RESULTS FROM CP, T AND CPT MEASUREMENTS AT CPLEAR

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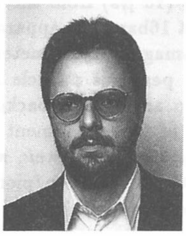

ABSTRACT

The CPLEAR experiment at CERN studies the CP, T and CPT symmetries in the neutral kaon system using initially tagged K^0 and $\overline{K^0}$. Results from the 1990 to 1993 data on η_{+-}, η_{+-0}, Δm and x are reported, as well as the first direct measurement of T violation and ε_S. Our results are consistent with CPT invariance and lead to an improved limit on the $K^0 - \overline{K^0}$ mass difference.

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1 Introduction

The aim of the CPLEAR experiment is to realize a complete and precise survey of the discrete symmetries CP, T and CPT in the neutral kaon system. In contrast to previous experiments which use K_L and/or K_S beams, the CPLEAR method [1] is based on the observation of the decay rates of initially tagged K^0 and $\overline{K^0}$ to a variety of final states, which allows to extract the relevant parameters through time dependent decay rate asymmetries of the form :

$$A_f(t) \;=\; \frac{R_{\overline{K}^0\to\overline{f}}(t) - R_{K^0\to f}(t)}{R_{\overline{K}^0\to\overline{f}}(t) + R_{K^0\to f}(t)}$$

where acceptances cancel, reducing systematic errors. This approach gives access to a wide range of parameters, such as η_{+-}, η_{+-0} and Δm, which are measured currently with a precision higher or at least comparable to that of previous experiments. Moreover, the direct measurement of T violation and CPT invariance, as well as the measurement of ε_S are possible for the first time. We can also improve the existing limits for the $\Delta S = \Delta Q$ rule validity and make an indirect CPT test comparing ϕ_{+-} to ϕ_{sw}.

K^0 and $\overline{K^0}$ mesons are produced in equal amounts in $p\overline{p}$ annihilation at rest, through the channels $p\overline{p} \to K^{\pm}\pi^{\mp}\overline{K^0}(K^0)$, each one with a branching ratio of $\approx 2\cdot 10^{-3}$. The neutral kaon strangeness at its production is tagged through the charge of the accompanying $K^{\pm}$. An intense beam of 200MeV/c antiprotons ($10^6\overline{p}/s$) from the LEAR machine stop and annihilate inside a target containing gaseous H_2 at 16bar. The apparatus consists of tracking and particle identification detectors and an electromagntic calorimeter, all inside a solenoid of 0.44T. A dedicated hardwired processor trigger performs particle identification, kinematical selection and shower counting, which results to an efficient background rejection. Special care was taken in the design and construction of the experiment to minimize material in the decay volume of neutral kaons. Offline, decays to $\pi^+\pi^-$, $\pi e\nu$, $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0$ are selected using reconstruction quality cuts, constrained fits, electron/pion identification and γ direction and energy reconstruction. The results from the analysis of data taken between 1990 and 1993 are presented here.

2 Results from $\pi^+\pi^-$ decays

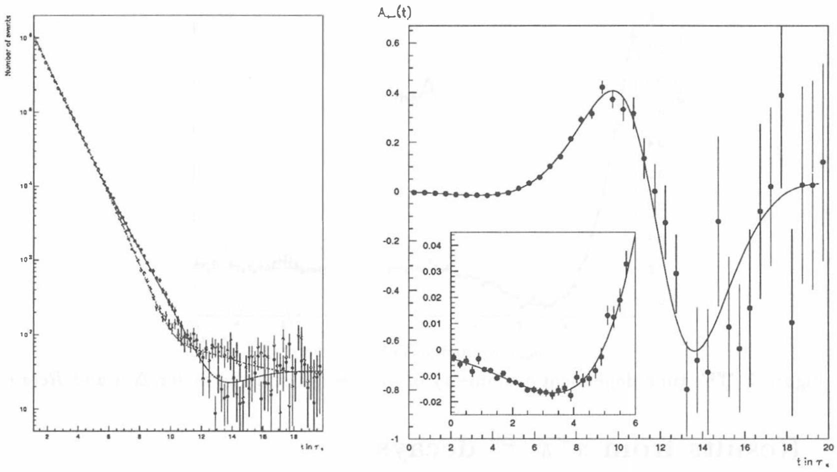
15 million events in the region $1 - 20\tau_s$ have been selected. The expected decay rate difference between particles and antiparticles due to CP violation is for the first time directly observed (fig. 1a) and the time dependent asymmetry :

$$A_{+-} = \frac{\overline{K^0} - \alpha K^0}{\overline{K^0} + \alpha K^0} = -2\frac{|\eta_{+-}|e^{\frac{1}{2}(\Gamma_S-\Gamma_L)t}\cos(\Delta m\; t - \phi_{+-})}{1 + |\eta_{+-}|^2 e^{(\Gamma_S-\Gamma_L)t}}$$

is constructed (fig. 1b) and fitted for $|\eta_{+-}|$, ϕ_{+-} and α, the last one taking into account an overall tagging efficiency difference for K^0 and $\overline{K^0}$ events resulting from the different interaction cross sections of the two charges of primary pions and kaons with the detector material. We get :

$$\begin{aligned} |\eta_{+-}| &= (2.275 \pm 0.047_{stat} \pm 0.030_{syst} \pm 0.010_{\tau_S}) \cdot 10^{-3} \\ \phi_{+-} &= 44.7^0 \pm 1.0^0_{stat} \pm 0.6^0_{syst} \pm 0.7^0_{\Delta m} \end{aligned}$$

for $\Delta m = (.5331 \pm .0023)\, 10^{10}\hbar s^{-1}$ (see below). The dependence of ϕ_{+-} on Δm and τ_s values is $+310(\Delta m - .5331)$ and $-42(\tau_s - .8926)$, (Δm in $10^{10}\hbar s^{-1}$, τ_s in $10^{-10}s$). In the absence of experimental data for the scattering amplitudes of K^0 and $\overline{K^0}$ in the momentum region of our experiment ($<$ 800MeV/c), we have used the values calculated recently by Eberhard and Uchiyama [2] in order to correct our events for coherent regeneration. We assume the forward scattering amplitudes for K^0 and $\overline{K^0}$ accurate to 13% and the regeneration phase to 9^0, which result in an uncertainty of 0.6^0 in ϕ_{+-} and $0.02 \cdot 10^{-3}$ in $|\eta_{+-}|$Diffractive regeneration and absorption are found to be negligible for the case of our experimental setup. The uncertainty on the regeneration parameters dominates our systematic errors currently; we plan to measure these parameters in a dedicated experiment in 1996, which should decrease our total systematic errors by a factor of at least 2. Anyway, our current precision on ϕ_{+-} is better or at least comparable to that of the best results published to date [3].



(a) (b)

Figure 1: (a): The measured decay rates of K^0 and $\overline{K^0}$ to $\pi^+\pi^-$ after acceptance correction (full trigger data). This is the first direct observation of decay rate difference of particles–antiparticles, as expected from CP violation. (b): Data(90-93) and fit of A_{+-} as described in previous paragraph

3 Results from $\pi e \nu$ decays

In this channel the neutral kaon strangeness at decay time is tagged through the lepton charge, assuming the $\Delta S = \Delta Q$ rule to be valid. Moreover, the validity of this rule (described by the parameter x) can be checked itself, independently from the other measurements. The results we obtain from our sample of 700,000 $\pi e \nu$ events are :

$$\begin{aligned}
\Delta m &= (0.5290 \pm .0034_{stat} \pm .0005_{syst} \pm .0009_{MC})10^{10}\,\hbar s^{-1} \\
Re(x) &= (12.4 \pm 11.9_{stat} \pm 6.9_{syst})\,10^{-3} \\
Im(x) &= (4.8 \pm 4.3_{stat} \pm 0.6_{syst})\,10^{-3}
\end{aligned}$$

where the last quoted error on Δm will decrease very much with higher Monte Carlo statistics. Using the double tag (at production and decay time) we can for the first time directly observe if CP violation is accompanied by T or CPT violation, and also measure ε_S. Our results are :

$$A_T = (6.3 \pm 2.1_{stat} \pm 1.8_{syst})\,10^{-3}$$

$$\begin{aligned} Re(\delta_{CPT}) &= (0.07 \pm 0.53_{stat} \pm 0.45_{syst})\, 10^{-3} \\ Re(\varepsilon_S) &= (1.51 \pm 0.78_{stat} \pm 0.37_{syst})\, 10^{-3} \end{aligned}$$

where T violation is observed at the 2.3σ level, $Re(\delta_{CPT})$ is measured to be compatible with 0 and $Re(\varepsilon_S)$ is found compatible with $Re(\varepsilon_L)$, as expected if CPT is not violated.

If we combine our Δm value with the values of [4], which are all the results contributing to the current world average [5] with the exception of [6], the only one to be dependent on ϕ_{+-}, we obtain the average $(0.5331 \pm 0.0023)10^{10}\, \hbar s^{-1}$, where an adittional factor of 1.14 is taken into account in the error estimation due to the dispersion of results (proccedure similar to the PDG [5] one). This value has been used in the determination of ϕ_{+-} presented earlier.

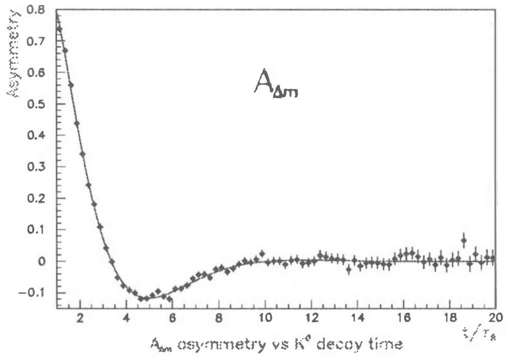


Figure 2: The time dependent asymmetry of $\pi e \nu$ decays and the fit for Δm and $Re(x)$

4 Results from $\pi^+\pi^-\pi^0$ decays

From a sample of 150,000 $\pi^+\pi^-\pi^0$ decays we have measured :

$$\begin{aligned} Re(\eta_{+-0}) &= (-4 \pm 17_{stat} \pm 3_{syst})\, 10^{-3} \\ Im(\eta_{+-0}) &= (-16 \pm 20_{stat} \pm 8_{syst})\, 10^{-3} \end{aligned}$$

These values are compatible to the corresponding values of η_{+-} and our precision is much better than all previous published measurements [5] [7].

5 Indirect CPT test

The difference between ϕ_{+-} and ϕ_{sw} yields the best CPT test available [5]. This test is based on the relation :

$$\eta_{+-} = \varepsilon_T + \delta_{CPT} + i\phi_0 + \varepsilon'$$

where δ_{CPT} is perpendicular to ε_T under the assumption that CPT is conserved in the decay matrix, ε' is the usual direct CP violation parameter in two π decays and $i\phi_0$ is a CP violating term arising from the interference of the $\pi^+\pi^-$ decay amplitude with K^0– $\overline{K^0}$ oscillation. We neglect ε' due to its small amplitude and its phase being close to ϕ_{sw} (as done by the PDG [5]). Neglecting final states like ($\pi\pi$, I=2), $\pi^+\pi^-\gamma$, $\gamma\gamma$, assuming that any possible violation of the $\Delta S = \Delta Q$ rule is the same for decays to e and μ and that $\eta_{+-0} = \eta_{000}$, the term $i\phi_0$ becomes

$$i\phi_0 = \frac{\Gamma_L}{\Gamma_S}[4BR(K_L \to \pi l \nu) Im(x) - BR(K_L \to \pi\pi\pi) Im(\eta_{2\pi} - \eta_{3\pi})]$$

In the PDG calculation this term is not taken into account, assuming $\Delta S = \Delta Q$ and $\eta_{+-0} = \eta_{+-}$. Taking the PDG [5] limits for $Im(x)$ and $Im(\eta_{+-0})$ would result in an additional error of $\approx 3^0$ in the difference $\phi_{+-} - \phi_{sw}$. Using the CPLEAR measurements presented above this error is reduced by a factor of 10. Thus we can give the limit

$$\delta_{CPT} < 9 \cdot 10^{-5} \quad (90\% \; C.L.)$$

where :

$$\delta_{CPT} = \frac{i\Delta\Gamma - 2\Delta m}{4\Delta m^2 + \Delta\Gamma^2} \left(M_{22} - M_{11} \right))$$

leading to :

$$\left| \frac{M_{\overline{K}^0} - M_{K^0}}{M_K} \right| < 1.8 \cdot 10^{-18} \quad (90\% \; C.L.)$$

6 Summary and prospects

We have reported measurements of $|\eta_{+-}|$, ϕ_{+-} and Δm which are compatible with earlier results from other experiments and with a very competitive accuracy (best in the case of ϕ_{+-}). We also reported the most precise measurements to date of η_{+-0} and the $\Delta S = \Delta Q$ parameter x. We reported the first direct measurements of T violation and CPT invariance and of the parameter ε_S. Finally, the analysis of the phase difference $\phi_{+-} - \phi_{sw}$ taking into account all the CPLEAR results leads to a very stringent test of the equality of mass between K^0 and $\overline{K^0}$, providing a very sensitive test of CPT invariance.

Analysis of data already collected during 1994 and to be collected in 1995 will decrease our statistical errors by a factor of ≈ 2 and a dedicated measurement of regeneration parameters in 1996 will help to decrease our systematic error in ϕ_{+-} by more than a factor of 2.

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