TESTS OF CPT WITH CPLEAR

CPLEAR Collaboration

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Abstract

Measurements of time-dependent K^0 / $\bar{\mathrm{K}}^0$ asymmetries with the CPLEAR detector yield experimental bounds on CPT violation parameters with minimal theoretical assumptions. Test of CPT violation in the mass matrix gives a bound on $|m_{\bar{\mathrm{K}}^0} - m_{\mathrm{K}^0}| < 4.5 \times 10^{-19}$GeV (90 % C.L.). In the framework of violation of CPT and quantum mechanics, limits on respective parameters approach the interesting region $\mathcal{O}(\frac{m^2_{\mathrm{K}^0}}{M_{Planck}})$.

Introduction

The CPT theorem is regarded as an axiom of physics. Its derivation requires a minimum of assumptions: a local field theory, Lorentz invariance and the usual spin-statistics relation. Nevertheless, as any postulate in physics, it should be subject to a rigorous experimental test. And there are even some theoretical suggestions, especially in the framework of Quantum Gravity as a non-local theory, that CPT might indeed be violated at the level of the Planck scale.

Neutral kaons play a special role in these tests. As the only system yet in nature where the violation of CP symmetry has been observed, it seems the obvious candidate for another surprise. In addition, experimental observation of interference effects provides a technique for measurements with a precision unachievable in other places.

Neutral Kaon System

The time evolution of the K^0 / $\bar{K^0}$ system can be described by a 2×2 Hamiltonian matrix $\hat{H}$. Because the weak interaction allows $K^0 \leftrightarrow \bar{K^0}$ transitions and kaon decays, the matrix is non-diagonal and complex [1]

$$\hat{H} = M - \frac{i}{2}\Gamma \tag{1}$$

where M is the mass and Γ the decay matrix, both of them Hermitian if unitarity holds.

The smallness of the weak interaction allows for a perturbation expansion

$$\begin{aligned} M_{\alpha\beta} &= <\alpha|H|\beta> + \sum_n \mathcal{P}\frac{<\alpha|H|n><n|H|\beta>}{m_K - m_n} && (2)\\ \Gamma_{\alpha\beta} &= 2\pi\sum_n <\alpha|H|n><n|H|\beta> \delta(m_K - m_n) && (3)\end{aligned}$$

where $\mathcal{P}$ denotes the principal value. The sum in M goes over all possible states while the delta function in Γ confines it to real states only.

Eigenstates of $\hat{H}$, K_L and K_S , have a sizable difference in lifetimes ($\tau_S = (89.26 \pm 0.12)$ ps; $\tau_L = (51.7 \pm 0.4)$ ns $\sim 580\ \tau_S$) and a small, but important, mass difference ($\Delta m = m_L - m_S = (0.5333 \pm 0.0027) \times 10^{10}\ \hbar/\mathrm{s} = (3.507 \pm 0.018) \times 10^{-12}$ MeV) [6].

T invariance places the following constraint on the off-diagonal elements of $\hat{H}$

$$\begin{aligned} |M_{12} - \frac{i}{2}\Gamma_{12}| &= |M_{21} - \frac{i}{2}\Gamma_{21}| && (4)\\ \Leftrightarrow arg(\Gamma_{12}) - arg(M_{12}) &= n \cdot \pi \end{aligned}$$

resulting in a single T violation parameter.

CPT invariance imposes equality of masses and lifetimes of K^0 and $\bar{K^0}$

$$M_{11} = M_{22} \quad \text{and} \quad \Gamma_{11} = \Gamma_{22} \tag{5}$$

making room for two CPT violation parameters.

CP violation in $\hat{H}$ is associated either to T or to CPT violation, if not to both.

The experimental data about CP violation, for example the branching ratio of $K_L \to \pi\pi$ of $\mathcal{O}(10^{-3})$, requires all CP violation parameters to be small. In addition, because of $\Gamma_S \gg \Gamma_L$ but $m_S < m_L$, CP violation resulting from T violation must be of the form $arg(\Gamma_{12}) - arg(M_{12}) = \pi - \delta\varphi$ with $\delta\varphi \ll 1$.

The T violation parameter is conveniently defined (with $\Delta\Gamma = \Gamma_L - \Gamma_S$) as

$$\begin{aligned} \epsilon_T &= \frac{1 + i\frac{2\Delta m}{\Delta\Gamma}}{4\Delta m^2 + \Delta\Gamma^2} \cdot 2(|M_{12} - \frac{i}{2}\Gamma_{12}|^2 - |M_{21} - \frac{i}{2}\Gamma_{21}|^2) && (6)\\ &= \frac{1 + i\frac{2\Delta m}{\Delta\Gamma}}{4\Delta m^2 + \Delta\Gamma^2} \cdot \Delta m \Delta\Gamma \delta\varphi. \end{aligned}$$

Its phase is fixed by the CP invariant quantities Δm and $\Delta\Gamma$ to the superweak phase

$$\tan\phi_{SW} = \frac{2\Delta m}{\Delta\Gamma} \approx \frac{\pi}{4}. \tag{7}$$

Similarly, the CPT violation parameters are composed into

$$\delta_{CPT} = i\frac{1 + i\frac{2\Delta m}{\Delta\Gamma}}{4\Delta m^2 + \Delta\Gamma^2} \cdot \Delta\Gamma[(M_{11} - M_{22}) - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})] \tag{8}$$

where the phase of the part associated with a mass difference is orthogonal to ϕ_{SW} while the phase of the part associated to a lifetime difference is the same as for ϵ_T.

CPLEAR Experiment

The CPLEAR experiment at CERN makes use of the intense $\bar{\mathrm{p}}$ beams available at LEAR to produce pure K^0 and $\bar{\mathrm{K}}^0$ by tagging the accompanying charged kaon in $\mathrm{p}\bar{\mathrm{p}}$ annihilation

$$\bar{\mathrm{p}}\mathrm{p} \to \mathrm{K}^0\mathrm{K}^-\pi^+ \qquad \bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{K}}^0\mathrm{K}^+\pi^- \tag{9}$$

both occurring at a branching ratio of $\approx 2 \times 10^{-3}$. The tagging of opposite strangeness states at production time maximizes the interference effects to be observed in K^0 , $\bar{\mathrm{K}}^0$ decays.

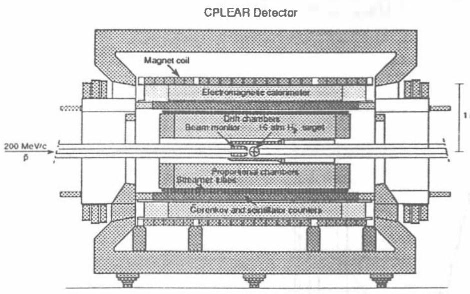

Figure 1: View of the CPLEAR detector

The experimental apparatus [2] is shown in Fig. 1. Ten chamber layers (2 of Proportional Chambers, 6 of Drift Chambers, 2 of Streamer Tubes) are used to trace charged particles resulting from annihilation and neutral kaon decays. A 32-segment scintillator-Čerenkov-scintillator [3] provides particle identification (kaons/pions/electrons). Photons are detected by a 18-layer fine-grain streamer tube / lead sampling calorimeter. Signals from all detectors are processed in a multilevel trigger, providing a rejection factor of over 1000 and allowing the detector to operate at a $\bar{\mathrm{p}}$ rate of 1 MHz. The material in the decay region up to the streamer tubes is minimized by using a gas target with mylar-kevlar walls and innovative low-mass chamber construction, thus reducing regeneration effects of neutral kaons. In 1995 a chamber was added at 1.7 cm radius to improve the trigger and tracking capabilities.

To isolate the interference term in K^0 , $\bar{\mathrm{K}}^0$ decays (see below) and to cancel systematic errors resulting from acceptance calculations, time-dependent asymmetries are formed from rates for each of the measured decay channels f,

$$\mathrm{A_f}(\tau) = \frac{\mathrm{R}(\bar{\mathrm{K}}^0 \to \mathrm{f}, \tau) \ - \ \mathrm{R}(\mathrm{K}^0 \to \mathrm{f}, \tau)}{\mathrm{R}(\bar{\mathrm{K}}^0 \to \mathrm{f}, \tau) \ + \ \mathrm{R}(\mathrm{K}^0 \to \mathrm{f}, \tau)}. \tag{10}$$

In total, about 100 million K^0 and $\bar{\mathrm{K}}^0$ decays were reconstructed. The results refer to about 40 M $\mathrm{K}^0, \bar{\mathrm{K}}^0 \to \pi^+\pi^-$ decays with $\tau > 1\,\tau_S$ and 1.2 M $\mathrm{K}^0, \bar{\mathrm{K}}^0 \to e\pi\nu$ decays from data taken up to mid 1995, while the 0.15 M $\mathrm{K}^0, \bar{\mathrm{K}}^0 \to \pi^+\pi^-\pi^0$ decays result from data up to the end of 1993.

$\pi^+\pi^-$ Decays

Selection of $K^0, \bar{K}^0 - \pi^+\pi^-$ decays [4] is based mainly on kinematical and geometrical constraints. As the events can be fully reconstructed, the background level is low throughout the interesting interference region.

The different acceptance for primary $K^+\pi^-$ versus $K^-\pi^+$ pairs represents a C-asymmetry of the detector, while different response of the apparatus, mainly the trigger, to tracks of opposite curvature adds a P-asymmetry. The former effect can be parametrized by a normalization parameter α which depends only on the kinematics of the primary pair and is not correlated with the decay path. The high statistics of $K^0, \bar{K}^0 \rightarrow \pi^+\pi^-$ decays allows for a control of the overall normalization to a level of 6×10^{-4}. P asymmetry is cancelled adequately by reversing the magnetic field several times a day.

The asymmetry, normalized to equal decay rates at production, reads

$$A_{+-}(\tau) = \frac{R(\bar{K}^0 \rightarrow \pi^+\pi^-) - \alpha R(K^0 \rightarrow \pi^+\pi^-)}{R(\bar{K}^0 \rightarrow \pi^+\pi^-) + \alpha R(K^0 \rightarrow \pi^+\pi^-)} = \frac{-2|\eta_{+-}| \cos(\Delta m\tau - \phi_{+-}) e^{\frac{1}{2}(\Gamma_S - \Gamma_L)\tau}}{1 + |\eta_{+-}|^2 e^{(\Gamma_S - \Gamma_L)\tau}} \quad (11)$$

with the complex CP violation parameter $\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}}$ corresponding to the amplitude ratio

$$\eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)}. \quad (12)$$

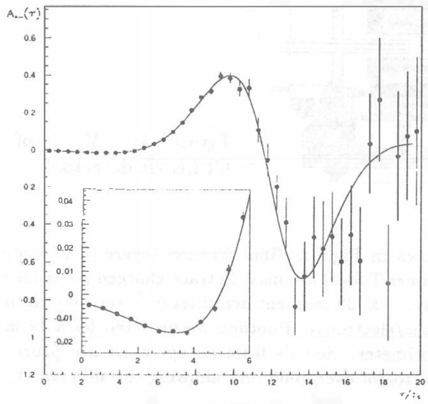

Figure 2: Two-pion time-dependent asymmetry. The region $0 - 6\tau_S$ is blown up in the insert.

Equation (11) is fitted to the measured asymmetry, shown in Fig. 2, leaving $|\eta_{+-}|$ and ϕ_{+-} as free parameters while fixing Δm to the CPLEAR measurement [5] and Γ_S and Γ_L to the PDG values [6]. The preliminary results for data until mid 1995 are

$$|\eta_{+-}| = (2.269 \pm 0.033_{stat} \pm 0.032_{syst}) \times 10^{-3}$$
$$\phi_{+-} = 42.2^o \pm 0.7^o_{stat} \pm 0.5^o_{syst} \pm 0.7^o_{\Delta m}$$

with ϕ_{+-} correlated to Δm by

$$\Delta\phi_{+-} = 0.316(\Delta m - 526.9)\frac{\text{deg}}{10^7\hbar s^{-1}}. \quad (13)$$

The parameter η_{+-} is connected to the CP violation parameters ϵ_T and δ_{CPT} by the expression

$$\eta_{+-} = \epsilon_T - \delta_{CPT} + \epsilon' + \Delta A + i\Delta\phi \tag{14}$$

where ϵ' is the parameter describing direct CP violation in neutral kaon decays into two pions and $\Delta A = \frac{1}{2}\frac{|A_{\pi\pi}|^2 - |\bar{A}_{\pi\pi}|^2}{|A_{\pi\pi}|^2 + |\bar{A}_{\pi\pi}|^2}$ measures the amplitude asymmetry between K^0 and $\bar{K^0}$ decays to two pions. $\Delta\phi = \frac{1}{2}(\arg\Gamma_{12} - \arg A^*_{\pi\pi}\bar{A}_{\pi\pi})$ represents the phase difference between the off-diagonal decay-matrix element and its dominant two-pion part.

Experimentally, ϵ' is measured to be small ($\mathcal{R}e(\frac{\epsilon'}{\epsilon}) < 3 \times 10^{-3}$ [7]) with its phase $\phi_{\epsilon'} = 48^o \pm 4^o$ [6] $\approx \phi_{SW}$ while in $K^0, \bar{K^0} \to \pi\pi$ decays the I=0 amplitude is dominant ($\approx$ 20 times larger than the I=2 amplitude). Retaining the main decay contributions, $\Delta\phi$ can be expressed as

$$\begin{aligned} \Delta\phi \quad = \quad & \frac{\Gamma_L}{\Gamma_S}[4BR(K_L \to l^+\pi^-\nu) \cdot \mathcal{I}m(x) - \\ & -BR(K_L \to \pi^+\pi^-\pi^0) \cdot \mathcal{I}m(\epsilon_T + \delta_{CPT} - \eta_{+-0}) - \\ & -BR(K_L \to \pi^0\pi^0\pi^0) \cdot \mathcal{I}m(\epsilon_T + \delta_{CPT} - \eta_{000})] \end{aligned} \tag{15}$$

with η_{+-0}, η_{000} the CP violation parameters in three-pion decays and x the $\Delta Q = \Delta S$ violation parameter in semileptonic decays.

Figure 3: Connection between ϵ_T and η_{+-} in the complex plane. The magnitude of all other parameters is exaggerated.

Equation (14) is depicted (not to scale) in Fig. 3. It is clear that only terms perpendicular to ϵ_T can contribute to the phase difference $\phi_{+-} - \phi_{SW}$, therefore there is no contribution from the lifetime difference in δ_{CPT} and that from ϵ' can be safely neglected. There remain two CPT violation contributions to $\phi_{+-} - \phi_{SW}$, one from the mass difference in δ_{CPT} and the second from ΔA which could result from direct CPT violation in $\pi\pi$ decays. $\Delta\phi$ is expected to be of $\mathcal{O}(10^{-7})$ in the Standard Model. However, relying on experimental limits [6] on x and η, expression (15) yields a limit on the contribution of $\Delta\phi$ to $\phi_{+-} - \phi_{SW}$ as high as 3^o. Hence it is obvious, that for a conclusion on limits of CPT violation from a comparison of ϕ_{+-} with ϕ_{SW}, an improvement on three-pion and semileptonic decays is essential.

$\pi^+\pi^-\pi^0$ Decays

The selection of $K^0, \bar{K^0} \to \pi^+\pi^-\pi^0$ decays [8] is also based on kinematical and geometrical constraints. In addition, at least one of the photons from the π^0 is required to produce a shower in the calorimeter.

The $\pi^+\pi^-\pi^0$ state can have isospin 0,1,2 and 3. I=0 is suppressed by kinematics and the I=3 by the $\Delta I = 1/2$ rule. By symmetry considerations I=1 is CP=-1 and I=2 is CP=+1. Thus the CP violation parameter is defined as

$$\eta_{+-0} = \frac{\int d\Omega A_S^{CP-}(I=1) A_L^{*CP-}(I=1)}{\int d\Omega A_L^{CP-}(I=1) A_L^{*CP-}(I=1)} \tag{16}$$

where the integral extends over phase space. As the CP conserving I=2 part of the K_S amplitude is odd in $p_{\pi^+} - p_{\pi^-}$ its contribution vanishes through integration. The CP violation asymmetry then reads

$$A_{+-0}(\tau) = 2(\mathcal{R}e(\eta_{+-0})\cos(\Delta m\tau) - \mathcal{I}m(\eta_{+-0})\sin(\Delta m\tau))e^{-\Delta\Gamma\tau/2}. \tag{17}$$

A fit to the measured asymmetry yields the values [8]

$$\begin{aligned} \mathcal{R}e(\eta_{+-0}) &= (6 \pm 13_{stat} \pm 1_{syst}) \times 10^{-3} \\ \mathcal{I}m(\eta_{+-0}) &= (-2 \pm 18_{stat} \pm 3_{syst}) \times 10^{-3} \end{aligned}$$

which represent an improvement over the previous best measurement [9] but are still nearly an order of magnitude above the expected level of CP violation.

Semileptonic Decays

The selection of semileptonic events [5] demands in addition to kinematical and geometrical constraints an electron identified by energy loss in the scintillators and number of photoelectrons in the Čerenkov detector. There are four measurable decay rates, labelled by the initial strangeness and final electron charge:

$$\begin{aligned} R^+ &= R(\mathrm{K}^0(\tau) \to e^+\pi^-\nu) & R^- &= R(\mathrm{K}^0(\tau) \to e^-\pi^+\bar{\nu}) \\ \bar{R}^- &= R(\bar{\mathrm{K}}^0(\tau) \to e^-\pi^+\bar{\nu}) & \bar{R}^+ &= R(\bar{\mathrm{K}}^0(\tau) \to e^+\pi^-\nu). \end{aligned}$$

By forming asymmetries from them, acceptances cancel and various relevant parameters can be isolated by a proper combination of the rates.

In the Standard Model, only $\Delta Q = \Delta S$ transitions are allowed to first order, resulting in a limit on the parameter

$$x = \frac{A(\bar{\mathrm{K}}^0 \to l^+\pi^-\nu)}{A(\mathrm{K}^0 \to l^+\pi^-\nu)} \tag{18}$$

at $\mathcal{O}(10^{-6})$. We use this "$\Delta Q = \Delta S$ rule" as a strangeness tag at decay time - the current experimental errors [6] ($\sigma_{\mathcal{R}e(x)} = 18 \times 10^{-3}$, $\sigma_{\mathcal{I}m(x)} = 26 \times 10^{-3}$) are improved by our measurement by at least a factor of ten.

Of special interest for the CPT test is the determination of Δm for its correlation with ϕ_{+-} and the determination of ϕ_{SW} as well as the measurement of $\mathcal{I}m(x)$ for its contribution to $\Delta\phi$ (eq. 15). The determination of Δm is best achieved by forming the asymmetry

$$A_{\Delta m}(\tau) = \frac{(R^+ + \bar{R}^-) - (R^- + \bar{R}^+)}{(R^+ + \bar{R}^-) + (R^- + \bar{R}^+)} = \frac{2\cos(\Delta m\tau)\, e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)\tau}}{(1 + 2\mathcal{R}e(x))e^{-\Gamma_S\tau} + (1 - 2\mathcal{R}e(x))e^{-\Gamma_L\tau}}. \tag{19}$$

The preliminary results of a fit to data up to mid 1995 are shown in Fig. 4 and yield

$$\Delta m = (526.9 \pm 2.2_{stat} \pm 0.5_{syst}) \times 10^7 \hbar/s.$$

This represents the most precise measurement of Δm with a precision better than the world average in [6].

The asymmetry between all K^0 and $\bar{\mathrm{K}}^0$ semileptonic decays

$$A_2 = \frac{(\bar{R}^+ + \bar{R}^-) - (R^+ + R^-)}{(\bar{R}^+ + \bar{R}^-) + (R^+ + R^-)} \tag{20}$$

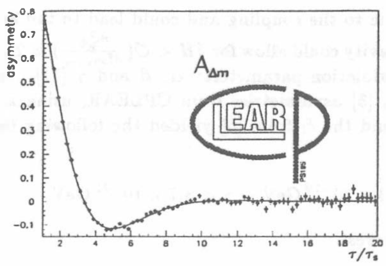

Figure 4: Time-dependent asymmetry $A_{\Delta m}$. Full line represents the fit to equation (19)

is sensitive to $\mathcal{I}m(x)$. The preliminary result from data up to mid 1995

$$\mathcal{I}m(x) = (0.5 \pm 2.4_{stat} \pm 0.6_{syst}) \times 10^{-3}$$

represents a tenfold improvement over the previous world average [6].

Test of CPT in the Mass Matrix

The improvements on $\mathcal{I}m(\eta_{+-0})$ and $\mathcal{I}m(x)$ made by the CPLEAR measurements greatly reduce the error on $\Delta\phi$. Assuming lepton universality ($x_e = x_\mu$) and the dominance of the I=1 amplitude in CP violation in $K^0 \rightarrow 3\pi^0$ decays ($\mathcal{I}m(\eta_{+-0}) = \mathcal{I}m(\eta_{000})$), the resulting uncertainty on the contribution to $\phi_{+-} - \phi_{SW}$ is diminished to 0.3°. Full use of this improvement is made by taking the values of ϕ_{+-} and ϕ_{SW} from the global fit of world data performed by CPLEAR [10]. The global fit values

$$\begin{aligned} \phi_{+-} &= 43.82^o \pm 0.63^o \\ \phi_{SW} &= 43.49^o \pm 0.08^o \end{aligned}$$

show that the limitation to the test of CPT violation now comes from the error on ϕ_{+-}.

To interpret the phase difference in terms of a bound on CPT violation in the mass matrix the following scenario is implied. Equation (2) allows a first order contribution to the mass matrix, while according to (3) contributions to the decay matrix start with the second order. Imagining a superweak type of CPT-violating interaction contributing differently in first order to $M_{11} = m_{K^0}$ and $M_{22} = m_{\bar{K}^0}$ implies an absence of CPT violating effects in decay and therefore sets ΔA to 0. Hence, the mass difference in δ_{CPT} remains the only source of a phase difference between ϕ_{+-} and ϕ_{SW}. The comparison yields a limit

$$|\delta_{CPT}| \quad < \quad 5 \times 10^{-5}\ (90\% C.L.)$$

which can be expressed as a mass difference

$$|m_{\bar{K}^0} - m_{K^0}| \quad < \quad 4.5 \times 10^{-19}\,\mathrm{GeV}\ (90\%\mathrm{C.L.}).$$

This represents the most precise test of CPT in the mass matrix.

Test of CPT in an Open Quantum-Mechanical System

There is a possibility of CPT violation resulting from an open quantum-mechanical system coupled to an unobserved environment. Such a system obeys a modified Liouville equation

$$\dot{\rho} = i[\rho, H] + \delta H \rho \tag{21}$$

where δH represents a loss of coherence due to the coupling and could lead to the breakdown of quantum mechanics and CPT. Quantum gravity could allow for $\delta H < \mathcal{O}(\frac{m^2_{K^0}}{M_{Planck}}) \approx 2\times 10^{-20} GeV$. δH can be parametrized by 3 real CPT violation parameters: α, β and γ [11]. A fit [12] to the published values of A_{+-} [4] and $A_{\Delta m}$ [5] asymmetries from CPLEAR, using as additional constraints the values of $|\eta_{+-}|$ from [13] and the δ_l from [6] yielded the following limits on the parameters (90 % C.L.)

$$\alpha < 4.0 \times 10^{-17}\,\mathrm{GeV} \quad \beta < 2.3 \times 10^{-19}\,\mathrm{GeV} \quad \gamma < 3.7 \times 10^{-21}\,\mathrm{GeV}$$

which, at least for γ, enter the region of interest.

Prospects

CPLEAR ended main data taking in 1995, the runs in 1996 are devoted to regeneration studies. The analysis of the remaining data will improve the statistical precision on ϕ_{+-}, Δm and $\mathcal{I}m(x)$ by 30% and that on $\mathcal{I}m(\eta_{+-0})$ by a factor 2.5. In addition, regeneration studies will allow us to reduce the systematic error on ϕ_{+-}, pushing the overall error to 0.5°, but for the Δm error.

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