0 or π.

In Fig. 1 we have superimposed on the data the expected distributions calculated from Eq. (2) and corrected for the geometric detection

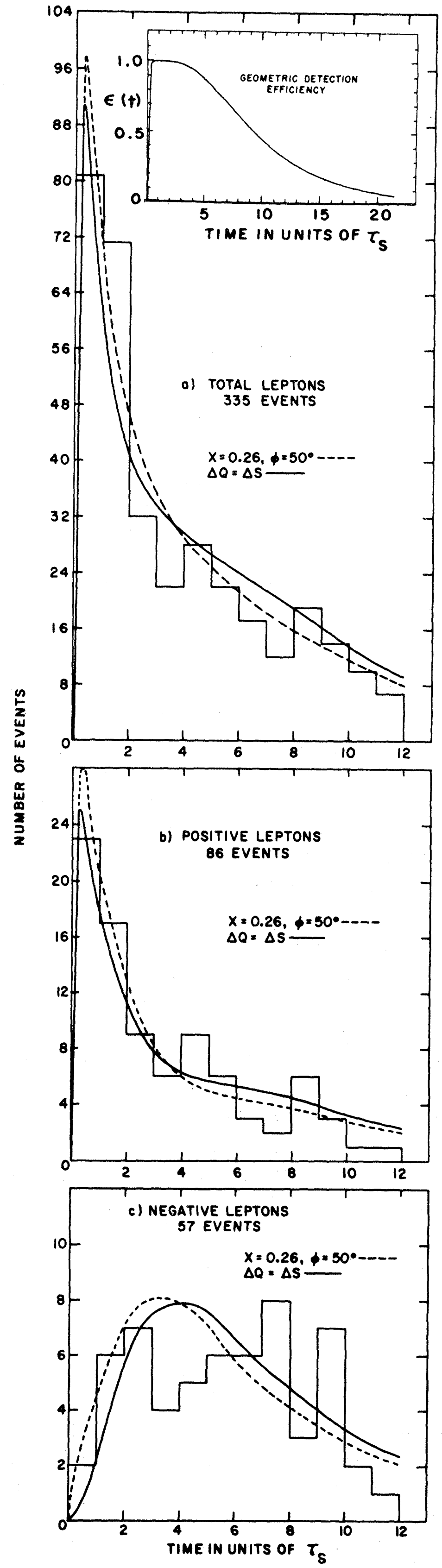

FIG. 1. Time distributions for the leptonic events. The solid curves are the expected ditributions for $\Delta S = \Delta Q$ and the dotted curves are for our best estimates of x and φ. The insert is the geometric detection efficiency.

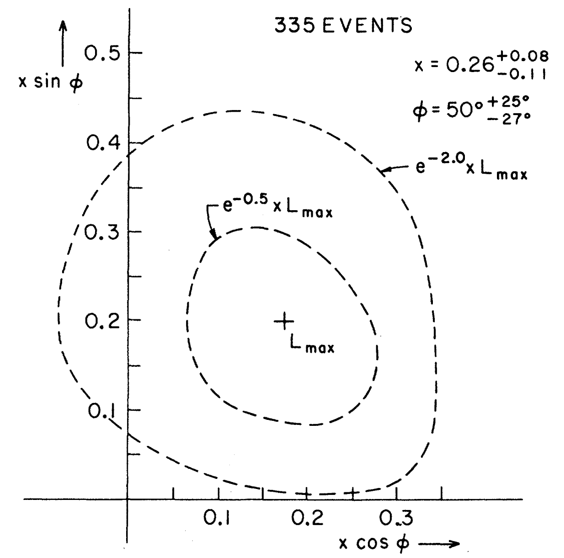

FIG. 2. Likelihood contour plot with contours for 1 and 2 standard deviations drawn as dotted curves.

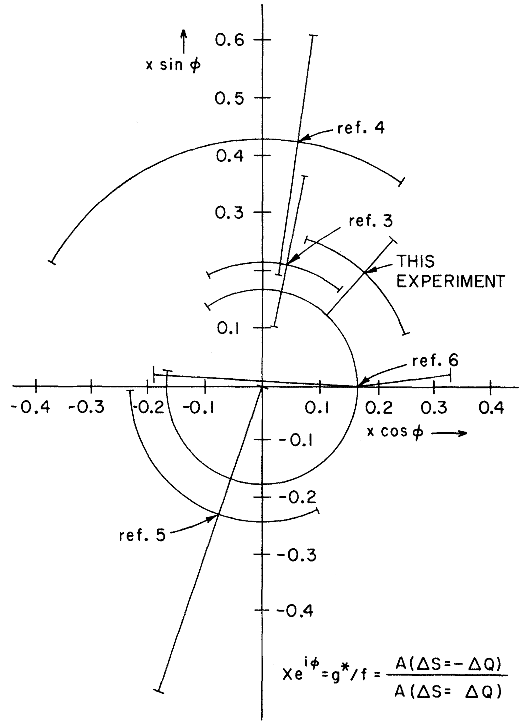

FIG. 3. Summary of our previous results. Errors are displayed in x and φ.

efficiency; the solid curves are for $\Delta S=\Delta Q$, while the dotted curves are based on our likelihood estimates of x and φ. The geometric detection efficiency for this experiment, obtained from a sample of 5000 two-body events, is shown in the insert of Fig. 1(a). The expected distributions for the total number of events includes a correction for the $K_S\rightarrow\pi\pi\gamma$ contribution.[8]

We have used the maximum-likelihood method to estimate the real and imaginary parts of g^*/f; i.e., $x\cos\varphi$ and $x\sin\varphi$, respectively. For each event we calculate the normalized a priori probability based on Eq. (2). We calculate three likelihood functions, L^+, L^-, and $L^{\rm sum}$, where $L^{\rm sum}$ refers to events for which the sign of the lepton is unknown. Figure 2 shows the contour plot for the joint likelihood (the product of L^+, L^-, and $L^{\rm sum}$) as a function of the variables $x\cos\varphi$ and $x\sin\varphi$. The maximum-likelihood estimates are

$$x=0.26^{+0.08}_{-0.11},\quad \varphi=50°{}^{+25°}_{-27°},$$

or

$$x\cos\varphi=0.17\pm0.10,\quad x\sin\varphi=0.20\pm0.10.$$

This result is insensitive to the value of δ, the mass difference. In Fig. 3 our results and previous results[3-5] are shown. While this experiment is consistent with the $\Delta S=\Delta Q$ rule, it does suggest a small violation[11] at the two-standard-deviation level.[12,13]

We have also computed $\Gamma_L(K_L\rightarrow\pi l\nu)$ assuming $\Delta S=\Delta Q$ and find that $\Gamma_L=(12.4\pm0.90)\times10^6$ sec^{-1}; assuming our best estimates for x and φ, we find that $\Gamma_L=(10.3\pm0.80)\times10^6$ sec^{-1}. We would expect $\Gamma_L=(12.32\pm0.66)\times10^6$ sec^{-1} assuming the $\Delta T=\frac{1}{2}$ rule and using data[14] on K^+ decays.

We are indebted to Professor L. Wolfenstein for valuable discussions. We would like to thank Dr. N. P. Samios for his very generous support. We thank Dr. T. Bacon and Dr. H. Hopkins for assisting us during the early phases of the experiment.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†Present address: Case Western Reserve University, Cleveland, Ohio.

[1]R. P. Ely, W. M. Powell, H. White, M. Baldo-Ceolin, E. Calimani, S. Ciampolillo, O. Fabbri, F. Farini, C. Filippi, H. Huzita, G. Miara, U. Camerini, W. F. Fry, and S. Natali, Phys. Rev. Letters 8, 132 (1962).

[2]G. Alexander, S. P. Almeida, and F. S. Crawford, Jr., Phys. Rev. Letters 9, 69 (1962).

[3]B. Aubert, L. Behr, F. L. Canavan, L. M. Chounet, J. P. Lowys, P. Mittner, and C. Pascaud, Phys. Let-

ters 17, 59 (1965).

[4]M. Baldo-Ceolin, E. Calimani, S. Ciampolillo, G. Filippi-Filosofo, H. Huzita, F. Mattioli, and G. Miari, Nuovo Cimento 38, 684 (1965).

[5]P. Franzini, L. Kirsch, P. Schimdt, J. Steinberger, and R. J. Plano, Phys. Rev. 140, B127 (1965).

[6]L. Feldman, S. Frankel, V. L. Highland, T. Sloan, O. B. Van Dyck, W. D. Wales, R. Winston, and D. M. Wolfe, Phys. Rev. 155, 1611 (1967).

[7]B. M. K. Nefkens, A. Abashian, R. J. Abrams, D. W. Carpenter, G. P. Fischer, and J. H. Smith, Phys. Letters 19, 706 (1966).

[8]Our correction uses the theoretical estimate for the $\pi^+\pi^-\gamma$ rate calculated by M. Bég, R. Friedberg, and J. Schultz as quoted in Ref. 5. Events which fit $\pi^+\pi^-\gamma$ with a γ momentum, in the K^0 rest frame, of less than 50 MeV/c have been removed from the sample. This cut results in a 2% loss of leptonic decays.

[9]N. P. Samios, Phys. Rev. 121, 275 (1961).

[10]We use $\delta = -0.58\hbar/c^2\tau_S$, $\lambda_S = 1.18\times10^{10}$ sec^{-1}, and $\lambda_L = 1.85\times10^7$sec^{-1}.

[11]Experiments are in progress to measure the charge asymmetry in $K_L \rightarrow \pi e \nu$ (J. Steinberger et al. at Brookhaven National Laboratory) and in $K_L \rightarrow \pi\mu\nu$ (M. Schwartz et al. at Stanford Linear Accelerator Center) in order to resolve the ambiguity in the Wu-Yang description of the neutral K system. One solution predicts an asymmetry which would be observed in these experiments, while the other does not, but the effects could, in principle, be suppressed by $\Delta S = -\Delta Q$ amplitudes. Our experiment rules out a suppression from these amplitudes of more than 10 to 20%.

[12]If we ignore the charge of the lepton in the likelihood fit, we still obtain a two–standard-deviation violation. A χ^2 test to the total lepton time distribution yields for no violation $P(\chi^2) = 1.5\%$ and for best estimates $P(\chi^2) = 34\%$. This also corresponds to a two standard effect.

[13]In a Monte Carlo study of experiments, in which 86 positive leptons and 57 negative leptons were generated with $x = \varphi = 0$, only 6% of the experiments resulted in a violation more significant statistically than our experiment.

[14]G. H. Trilling, Argonne National Laboratory Report No. ANL 7130, 1965 (unpublished), p. 115.

RECOIL-PROTON POLARIZATION IN π^0 PHOTOPRODUCTION*

E. D. Bloom,† C. A. Heusch, C. Y. Prescott, and L. S. Rochester
California Institute of Technology, Pasadena, California
(Received 24 July 1967)

In this Letter, we wish to communicate the results of an investigation into the energy dependence of the polarization of the final-state proton in neutral pion photoproduction. The energy region covered extends from 750 to 1450 MeV/c incoming photon momentum, at π^0 c.m. angles around 60°.

The results of this experiment indicate a zero crossing of the 60° polarization in the energy region covered, and a very strong angular dependence. We have attempted to incorporate this information into a unified picture of π^0 photoproduction, making use of all the presently available experimental information.[1]

In the absence of polarization data from π^0 photoproduction above ~900 MeV and outside the 90° region, we choose c.m. angles around 60° for the higher energies. This was done because, in a simple isobar model incorporating a possible elementary vector meson exchange,[2] it promised to yield the most significant information short of a fuller angular distribution (which was excluded by limitations on running and subsequent scanning time); and because our experimental method was best applicable in this region.

In order to obtain a pure sample of protons from π^0 photoproduction, we detected the recoiling proton and both decay photons of the π^0. This procedure sufficiently overdetermines the kinematics so as to give us an event sample which is clean to better than 98%; also, it allows us to determine, within the resolution of our apparatus, the inelasticity of the analyzing scatter of the recoil proton.

The experimental procedure employed is the following: A bremsstrahlung beam from the 1.5-BeV California Institute of Technology electron synchrotron impinged on a liquid-hydrogen target. The recoil proton passed through three scintillation counters and two thin-foil spark chambers; it subsequently entered a modular spark chamber built out of modules of carbon plates of varying thickness and two-gap sparking units, which served as both a range and scattering chamber. The dimensions were chosen such that all protons are stopped in the chamber, whether they undergo a scatter off a carbon nucleus or not. Carbon was chosen as a scatterer, because its analyzing power has been extensively studied over the energy region of interest to us (80 MeV $\leq T_p$