DIRECT EVIDENCE FOR T VIOLATION IN THE NEUTRAL KAON SYSTEM

The CPLEAR Collaboration

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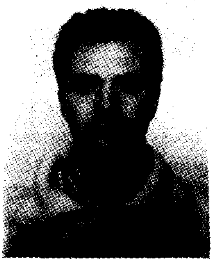

Abstract

We present the first direct observation of T violation in the neutral kaon system, showing a positive signal with a significance of more than two standard deviations. The result does not rely on the validity of the CPT theorem.

1 Introduction

The discrete symmetries charge conjugation (C), parity transformation (P) and time reversal (T) are of fundamental importance in particle physics. There are strong theoretical arguments that physics is invariant under the CPT symmetry and so far there is no experimental evidence of CPT violation. CP violation has been observed in the neutral kaon system: in the decays of K_L into $\pi^+\pi^-$, $\pi^0\pi^0$ and $\pi^+\pi^-\gamma$, and in the lepton charge asymmetry of K_L semileptonic decays. Assuming CPT invariance one expects the time reversal symmetry to be violated to the same extent as the CP symmetry. However, until now T violation has not been directly measured.

Among the aims of the CPLEAR experiment, there is the measurement of the semileptonic decay modes $\pi^+e^-\overline{\nu}$ and $\pi^-e^+\nu$ for $K^0$and $\overline{K}^0$. It allows the detection of a possible difference between the transition probability $\mathcal{P}(\overline{K}^0 \to K^0)$ and the probability of the time reversed process $\mathcal{P}(K^0 \to \overline{K}^0)$. A non-zero value of this difference is a model independent evidence for T violation [1].

2 The CPLEAR Method

The neutral kaons are produced in $p\overline{p}$ annihilations at rest:

$$p\overline{p} \to K^0K^-\pi^+ \quad (1)$$
$$p\overline{p} \to \overline{K}^0K^+\pi^-. \quad (2)$$

Each of the two channels has a branching ratio of $\approx 0.2\%$. The neutral kaon strangeness is tagged at the production time ($\tau = 0$) by measuring the charge of the accompanying charged kaon ($K^+ \to \overline{K}^0$, $K^- \to K^0$). According to the $\Delta S = \Delta Q$ rule, governing the semileptonic decay in the Standard Model, K^0 is only allowed to decay into a positive lepton and $\overline{K}^0$ into a negative one. Thus by measuring the sign of the lepton in the semileptonic decay, one is able to tag the neutral kaon strangeness at the decay time.

We measure four decay rates, as functions of the decay eigentime, according to the initial strangeness of the neutral kaon (K^0or $\overline{K}^0$) and the charge of the decay lepton (e^+or e^-):

$$R^+(\tau) \equiv R(K^0_{(\tau=0)} \to \pi^-e^+\nu_e) \qquad \overline{R}^-(\tau) \equiv R(\overline{K}^0_{(\tau=0)} \to \pi^+e^-\overline{\nu}_e) \quad (3)$$
$$R^-(\tau) \equiv R(K^0_{(\tau=0)} \to \pi^+e^-\overline{\nu}_e) \qquad \overline{R}^+(\tau) \equiv R(\overline{K}^0_{(\tau=0)} \to \pi^-e^+\nu_e) \quad (4)$$

By measuring the asymmetry

$$A_T = \frac{\overline{R}^+(\tau) - R^-(\tau)}{\overline{R}^+(\tau) + R^-(\tau)} \quad (5)$$

we measure directly the difference of the probabilities $\mathcal{P}(\overline{K}^0 \to K^0)$ and $\mathcal{P}(K^0 \to \overline{K}^0)$, provided that the $\Delta S = \Delta Q$ rule is valid, *i.e.* the decays (4) occur only if the neutral kaon has oscillated into its antiparticle, and that the decay amplitudes $\mathcal{A}(K^0 \to \pi^-e^+\nu)$ and $\mathcal{A}(\overline{K}^0 \to \pi^+e^-\overline{\nu})$ are equal, which requires that the direct CP violation in the decay can be neglected. One can show that if these two hypothesis hold at the 1% level, a non-zero value of A_T is a direct evidence for T violation. No hypothesis has to be made on CPT invariance.

In the frame of the neutral kaon phenomenology [2], the physical eigenstates K_S and K_L can be expressed in terms of the CP eigenstates K_1 and K_2 as $|K_S> = |K_1> + \epsilon_S|K_2>$ and $|K_L> = |K_2> + \epsilon_L|K_1>$. The parameters ϵ_S and ϵ_L can be written as $\epsilon_S = \epsilon_T + \delta_{CPT}$, and $\epsilon_L = \epsilon_T - \delta_{CPT}$, where ϵ_T and δ_{CPT} express a possible violation of the T and CPT symmetries, respectively, in the $K^0 - \overline{K}^0$ oscillations [2]. If CPT holds the relations $\epsilon_S = \epsilon_L = \epsilon_T$ and $\delta_{CPT} = 0$ are valid.

We can write the two semileptonic decay rates used in the asymmetry as

$$\begin{aligned}
{R^-(\tau) \atop \overline{R}^+(\tau)} \propto\ & [1 + 2\Re e(x) \mp 2\Re e(\epsilon_S) \mp 2\Re e(\epsilon_L))]e^{-\Gamma_S\tau} \\
+\ & [1 - 2\Re e(x) \mp 2\Re e(\epsilon_S) \mp 2\Re e(\epsilon_L))]e^{-\Gamma_L\tau} \\
+\ & 2[-1 \pm 2\Re e(\epsilon_S) \pm 2\Re e(\epsilon_L)]e^{-\Gamma\tau}\cos(\Delta m\tau) \\
+\ & 4[\mp\Im m(x)]e^{-\Gamma\tau}\sin(\Delta m\tau)
\end{aligned} \quad (6)$$

where Γ_S and Γ_L denote the decay widths of K_S and K_L respectively and Γ the average decay width, Δm denotes the mass difference of K_L and K_S and x is a parameter expressing a possible violation of the $\Delta S = \Delta Q$ rule. Assuming $x = 0$ one deduces from Eqs. (5) and (6)

$$A_T = 2(\Re e(\epsilon_S) + \Re e(\epsilon_L)) = 4Re(\epsilon_T). \quad (7)$$

If CPT is valid ($\delta_{CPT} = 0$), we can estimate the expected value of A_T, by using the measured value of the lepton charge asymmetry in K_L semileptonic decays, $\delta_l = (0.327 \pm 0.012)\%$[3]. Since $\delta_l = 2\Re e(\epsilon_T + \delta_{CPT})$, we expect $A_T = 6.54 \times 10^{-3}$.

3 The CPLEAR Detector

Antiprotons provided by LEAR annihilate at rest in a gaseous, 16 bar pressure, hydrogen target. The detector has a cylindrical geometry. It is contained inside a solenoidal magnet with a field of 0.44 T. The charged tracks are measured by two multi-wire proportional chambers, six drift chambers and two layers of streamer tubes. The particle identification detector (PID), placed behind the streamer tubes, consists of a Cherenkov counter (CE) sandwiched between two scintillator counters (S1, S2). It is designed to distinguish charged kaons and pions. It is also used to identify the electrons produced in the semileptonic decays of the neutral kaons. Photons from neutral pions are detected in the 18 layer gas sampling electro-magnetic calorimeter.

Due to the small branching ratio of the desired annihilation channels, Eqs. (1) and (2), the experiment requires a high annihilation rate ($\approx$ 1 MHz) and a fast online event selection. A sophisticated multi-level trigger with hardwired processors has been designed to recognize the desired events from the dominant multipionic background.

4 Event Selection and Correction Procedure

A first selection requires four tracks with zero total charge, good track quality and at least one charged kaon candidate. The annihilation vertex must lie inside the beam spot (primary vertex), and a separate vertex for the decay of the neutral kaon (secondary vertex) is required. A cut on the distance between the two vertices (1 cm in the transverse plane) is needed to remove ambiguities on the track assignment to either vertex, and to reduce the background from other $p\bar{p}$ annihilation channels. A fit requiring a K^0missing mass at the primary vertex is performed to validate the hypothesis of the ($K^{\pm}\pi^{\mp}K^0$) channel.

The semileptonic decay channel is selected by identifying one of the secondary tracks as an electron or a positron, using the PID information. Due to the difference of velocity between electrons and pions of the same momentum, electron-pion separation can be obtained by looking at the energy loss in S1 and S2, the number of photo-electrons per unit path length in CE and the time of flight of the particle from the decay vertex to S1. The selection has been optimized with electron data from converted photons and with pions from decays of neutral kaons into $\pi^+\pi^-$. The electron identification

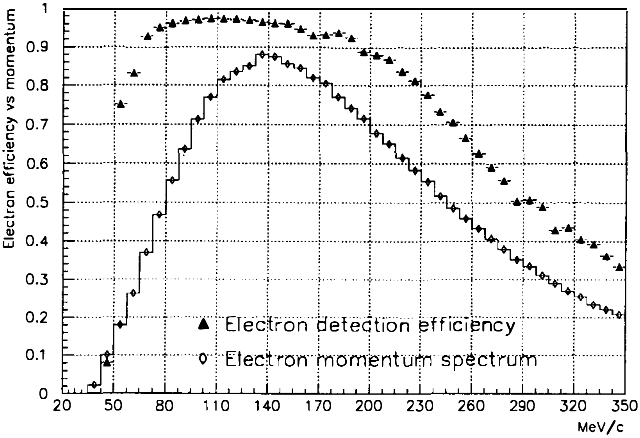

Figure 1: Electron detection efficiency versus electron momentum requiring that only 2% of pions fake electrons, (full points). Expected momentum spectrum for electrons in semileptonic decays (open points).

efficiency versus momentum is shown in Fig. 1, superimposed with the momentum spectrum of electrons obtained from Monte Carlo generated events. This efficiency corresponds to a momentum independent fraction of 2% of pions misidentified as electrons. A fit requiring the energy-momentum conservation with a missing neutrino hypothesis and the alignment of the K^0momentum with the line joining the two vertices is performed. Events which fit to the ($K\pi K^0$, $K^0 \rightarrow \pi^+\pi^-$) hypothesis with high probability are removed in order to reduce the $\pi^+\pi^-$background which is dominant at short decay eigentimes. The final sample contains $\approx 600,000$ (K^0, $\overline{K}^0 \rightarrow \pi e \nu$) events collected up to end 1993. Only half of it is used to built the asymmetry since we compare two rates out of four.

Due to the different strong interaction cross-sections of $K^+$and K^-, as well as of $\pi^+$and $\pi^-$with matter, the detection efficiencies of a ($K^+\pi^-$) pair and a ($K^-\pi^+$) pair are not identical. The difference of the overall ($K^+\pi^-$) and ($K^-\pi^+$) efficiencies is of the order of 15%. To restore the initial K^0-$\overline{K}^0$production symmetry, we have to correct for this tagging asymmetry. Let α denote the ratio of the two efficiencies, $\alpha = \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$. It depends exclusively on the momentum of the primary pion and kaon $[\alpha(p_t^K, p_z^K, p^\pi)]$, independently of the decay mode. It is determined, for statistical reason, by analysing decays of neutral kaons into $\pi^+\pi^-$at short decay times ($\tau < 4\tau_S$). The $\pi^+\pi^-$data are corrected for the expected CP violation using the present world average values for all the relevant parameters[3]. This correction is small and does not vary by more than 5×10^{-4} if these parameters are changed within 3 standard deviations. Furthermore, this correction does not imply any hypothesis on CPT conservation in the mixing matrix. The weight $\alpha(p_t^K, p_z^K, p^\pi)$ is then applied event by event to the semileptonic data. The error on the normalisation correction due to the statistics of $\pi^+\pi^-$events, corresponds to $\Delta(<\alpha>) = \pm 0.0015$. The effect of this uncertainty is studied in the next section.

We have also to correct for any asymmetry in the detection of the two possible final states ($\pi^+e^-\overline{\nu}$) and ($\pi^-e^+\nu$). Using data from photon conversions, we have not observed any difference in the detection of $e^+$and e^-. On the other hand, the difference between the $\pi^+$and π^-cross-sections with matter leads to the detection of a small excess of π^+. We define the parameter η as the ratio of the two detection efficiencies $\epsilon(\pi^+)$ and $\epsilon(\pi^-)$. Neutral kaons decays into $\pi^+\pi^-$are used to establish the momentum dependence of this parameter. The absolute level of this correction is not accessible by this method, since in each event we have one $\pi^+$and one π^-. We fit it to the charge asymmetry in the semileptonic K_L decays, which is known[3] at the level of $\pm 1.2 \times 10^{-4}$. This parameter $\eta(p_t^\pi, p_z^\pi)$ is used as a weight to correct the data. The average over the semileptonic phase space, amounts to $<\eta>= 1.0155 \pm 0.0031$. The error is dominated by our own statistical uncertainty.

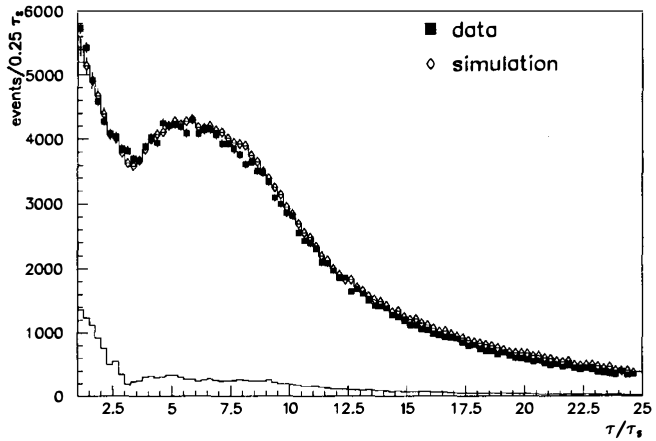

Figure 2: Decay eigentime distribution for real data (full points) and Monte Carlo generated semileptonic events (open points). The total background contribution is represented by the bottom line.

Figure 2 shows the decay eigentime distribution above $1\tau_S$ of selected events weighted by α and η, both for real and simulated data. The signal consists of correctly reconstructed $\pi e \nu$ events and of $\pi \mu \nu$ events seen as $\pi e \nu$. The main background source consists of residual neutral kaon decays to $\pi^+\pi^-$, and is concentrated at short decay times. The annihilation background is negligible ($< 1\%$) above $1\tau_S$. At large decay times there are contributions from $\pi^+\pi^-\pi^0$decays and from $\pi l \nu$ decays where the pion and the lepton assignments are exchanged. In the simulation, each channel contribution is normalized to the same number of generated $p\bar{p}$ annihilations. The sum of the contributions to the background is plotted as the bottom line in Fig. 2.

5 Result and Discussion of Systematic Errors

For each class of events defined in Eq. 4, we compute the expected rate by adding signal and background contributions:

$$\overset{(-)}{R^{\pm}}_{exp}(\tau) = \overset{(-)}{R^{\pm}}(\tau) + \overset{(-)}{B^{\pm}}(\tau) \tag{8}$$

Since signal and background come from neutral kaon decays, we assume the same normalization factor α for both. The expected asymmetry

$$A_{exp}(\tau) = A_T(\tau) \times \frac{1 + \frac{\overline{B}^+(\tau) - B^-(\tau)}{\overline{R}^+(\tau) - R^-(\tau)}}{1 + \frac{\overline{B}^+(\tau) + B^-(\tau)}{\overline{R}^+(\tau) + R^-(\tau)}} \equiv A_T(\tau) \times f_b(\tau) \tag{9}$$

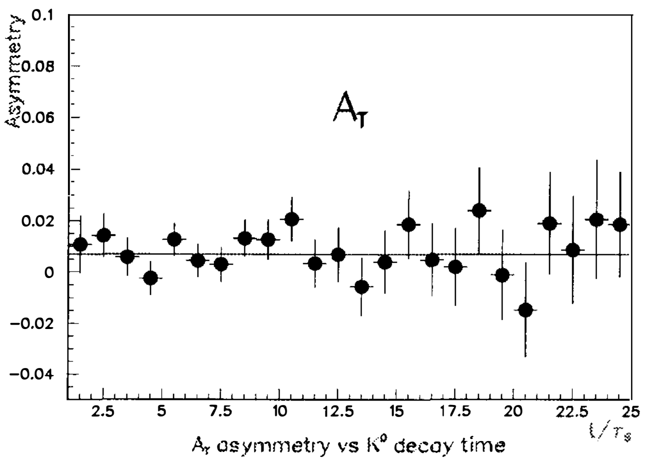

Figure 3: The A_T asymmetry versus the decay time (in units of τ_S). The solid line represents the fit of Eq. 7 to the data.

is fitted to the data, and we get :

$$A_T = [6.3 \pm 2.1_{stat}] \times 10^{-3} \quad (10)$$

$$\text{and } \Re e(\epsilon_T) = [1.6 \pm 0.5_{stat}] \times 10^{-3} \quad (11)$$

The A_T asymmetry is plotted in Fig.3. The solid line represents the result of the fit. The data points are corrected for the background dilution factor $f_b(\tau)$.

The uncertainty on the background estimation ($\approx$ 10%) induces no significant systematic error on the measurement of A_T. Only a charge asymmetry in the background has an effect on this measurement. The calibration data which have been used to calibrate the e/π separation shows an asymmetry of $(3.0 \pm 1.0)\%$ between the number of π^+which are misidentified as positrons and the number of π^-which are misidentified as electrons. This asymmetry is taken into account in the fit, and its uncertainty affects the result at the level of $\pm 0.3 \times 10^{-3}$.

The effects due to the uncertainty of the evaluation of α and η are measured by changing these two normalisation factors within their errors. we get for A_T systematic errors of $\pm 0.8 \times 10^{-3}$ due to α and $\pm 1.5 \times 10^{-3}$ due to η.

The systematic errors mentioned above are summarized in Table 1.

6 Conclusion

We have reported the first direct evidence for T violation in the neutral kaon system. This measurement relies on the (weak) assumption that in the kaon decay, the direct violation of CP and the violation of

Table 1: Systematic errors

Systematic effect	precision	$\Delta(A_T)$ $[10^{-3}]$	$\Delta(\epsilon_T)$ $[10^{-3}]$
α	$\pm 0.15\%$	± 0.8	± 0.20
η	$\pm 0.32\%$	± 1.5	± 0.39
background asymmetry	$\pm 1\%$	± 0.3	± 0.08
total		± 1.8	± 0.45

the $\Delta S = \Delta Q$ rule are both small. A violation of the $\Delta S = \Delta Q$ rule at the level of 1% ($|x| = 1\%$) would change the value of A_T by 1×10^{-3}. The value found for the asymmetry between the two probabilities $\mathcal{P}(K^0 \rightarrow \overline{K}^0)$ and $\mathcal{P}(\overline{K}^0 \rightarrow K^0)$, $A_T = [6.3 \pm 2.1_{stat} \pm 1.8_{syst}] \times 10^{-3}$ shows a positive signal with more than two standard deviations from zero, and is compatible with the CPT conservation hypothesis. The value obtained for the T violation parameter is $\Re e(\epsilon_T) = [1.6 \pm 0.5_{stat} \pm 0.4_{syst}] \times 10^{-3}$. The statistical significance of these measurements will be increased by a factor of two by the end of 1995.

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