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Test of the quantum-theoretical behavior of the K^0-$\bar{K}^0$ system

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The magnitude of the K_S-K_L interference term in the $\pi^+\pi^-$ decay mode of regenerated K^0's has been studied. The data at each momentum are consistent with the general expectations of quantum theory and with the conventional phenomenology of CP violation. The ratio of the measured amplitude of the interference to its predicted value is $k = 0.95 \pm 0.034$ using our data alone. When additional data from other experiments are used, $k = 0.97 \pm 0.02$.

In conventional formulations of the quantum theory, a system in an initially pure state will remain in a pure state if totally isolated from external perturbations. Although tests of this and other fundamental aspects of conventional quantum theory (CQT) have exhibited no contradictory evidence, these tests have mostly been confined to the domain of atomic physics[1] and very few at higher energies.[2] It is of interest, therefore, to examine those processes in high-energy physics and in weak interactions which could provide a test of the CQT framework.

There are different ways in which CQT could be extended.[3-7] For example, according to CQT, the magnitude of the interference term of $K_{S,L}$ decay into $\pi^+\pi^-$ after regeneration of pure K_L^0 particles should be characteristic of a pure state. A dilution of the interference would indicate either a violation of CQT in the regeneration process due to strong interactions, or in the decay due to weak interactions,[3,5,6] or the necessity to consider the long-lived K^0's as a mixed state.[8] This article describes a study of the $K_{S,L} \to \pi^+\pi^-$ decay in which the data have been analyzed to search for just such a dilution.

After correction for the over-all detection efficiency of the apparatus and data analysis, $\epsilon(\tau, p)$, the intensity $I(\tau, p)$ of the $K_{S,L} \to \pi^+\pi^-$ decays in the beam direction (transmission regeneration) for an initially pure K_L beam incident on a regenerator can be written as

$$I(\tau,p)=\frac{N(\tau,p)}{\epsilon(\tau,p)}=S(p)\left[Ae^{-\Gamma_S\tau}+Be^{-\Gamma_L\tau}+2k\sqrt{AB}\,e^{-(\Gamma_S+\Gamma_L)\tau/2}\cos(\Delta m\tau+\phi)\right]. \tag{1}$$

Here τ is the proper time measured from the exit face of the regenerator, p is the K^0 momentum, $N(\tau, p)$ is the number of K^0 decays observed per unit of p and of τ, $S(p)$ is the momentum spectrum, Γ_S (Γ_L) is the total K_S (K_L) decay rate, and Δm is the K_L-K_S mass difference. A and B are proportional to the product of the square of the amplitudes of K_S and K_L and their decay rates into $\pi^+\pi^-$. The angle ϕ is the phase difference between the two K_S and K_L decay amplitudes.

The prediction of CQT is that $k=1$. Therefore, the parameter k measures the ratio of the observed interference term to that expected from CQT.[9] Measurements of the parameter k have

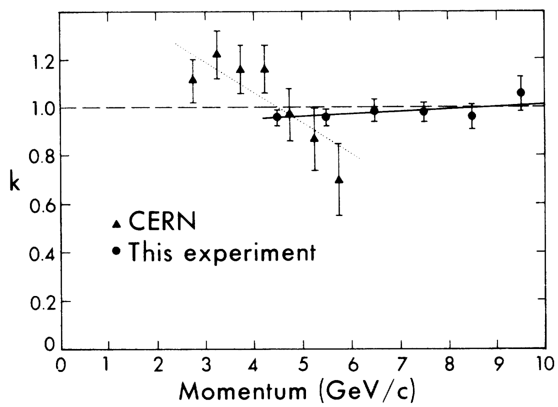

FIG. 1. The parameter k as a function of K^0 momentum. Triangles are results from Ref. 12 and the dotted line is the best fit of these data to a straight line. Dots are results from this experiment, and the solid line is the corresponding best fit to a straight line.

been reported.[10-12] For Ref. 11, $k = 1.20 \pm 0.14$, compatible with 1. In Ref. 12, measured values of k are reported as a function of K^0 momentum, and these values are shown in Fig. 1. Taking their indicated errors at face value and ignoring possible correlations between the different momenta, the χ^2 for the hypothesis $k = 1$ is 16.5 for 7 degrees of freedom, whereas, if a linear dependence of k as a function of momentum is assumed (dotted line in Fig. 1), the χ^2 is 4.9 for 5 degrees of freedom. The difference of 11.6 in χ^2 for two additional degrees of freedom (confidence level of about 0.5%) shows either that other errors have to be added to the errors shown in Ref. 12 or that a momentum-dependent violation of CQT is indicated by their data.

In the present experiment, a pure K_L^0 beam impinged on a carbon regenerator. Results for ϕ from the same data have been previously reported.[13]

The events between 4 and 10 GeV/c were binned in 1-GeV/c-momentum intervals and 0.05×10^{-9} second proper-time intervals. The efficiency $\epsilon(\tau, p)$ was evaluated by a Monte Carlo technique. Using a minimum-χ^2 technique, fits of the data were made to Eq. (1) allowing Γ_S, Δm, and, for each momentum interval, a different set of parameters A, B, and ϕ to vary. Γ_L was fixed at the value 1.931×10^7 sec^{-1} as given by Ref. 14, but our results were quite insensitive to the value of Γ_L used. We present here several fits to the data. In the first fit, k was constrained to be 1 as expected from CQT. In the second fit, k was allowed to vary but was constrained to be the same at all momenta. The results of both fits are given in the first two columns of Table I. The difference in χ^2 is sufficiently small that the conclusion can be drawn that this test, using only our data, is consistent with CQT, yielding for k the value 0.947 $\pm$ 0.034.

However, owing to the correlations between k, Γ_S, and Δm, the determination of k can be improved by better knowledge of Γ_S and Δm. Accordingly, we present a third fit using two additional data points corresponding to the values of Γ_S and Δm and their errors as given by the Particle Data Group compilation.[14] The result of this fit, shown in column 3 of Table I, is also consistent with CQT, with a slightly reduced error for k.

In the compilation of Ref. 14, the error given for Γ_S is larger than some of the input data. This is due to substantial inconsistencies between recent measurements and two older determinations, both using the same technique.[15] In the fourth fit, we have chosen to reject the older results and have selected experiments[16-19] that measured Γ_S or Δm with high accuracy and that were not vulnerable to uncertain corrections due to the recent controversy on the magnitude of the CP-violation parameter η_{+-}. With our data and these values as additional data points, the fourth fit gave the results shown in column 4 of Table I. The value of k obtained with this less conservative viewpoint is

TABLE I. Results of the fits.

Constraint of $k=1$ other experimental data used	Used none	Not used none	Not used Ref. 14	Not used Refs. 16–19
k	1	0.947 ± 0.034	0.988 ± 0.030	0.972 ± 0.021
χ^2	101.0	98.8	103.5	106.4
Number of degrees of freedom	126	125	127	129
Change of χ^2 when unitarity constraint is relaxed	...	2.2[a]	0.2[a]	1.7[a]

[a] This is the difference in χ^2 between fits made with and without the constraint $k=1$, for a difference of 1 between the degrees of freedom. Column 2 is to be compared with column 1, while columns 3 and 4 are compared to fits with $k=1$ (not shown here).

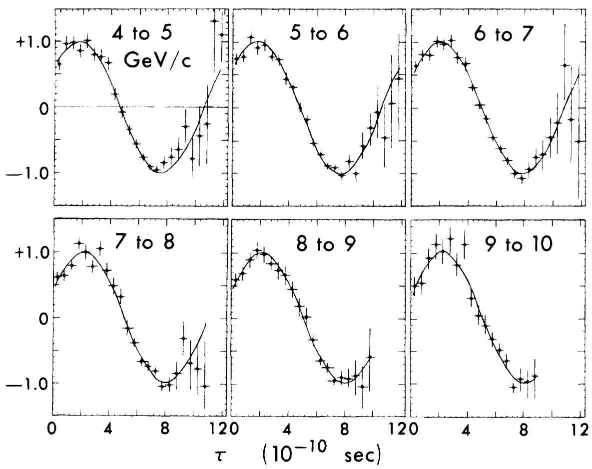

FIG. 2. The extracted interference term for each 1-GeV/c-momentum interval from 4–10 GeV/c. The fit of Eq. (1) to the data assumed $k=1$. The interference term was isolated by subtracting the first two (noninterference) terms from the efficiency-corrected data, and then dividing by the multiplicative factor of the cosine (interference) term, $2\sqrt{AB}\,e^{-(\Gamma_S+\Gamma_L)\tau/2}$.

0.97 ± 0.02, also in good agreement with the expectations of CQT. In our judgment, the reliability of the input data used in the fourth fit is sufficiently high that we prefer to quote this value of k as our best result.

Other fits of the data were performed, still using the results from Refs. 16–19 as additional data points. If k is constrained to be 1, the χ^2 is 108.1; if k is allowed to have a linear dependence as a function of momentum (two degrees of freedom for k), the χ^2 is 105.5 and the best fit is represented by the solid line in Fig. 1; if k is allowed to take a different value at each momentum (6 degrees of freedom for k), the χ^2 is 104.2 and the values of k are represented by the dots in Fig. 1. The differences in χ^2, 2.6 for two degrees of freedom and 3.9 for 6 degrees of freedom, show that our data are compatible with the CQT prediction $k=1$. To further illustrate the quality of the fits with $k=1$, an interference term was extracted from the data and is shown in Fig. 2, along with the corresponding fitted values, for each momentum interval.

In conclusion, the amplitude of the interference is found to be consistent with CQT; it is measured to be equal to 0.97 ± 0.02 when averaged over all momenta. These results limit the possible extensions of quantum theory.[5,6] The conjectures[8,20] proposed to explain the long-life $\pi^+\pi^-$ decay mode of the K^0 meson without CP violation require a large reduction of the interference term. Our result reinforces the result of Refs. 11 and 12 that already ruled out such hypotheses.

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