A TEST OF CPT SYMMETRY IN THE NEUTRAL KAON SYSTEM

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ABSTRACT

The E731 collaboration has measured the phase difference $\Delta\phi \equiv \phi_{00} - \phi_{+-}$ between the two CP violating parameters η_{00} and η_{+-}. We find $\Delta\phi = -0.3° \pm 2.4°(\text{stat}) \pm 1.2°(\text{syst})$. Using this result together with the world average ϕ_{+-}, we find that the phase of the K^0-$\overline{K^0}$ mixing parameter ϵ is $44.5° \pm 1.5°$. Both of these results agree well with the predictions of CPT symmetry.

INTRODUCTION

CPT symmetry is expected to be exact in local quantum field theories (CPT theorem[1]), and as a consequence the masses and lifetimes of particle-antiparticle pairs should be equal. Direct measurements of mass and lifetime differences ($\delta M/M$ and $\delta\Gamma/\Gamma$) have achieved sensitivity at the 10^{-7} level.[2] Since the mass difference between K^0 and $\overline{K^0}$ is limited by the difference (Δm) between K_L and K_S, and with $\Delta m/m_K = 7 \times 10^{-15}$, the neutral kaons are expected to provide a strong limit on CPT violation. Reviews of the neutral kaon system together with the CP and CPT phenomenology can be found in the literature.[3,4] Here, a very brief outline will be given in order to introduce the predictions of CPT symmetry that can be tested experimentally.

Because the strong interaction conserves strangeness (S), the K^0 ($S = +1$) and $\overline{K^0}$ ($S = -1$) are the neutral kaon eigenstates during production. The kaons decay thanks to the weak interaction which allows $\Delta S = \pm 1$ transitions. They also mix with each other through intermediate states with $S = 0$ (*e.g.*, 2π and 3π). Taking into account the small ($\epsilon \simeq 2 \times 10^{-3}$) CP violation in the K^0-$\overline{K^0}$ mixing, the vacuum eigenstates are $K_{S,L} = [(1+\epsilon)K^0 \pm (1-\epsilon)\overline{K^0}]/\sqrt{2(1+\epsilon^2)}$, where the plus sign is for K_S and the minus sign for K_L. The parameter ϵ introduces a small CP-even impurity into the long-lived state (K_L), allowing it to decay into the 2π final states. This "indirect" CP violation was first seen in 1964.[5]

The two complex parameters η_{+-} and η_{00} are defined as the ratios of K_L and K_S decay amplitudes into $\pi^+\pi^-$ and $\pi^0\pi^0$: $\eta \equiv \mathrm{amp}(K_L \to \pi\pi)/\mathrm{amp}(K_S \to \pi\pi)$. Neglecting the small ($\simeq 5\%$) violation of the $\Delta I = 1/2$ rule, we have $\eta_{+-} \equiv |\eta_{+-}|e^{i\phi_{+-}} = \epsilon + \epsilon'$ and $\eta_{00} \equiv |\eta_{00}|e^{i\phi_{00}} = \epsilon - 2\epsilon'$. Here, ϵ' parametrizes any additional CP violation arising directly from the 2π decay amplitudes (known as "direct" CP violation). By measuring the ratio of $|\eta_{+-}|$ and $|\eta_{00}|$, the quantity $\mathrm{Re}(\epsilon'/\epsilon)$ can be determined. The most recent measurement[6] finds that $\mathrm{Re}(\epsilon'/\epsilon)$ is consistent with zero, while another recent measurement[7] shows a three sigma deviation from zero. In any event, ϵ' is much smaller than ϵ.

CPT PREDICTIONS

The issue of CPT symmetry for neutral kaons is connected to the phases of ϵ and ϵ', which are related to the (measurable) phases of η_{+-} and η_{00}. The expression for ϵ is:

$$\epsilon = \frac{1}{2}\frac{\langle\overline{K^0}|H|K^0\rangle - \langle K^0|H|\overline{K^0}\rangle}{(m_L - m_S) + i(\Gamma_S - \Gamma_L)/2}$$

Here, $H = M - i\Gamma/2$ is the Hamiltonian of the K^0-$\overline{K^0}$ system, and m_L, m_S, Γ_L and Γ_S are the K_L and K_S masses and decay rates. The mass and decay matrices (M and Γ) are both hermitean, making the numerator equal to $2i\,\mathrm{Im}\,M_{12} + \mathrm{Im}\,\Gamma_{12}$. Using results from the

3π and semileptonic decay modes, one can show[4] that the contribution to ϵ from the decay matrix is very small compared to the contribution from the mass matrix. Consequently, the phase of ϵ (measured as $2\phi_{+-}/3 + \phi_{00}/3$) should be close (within a couple of degrees) to the argument of $\Gamma_S/2 + i\Delta m$. This "natural angle" is equal to $43.7 \pm 0.2°$.

Another prediction of CPT symmetry is obtained by considering the phase of ϵ'. This parameter is written as

$$\epsilon' = \frac{i}{\sqrt{2}} \frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_0} e^{i(\delta_2 - \delta_0)}$$

where A_I is the decay amplitude of K^0 into a 2π final state of isospin I with a phase shift δ_I from final state interactions. Using the experimental value[8] $\delta_2 - \delta_0 = -45 \pm 10°$ and the smallness of $\mathrm{Re}(\epsilon'/\epsilon)$, it can be seen that the difference between ϕ_{+-} and ϕ_{00} should be much less than one degree. However, the world average values[9] $\phi_{+-} = 44.6 \pm 1.2°$ and $\phi_{00} = 54 \pm 5°$ violate both CPT predictions at about two standard deviations.

EXPERIMENT

The 800 GeV protons from the Fermilab Tevatron strike a Be target, after which collimators and sweeping magnets produce two neutral kaon beams. The average kaon energy is about 70 GeV. A boron carbide (B_4C) regenerator is placed in one of the beams about 123 m downstream of the target in order to recreate a K_S component. It is in this "regenerated" beam that we measure the phases ϕ_{+-} and ϕ_{00} from the interference between $K_L \rightarrow 2\pi$ and $K_S \rightarrow 2\pi$. The other "vacuum" beam is essentially a pure K_L beam, which will serve to normalize the incident kaon flux. In order to cancel any differences in intensity and momentum spectrum between the two beams, the regenerator alternates between them once every machine cycle. (At Fermilab the beam is on for twenty seconds every minute.)

The regeneration of K_S comes about because of the difference between the K^0 and $\overline{K^0}$ cross sections in ordinary matter. An incident K_L (which is one particular linear combination of K^0 and $\overline{K^0}$) will turn into a different linear combination, thus picking up a K_S component. Only the coherently scattered kaons (in the forward direction) have the same beam profile and angular divergence as the vacuum beam. To extract this coherent signal, the incoherently scattered kaons (elastic and inelastic) are subtracted using the kaon transverse momentum or some other similar variable. By instrumenting the regenerator with scintillator and phototubes, we reject a good fraction of the inelastically scattered kaons at the trigger level.

Figure 1 shows the E731 detector which is described in detail elsewhere.[10] The two beams enter the decay volume with one of them passing through the regenerator. The end of the upstream decay volume is defined by a pair of thin scintillator planes, which are used in the $\pi^+\pi^-$ trigger together with another pair of scintillator planes located after the spectrometer.

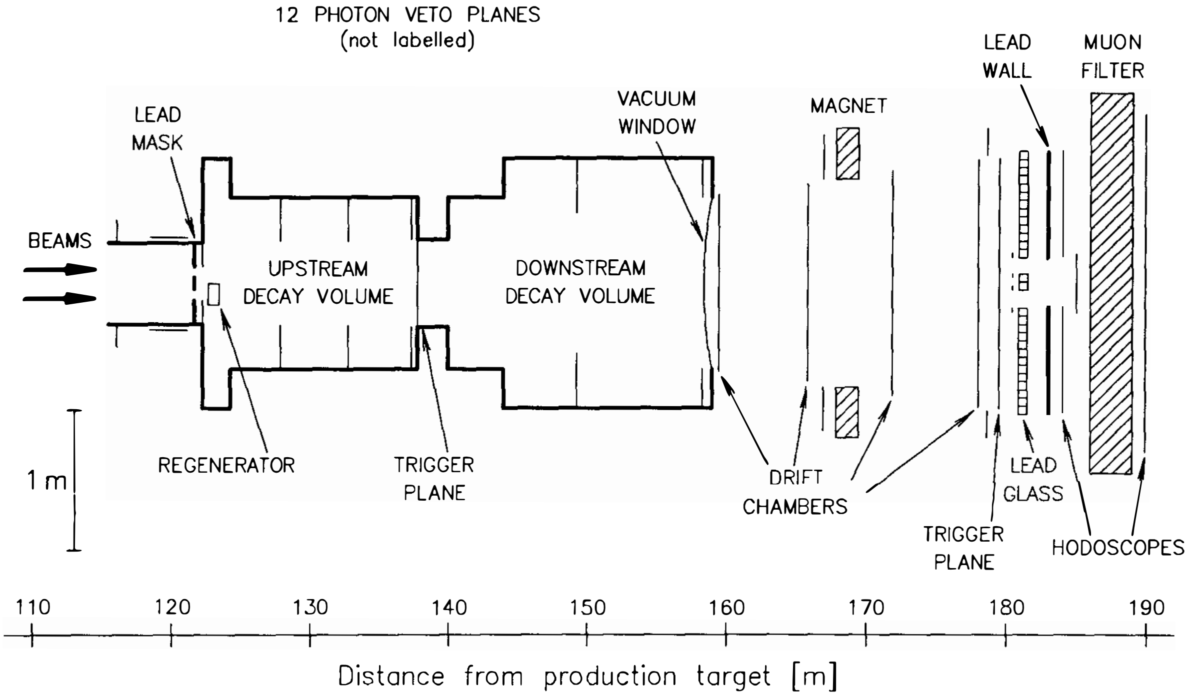

Figure 1: The E731 detector.

The two charged tracks from the $\pi^+\pi^-$ events are reconstructed using the four drift chambers and the track momenta determined by the analysis magnet. Each drift chamber has two x and two y planes with a resolution of about 110 μm per plane. The $\pi\mu\nu$ decays are rejected with the muon hodoscope behind the muon filter.

The $\pi^0\pi^0$ decays result in four photons which shower in the lead glass calorimeter with an energy resolution of $2.5\%+5\%/\sqrt{E}$ (E in GeV). There are 804 lead glass blocks stacked in a roughly circular array (with two holes for the beams), and the number of clusters is determined by a trigger processor. The trigger requires four clusters and a total energy of about 28 GeV. The main background comes from $3\pi^0$ decays where two photons escape the lead glass or merge with other photons. To suppress this background, a number of veto counters are set up to intercept photons leaving the detector. The calorimeter is followed by a hadron veto consisting of a lead wall and a scintillator hodoscope.

The data taking took place between July 1987 and February 1988, and the results presented here are based on 20% of the total sample. During this particular data set, the $\pi^+\pi^-$ and the $\pi^0\pi^0$ decays were collected simultaneously, providing for very good control of many systematic uncertainties.

ANALYSIS

The $\pi^+\pi^-$ invariant mass is calculated assuming the charged pion mass for each track. Projecting the kaon back from the decay vertex to the regenerator, the transverse momentum is determined with respect to a line from the target. The $\pi e\nu$ decays are suppressed by using the measured energy in the lead glass to calculate E/p for the tracks. Figure 2 shows the invariant mass in the regenerated beam after all other cuts. The low-side tail is due to radiative $\pi^+\pi^-\gamma$, and there is a small remaining background from $\pi e\nu$ decays. The signal region is defined as 484–512 MeV/c^2. The transverse momentum squared is plotted in Figure 3 for kaons with good mass in the regenerated beam, where the background is dominated by incoherently scattered kaons. The background is fit to a functional form with exponential terms representing the elastic and inelastic contributions. With a cut of 250 (MeV/c)^2, the background under the coherent peak is found to be 0.13%. The corresponding background in the vacuum beam (0.32%) is due to the $\pi e\nu$ decays. For kaon energies between 30 and 130 GeV and a decay vertex range of 123–137 meters from the target, there are 198,000 signal events in the regenerated beam and 41,000 in the vacuum beam.

For $\pi^0\pi^0$ events, the longitudinal position of the decay vertex and the invariant mass are calculated by assuming the π^0 mass. Figure 4 shows the invariant mass in the regenerated beam after all other cuts. The signal region is between 480 and 516 MeV/c^2. The small (0.04%) background is due to $3\pi^0$ decays and to nuclear interactions in the regenerator and

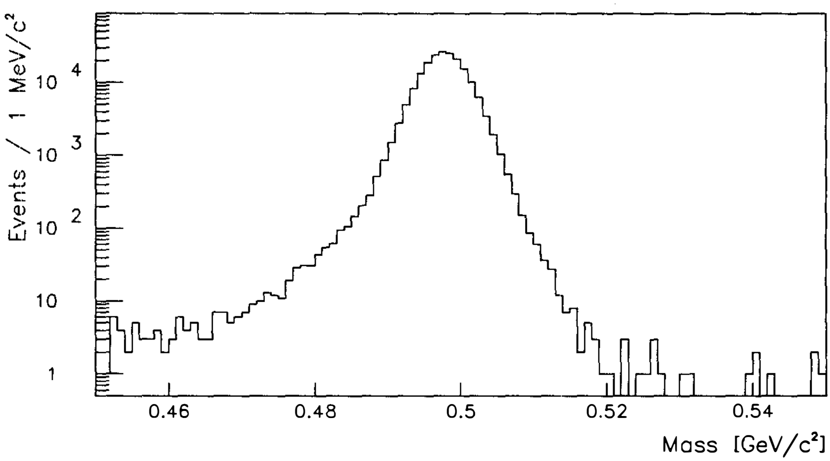

Figure 2: $\pi^+\pi^-$ invariant mass in the regenerated beam.

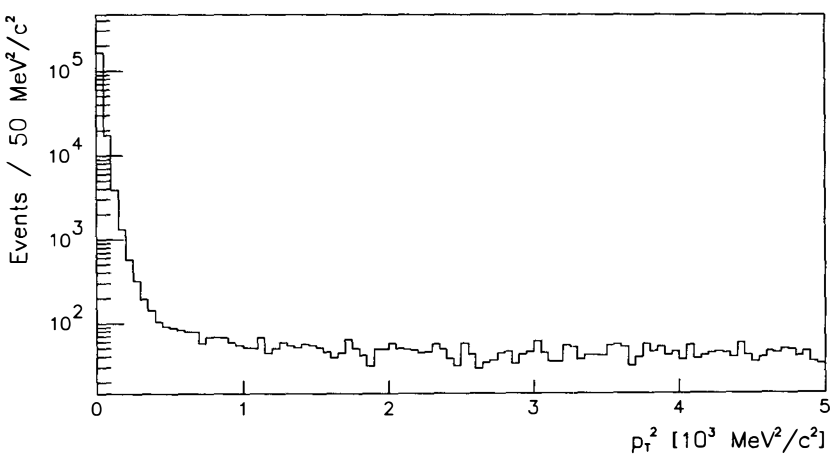

Figure 3: Transverse momentum squared in the regenerated beam.

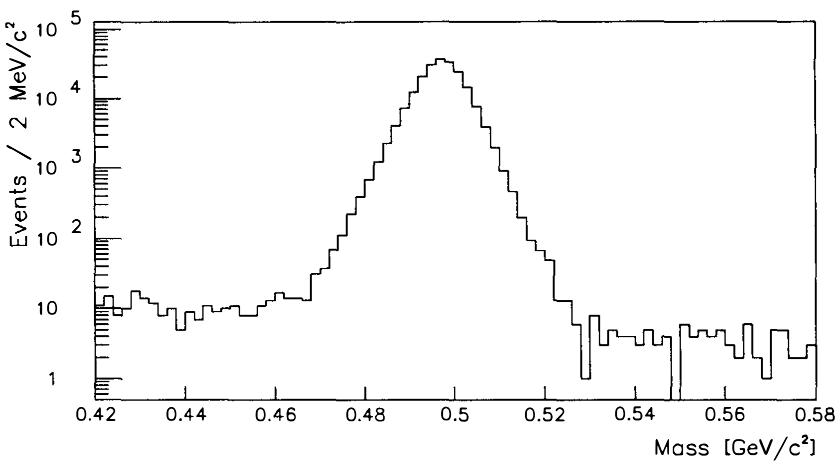

Figure 4: $\pi^0\pi^0$ invariant mass in the regenerated beam.

in the trigger hodoscopes at 138 m. In the vacuum beam, the $3\pi^0$ background (0.99%) dominates. It is not possible to determine the transverse momentum as for the $\pi^+\pi^-$ events, so we use the center of energy at the lead glass instead. The shape of the incoherent background in the center of energy variable is predicted from the p_T^2 shape obtained from the $\pi^+\pi^-$ decays. Both the size and shape of this prediction agree very well with the observed distribution. The background under the coherent peak is found to be 2.7% in the regenerated beam and 2.8% in the vacuum beam. For kaon energies between 40 and 120 GeV and a decay vertex range of 121–147 meters from the target, there are 190,000 signal events in the regenerated beam and 73,000 in the vacuum beam.

The signal events are binned according to kaon energy and decay vertex with a bin size of 10 GeV$\times$1 m. In order to determine the acceptances, a corresponding Monte Carlo distribution is obtained from a detailed simulation of the beam and the detector. This Monte Carlo sample has about six times more events than the data sample.

EXTRACTION OF THE PHASES

The Monte Carlo distribution is generated from the predicted 2π decay rates, and let us now consider the expressions for these rates. The coherent kaon beam coming out of the regenerator is written as $K_L + \rho K_S$, where $\rho \equiv |\rho| e^{i\phi_\rho}$ is the coherent regeneration amplitude. (Recall that only the coherently scattered kaons are used.) The 2π decay rates as a function of proper time t (measured from the regenerator) are given by $|\eta|^2 e^{-t/\tau_L}$ for the vacuum beam, and $e^{-X}[|\rho|^2 e^{-t/\tau_S} + |\eta|^2 e^{-t/\tau_L} + 2|\rho||\eta| e^{-t/2\tau_S} \cos(\Delta m\, t + \phi_\rho - \phi_\eta)]$ for the regenerated beam.

Given that the regenerator alternates, the incident kaon momentum spectrum is the same for both beams, except that the flux in the regenerated beam is reduced by absorption, which is accounted for by the factor e^{-X}. This factor is measured with sufficient precision (less than one percent of itself) by comparing the number of $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi^0\pi^0\pi^0$ decays in the two beams.

By fitting the data and Monte Carlo distributions against each other, the phases ϕ_{+-} and ϕ_{00} (denoted ϕ_η above) are extracted from the interference pattern in the regenerated beam. The overall normalization is provided by the event totals in the vacuum beam. In this fit, the parameters τ_S, τ_L ($K_{S,L}$ lifetimes) and Δm (K_L-K_S mass difference) are held at their world average values.[9] The remaining quantities entering the decay rate expressions are $|\eta_{+-}|$, $|\eta_{00}|$, $|\rho|$ and ϕ_ρ. The ratio $|\eta_{+-}|/|\eta_{00}|$ is related to $\mathrm{Re}(\epsilon'/\epsilon)$, which was measured[6] using the same data set. In that analysis, however, CPT was assumed to be exact with ϕ_{+-} and ϕ_{00} fixed in the fit. In the fit for the phases, we therefore have to let $|\eta_{+-}|/|\eta_{00}|$ float. The regeneration amplitude ρ is related to the difference between the K^0 and $\overline{K^0}$ forward scattering amplitudes, $(f-\overline{f})/k$, by $\rho = \pi i N L g(f-\overline{f})/k$, where N is the density of scattering centers and L the length of the regenerator. The geometric factor $g = (1 - e^{-x})/x$, where $x = (1/2 - i\Delta m/\Gamma_S)L/\Lambda_S$ with Λ_S the K_S decay length, comes from the integration over a thick regenerator. The magnitude of $(f - \overline{f})/k$ is assumed to have a power law dependence on the kaon momentum, *i.e.*, $|\rho| \propto p_K^{-\alpha}$. The proportionality constant and α are free in the fit. The phase ϕ_ρ is fixed by the analyticity condition $\arg[(f - \overline{f})/k] = -(2 - \alpha)\pi/2$. These assumptions about the regeneration amplitude are supported by previous experiments[11] and by our own data.

The result of the fit, with statistical errors, is $\phi_{+-} = 47.7 \pm 2.0°$ and $\phi_{00} = 47.4 \pm 1.4°$. The quality of the fit is good, with $\chi^2 = 316$ for 340 degrees of freedom. Figures 5-6 show the extracted cosine factor from the interference term together with the best fit. The available proper time interval is shorter for the $\pi^+\pi^-$ decays, due to the trigger plane at 138 meters. (A rule of thumb: One K_S lifetime is equivalent to about 27 degrees.) The results for ϕ_{+-} and ϕ_{00} depend directly on the value of ϕ_ρ, but the difference $\Delta\phi \equiv \phi_{00} - \phi_{+-}$ is insensitive to ϕ_ρ. By varying the fixed parameters Δm and τ_S one standard deviation around their world average values, the uncertainty in ϕ_{+-} (ϕ_{00}) is found to be 0.4 (0.5) degrees for Δm and 0.8 (0.6) for τ_S. Similarly, the uncertainty in the factor e^{-X} leads to a systematic error of 0.4 (0.3) degrees. In all three cases, the effect on the difference $\Delta\phi$ is negligible.

The Monte Carlo simulation is checked with 10^7 $\pi e \nu$ and 6×10^6 $\pi^0\pi^0\pi^0$ decays, which were collected at the same time as the 2π decays. The resulting systematic uncertainty in $\Delta\phi$ is 1.2° and is limited by the statistics of the $\pi e \nu$ and $\pi^0\pi^0\pi^0$ decay modes. As an additional check of the acceptance, we use the same analysis to fit for τ_S and Δm. The results obtained (with statistical error only), $\tau_S = (0.8902 \pm 0.0021) \times 10^{-10}$ sec and $\Delta m = (0.5377 \pm 0.0098) \times 10^{10}\,\hbar\,\mathrm{sec}^{-1}$, agree well with the world average values.[9] There is

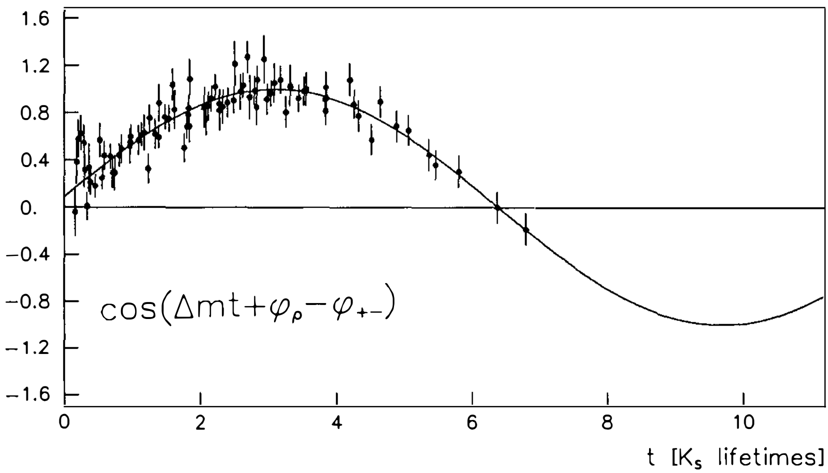

Figure 5: Extracted cosine term from the $\pi^+\pi^-$ decay rate.

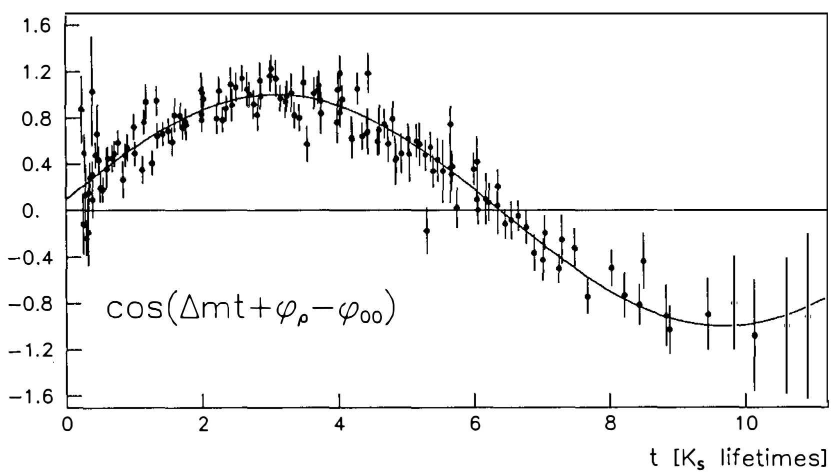

Figure 6: Extracted cosine term from the $\pi^0\pi^0$ decay rate.

a 0.6° systematic error in $\Delta\phi$ from the uncertainty in the absolute energy scale of the lead glass calorimeter. The systematic uncertainty in $\Delta\phi$ from the background subtractions is 0.3°.

Accidental events are recorded together with the 2π data. The events are triggered by a coincidence between two small scintillator counters placed in such a way that a particle going through the counters misses the detector by a wide margin. The accidental trigger rate is therefore proportional to the $K \to 2\pi$ rates, but uncorrelated with any particular detector element. Overlaying the accidental events on Monte Carlo 2π events, the effect on the phases is found to be negligible.

CONCLUSIONS

The final result is $\Delta\phi \equiv \phi_{00} - \phi_{+-} = -0.3° \pm 2.4°(\text{stat}) \pm 1.2°(\text{syst})$. Together with the world average value of ϕ_{+-}, we find that $\phi_\epsilon = 2\phi_{+-}/3 + \phi_{00}/3 = 44.5° \pm 1.5°$. Both results agree with the predictions of CPT symmetry. A recent measurement[12)] by the NA31 group also finds that $\Delta\phi$ is consistent with zero.

If there were any CPT violation in the K^0-$\overline{K^0}$ mixing, it would be parametrized by

$$\Delta = \frac{1}{2}\frac{\langle\overline{K^0}|H|\overline{K^0}\rangle - \langle K^0|H|K^0\rangle}{(m_L - m_S) + i(\Gamma_S - \Gamma_L)/2}$$

and any violation in the 2π decay amplitudes by $a = (A_0 - \overline{A}_0)/(A_0 + \overline{A}_0)$. The K_L to K_S amplitude ratios would then be given by $\eta_{+-} = \epsilon - \Delta + a + \epsilon'$ and $\eta_{00} = \epsilon - \Delta + a - 2\epsilon'$. The expression for Δ contains the K^0-$\overline{K^0}$ mass and lifetime differences in its numerator. Together with limits from the 3π and semileptonic decay modes, our results set a limit of about 4×10^{-18} for $\delta M/M$ and about 2×10^{-4} for $\delta\Gamma/\Gamma$. See reference 4 for detailed discussions of the algebra behind these limits.

The E731 experiment was designed to measure the quantity $\mathrm{Re}(\epsilon/\epsilon')$. A new experiment (E773) by the same collaboration will make a dedicated measurement of $\Delta\phi$ later this year (1990). To optimize the sensitivity to ϕ_{+-} and ϕ_{00}, both beams are equipped with a regenerator. By choosing the thicknesses and relative locations of the two regenerators, the statistical sensitivity is improved, and by taking the ratio of events in the two beams, the systematic uncertainties are minimized. The total error in $\Delta\phi$ is expected to be less than one degree.

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