Highlights on neutral K decays

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Recent results on kaon decays allow a new determination of the CP and CPT parameters $\Re\epsilon$ and $\Im\delta$ based on the unitarity relation. In particular, the new experimental limit on $BR(K_S \to 3\pi^0)$ and the determination of the charge asymmetry in $K_S \to \pi e\nu$ decays allow us to test the CPT symmetry with a sensitivity of order m_K/M_{Planck}.

1. Introduction

The neutral kaon system has long been used to test discrete symmetries. The most stringent limit on CPT-symmetry violation is provided by the mass difference $|m_{K^0} - m_{\bar{K}^0}|/m_{K^0}$. This difference is related to the quantity δ that parametrizes the CPT violation in the mixing:

$$\delta = \frac{i\,(m_{K^0} - m_{\bar{K}^0}) + 1/2\,(\Gamma_{K^0} - \Gamma_{\bar{K}^0})}{\Delta\Gamma} \times \cos\phi_{SW} e^{i\phi_{SW}} \quad (1)$$

where $\tan\phi_{SW} = 2\Delta M/\Delta\Gamma$, $\Delta\Gamma = \Gamma_S - \Gamma_L$, and $\Delta M = m_L - m_S$. If we assume that the CPT violation is negligible in the decay width ($\Gamma_{K^0} - \Gamma_{\bar{K}^0} = 0$), we have:

$$\frac{m_{K^0} - m_{\bar{K}^0}}{m_{K^0}} = 3 \times 10^{-14}\Im\delta. \quad (2)$$

Violation at first order in $m_K/M_{Planck} \sim 10^{-19}$, coming from quantum gravity effects, can thus be tested by putting an upper limit on $\Im\delta$ of order $\sim 10^{-5}$.

$\Re\delta$ and $\Im\delta$ are measured in two different ways. $\Re\delta$ is measured both from the difference $A_S - A_L$ of the charge asymmetries in K_S and K_L semileptonic decays, and from the time-dependent asymmetry

$$A_{CPT} = \frac{P(\bar{K}^0 \to \bar{K}^0(t)) - P(K^0 \to K^0(t))}{P(\bar{K}^0 \to \bar{K}^0(t)) + P(K^0 \to K^0(t))}, \quad (3)$$

where $P(K^0 \to K^0(t))$ ($P(\bar{K}^0 \to \bar{K}^0(t))$) is the probability for a K^0 ($\bar{K}^0$) to be observed as a K^0 ($\bar{K}^0$) after a time t.

$Im\delta$ is obtained from the unitarity (Bell-Steinberger) relation:

$$\left[\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i\tan\phi_{SW}\right]\frac{\Re\epsilon - i\Im\delta}{1 + |\epsilon|^2} = \frac{1}{\Gamma_S - \Gamma_L}\sum_f a_S^*(f)a_L(f) = \sum_f \alpha_f \quad (4)$$

where $a_{S,L}(f)$ are the $K_{S,L}$ decay amplitudes to the final state f.

2. Experimental inputs to $\Re\delta$

Using the time-dependent asymmetry in semileptonic decays [1] the CPLEAR Collaboration has obtained $\Re\delta$. They measure the distribution

$$A_\delta(t) = 4\Re\delta + \mathcal{F}\left(\Im\delta, y, \Re x_-, \Im x_+\right) \quad (5)$$

that depends, beside the CPT-violating parameter δ, on the parameters y and $x_\pm$ that describe the CPT violation in the decays and the violation of the $\Delta S = \Delta Q$ rule, respectively. They obtain:

$$\begin{aligned} \Re\delta &= (3.0 \pm 3.3 \pm 0.6) \times 10^{-4} \\ \Im\delta &= (-1.5 \pm 2.3 \pm 0.3) \times 10^{-2} \\ \Re x_- &= (0.2 \pm 1.3 \pm 0.3) \times 10^{-2} \\ \Im x_+ &= (1.2 \pm 2.2 \pm 0.3) \times 10^{-2} \end{aligned} \quad (6)$$

This result is improved by adding as a constraint the measurement [2,3] $A_S - A_L = 4\left[\Re\delta + \Re x_-\right] =$

*KLOE Collaboration

$(-1.8 \pm 10.0) \times 10^{-3}$ to the original CPLEAR fit, obtaining:

$$\begin{aligned} \Re\delta &= (3.3 \pm 2.8) \times 10^{-4} \\ \Im\delta &= (-1.1 \pm 0.7) \times 10^{-2} \\ \Re x_- &= (-0.03 \pm 0.25) \times 10^{-2} \\ \Im x_+ &= (0.8 \pm 0.7) \times 10^{-2} \end{aligned} \quad (7)$$

The uncertainty on $\Im x_+$ is reduced by a factor three. As we will see in the next section, this parameter enters in the unitarity relation and is one of the limiting factors in the determination of $\Im\delta$ and $\Re\epsilon$.

3. Experimental inputs to $\Im\delta$ and $\Re\epsilon$

The only decay modes relevant for the evaluation of Eq. (4) are the $\pi\pi(\gamma)$, $\pi\pi\pi$, and semileptonic modes. The product of amplitudes α_f are obtained from the lifetimes of the kaons, the ratios of K_S and K_L amplitudes η, and the branching ratios, in the following way:

$$\begin{aligned} \alpha_{\pi\pi} &= \eta_{\pi\pi} BR(K_S \to \pi\pi) \\ \alpha_{\pi\pi\gamma(DE)} &= \sqrt{\frac{\tau_S}{\tau_L} BR(K_L) BR(K_S)} e^{i\phi+-\gamma} \\ \alpha_{\pi\pi\pi} &= \frac{\tau_S}{\tau_L} \eta_{\pi\pi\pi} BR(K_L \to \pi\pi\pi) \end{aligned}$$

where $\pi\pi = \pi^+\pi^-, \pi^0\pi^0$, and $\pi\pi\pi = \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$. The $\pi^+\pi^-$ mode includes the inner bremsstrahlung (IB) emission. On the contrary, the direct emission (DE) component is added independently since there is no interference with the IB term.

The contribution of semileptonic decays to Eq. (4) is given by:

$$\begin{aligned} \alpha_{\pi l\nu} &= 2\frac{\tau_S}{\tau_L} BR(K_L \to \pi l\nu) \times \\ &\quad [\Re\epsilon - \Re y - i\Im\delta - i\Im x_+] \\ &= [(A_S + A_L)/4 - i\Im\delta - i\Im x_+] \end{aligned} \quad (8)$$

where $\Im x_+$ is given by Eq. (7), and $(A_S + A_L)/4 = \Re\epsilon - \Re y = (-4.8 \pm 19.0) \times 10^{-3}$, while $\Im\delta$ is the unknown of Eq. (4). The determination of $\Re y$ is of primary importance for the measurement of A_S [2].

Some of the most recent measurements entering in the determination of the α parameters are described in the following sections. The numerical results are shown in Tab. 1.

3.1. $\pi\pi$

The two body decays give the largest contribution to Eq. (4). The K_S branching ratios are obtained from the recent KLOE measurement of the ratio $\Gamma(K_S \to \pi^+\pi^-)/\Gamma(K_S \to \pi^0\pi^0) = (2.2549 \pm 0.0054)$ [4] with a sample of 400×10^6 $\phi \to K_S K_L$ decays. The $K_L \to \pi^+\pi^-$ branching ratio has been recently measured by KLOE [5] with ~ 45000 events, they find $BR(K_L \to \pi^+\pi^-(\gamma_{IB+DE})) = (1.963 \pm 0.021) \times 10^{-3}$, where both the IB and DE components are included. The DE component is then subtracted using the KTeV result described in the following. KTeV [6] measured both the charged and neutral decays with $\sim 10^5$ events each. They find $BR(K_L \to \pi^+\pi^-(\gamma_{IB})) = (1.975 \pm 0.012) \times 10^{-3}$, and $BR(K_L \to \pi^0\pi^0) = (0.865 \pm 0.010) \times 10^{-3}$. The measurement of charged mode includes only the IB component. The two new measurements of $BR(K_L \to \pi^+\pi^-)$ are in agreement but disagree with the PDG value of 2004.

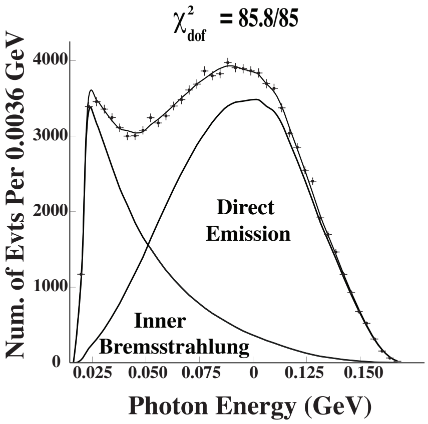

Figure 1. Spectrum of photon energy in $K_L \to \pi^+\pi^-\gamma$ events, measured by the KTeV Collaboration.

The DE component is measured with two different methods. With the first method, the photon spectrum is measured directly in $K_L \to \pi^+\pi^-\gamma$ decays. KTeV [7] has measured it from a

Table 1
Values of the α parameters.

α parameters	Real Part $\times 10^3$	Imaginary Part$\times 10^3$
$\alpha(\pi^+\pi^-)$	1.126 ± 0.014	1.064 ± 0.014
$\alpha(\pi^0\pi^0)$	0.494 ± 0.007	0.472 ± 0.008
$\alpha(\pi^+\pi^-\gamma(DE))$	0.000 ± 0.002	0.000 ± 0.002
$\alpha(\pi l\nu)_{\Im\delta=0}$	0.003 ± 0.002	-0.019 ± 0.017
$\alpha(\pi^+\pi^-\pi^0)$	0.001 ± 0.002	-0.001 ± 0.002
$\alpha(\pi^0\pi^0\pi^0)$	< 0.007 at 95% C.L.	< 0.007 at 95% C.L.

sample of $\sim 10^5$ $\pi\pi\gamma$ events with $E^*_\gamma > 20$ MeV (Fig. 1). They find that the fraction of DE component for $E^*_\gamma > 20$ MeV is $DE/(DE+IB) = 0.689 \pm 0.021$. With the second method, the internal conversion of the photon into a pair e^+e^- is used. The resulting decay $K_L \to \pi^+\pi^-e^+e^-$ shows an asymmetry in the distribution of the angle between the $\pi^+\pi^-$ and e^+e^- planes. This asymmetry is due to the interference between the IB and DE components. KTeV [8] measures this asymmetry with ~ 5000 selected events and extracts the information on the DE. The results are in agreement with the previous method, but less precise.

The DE component in K_S decay is suppressed by CP violation. The K_S photon spectrum has been measured in [9].

3.2. $\pi l\nu$

The semileptonic decays of K_L have been recently measured by KLOE [10], KTeV [6], and NA48 [11] in order to determine the Cabibbo angle. At this conference this item has been discussed in a different talk [12].

The $K_S \to \pi e\nu$ branching ratio and its charge asymmetry have been recently measured by KLOE [2] with a sample of 6500 selected events for each charge mode. The distribution of the missing energy minus the missing momentum $\Delta E_{\pi e}$ is shown in Fig. 2 for the $\pi^-e^+\nu$ sample. The signal is centered at zero as expected for a missing neutrino. KLOE finds $BR(K_S \to \pi e\nu) = (7.028 \pm 0.092) \times 10^{-4}$ and $A_S = (1.5 \pm 10.0) \times 10^{-3}$.

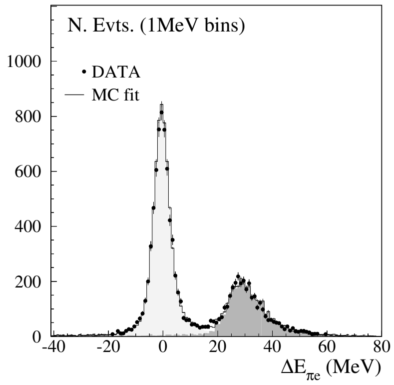

Figure 2. $E_{miss} - P_{miss}$ distribution for $K_S \to \pi^-e^+\nu$ decays.

3.3. $\pi\pi\pi$

The amplitudes for $K \to 3\pi$ decays can be decomposed according to the CP state of the three pion system:

$$\begin{aligned} a_L &= a_L^{CP-}(X,Y) \\ a_S &= a_S^{CP+}(X,Y) + a_S^{CP-}(X,Y) \end{aligned} \quad (9)$$

where $a^{CP+(-)}$ is the amplitude for the decay to the final state with $CP = +1(-1)$, and $X \propto E_+ - E_-$ and $Y \propto E_0$. The decay to the $CP = +1$ state is suppressed by the centrifugal barrier. Therefore, a_L^{CP+} is suppressed both by the centrifugal barrier and by CP violation and can be neglected. On the contrary, both K_S amplitudes are retained being one suppressed by CP violation and the other one by the centrifugal barrier. The amplitudes have the following symmetry property:

$$a^{CP\pm}(X,Y) = \mp a^{CP\pm}(-X,Y) \quad (10)$$

Hence, the only contribution to Eq. (4) comes from:

$$\eta_{+-0} = \frac{\int dXdY a_L^* a_S^{CP-}}{\int dXdY |a_L|^2} \quad (11)$$

while

$$\frac{\int dXdY a_L^* a_S^{CP+}}{\int dXdY |a_L|^2} = 0 \quad (12)$$

CPLEAR measures η_{+-0} from the time-dependent asymmetry [1]:

$$\frac{\bar{N}_{3\pi}(t) - N_{3\pi}(t)}{\bar{N}_{3\pi}(t) + N_{3\pi}(t)} \quad (13)$$

where $N_{3\pi}(t)$ ($\bar{N}_{3\pi}(t)$) is the number of decays to three pions observed at time t for kaons tagged as K^0 ($\bar{K}^0$) at time $t = 0$. They find:

$$\eta_{+-0} = (-2 \pm 7) \times 10^{-3} + i(-2 \pm 9) \times 10^{-3} \quad (14)$$

The CP-conserving component of the decay, parametrized by the quantity:

$$\lambda = \frac{\int_{X>0} dXdY a_L^* a_S^{CP+}}{\int_{X>0} dXdY |a_L|^2} \quad (15)$$

has been measured by NA48 [13] by fitting the time-dependent asymmetry:

$$\frac{N_{3\pi}^{X>0}(t) - N_{3\pi}^{X<0}(t)}{N_{3\pi}^{X>0}(t) + N_{3\pi}^{X<0}(t)} \quad (16)$$

They find:

$$\lambda = (0.038 \pm 0.010) + i(-0.013 \pm 0.007) \quad (17)$$

A similar result has been obtained also by CPLEAR [1].

Because of its symmetry property $a_S^{CP+}(X,Y) = 0$ for three equal pions, as in $K_S \to 3\pi^0$ decays. Therefore, this decay is CP violating, and its branching ratio is expected to be $\sim 10^{-9}$. Before the recent measurements of KLOE and NA48, $\Im\delta$ was limited by the poor knowledge of $\eta_{000} = a_S(000)/a_L(000)$.

There are two different ways of measuring this quantity. NA48 measures the interference in $K \to 3\pi^0$ decays as a function of the proper time, with 5×10^6 decays from the *near target*, normalized to the rate of 10^8 $K_L \to 3\pi^0$ from the *far target* [14]:

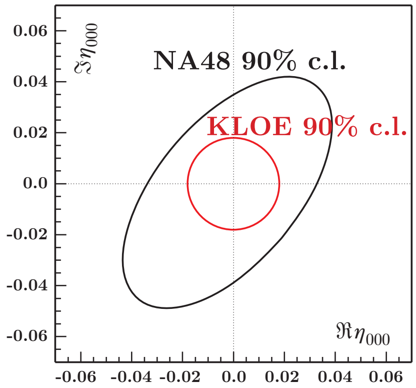

Figure 3. 90% C.L. limits on the plane $\Im\eta_{000}$-$\Re\eta_{000}$ obtained from the measurements of NA48 and KLOE.

$$\begin{aligned} f_{3\pi^0}(t) \quad \propto \quad & 1 + |\eta_{000}|^2 e^{-(\Gamma_S - \Gamma_L)t} \\ & +2D(p)\left[\Re\eta_{000}\cos\Delta mt - \Im\eta_{000}\right. \\ & \left.\sin\Delta mt\right] e^{-1/2(\Gamma_S-\Gamma_L)t} \end{aligned} \quad (18)$$

where $D(p)$ is the *dilution* factor that describes the momentum dependent production asymmetry between K^0 and $\bar{K}^0$ at the target. NA48 measures:

$$\eta_{000} = (-0.002 \pm 0.019) + i(-0.003 \pm 0.021) \quad (19)$$

KLOE uses a pure K_S beam tagged with a K_L. This allows KLOE to directly search $K_S \to 3\pi^0$ decays [15]. The selection is done on a sample of $\sim 5 \times 10^8$ $K_L - K_S$, looking for six photon clusters in the calorimeter and applying a veto for charged tracks in the drift chamber. For each decay both $2\pi^0$ and $3\pi^0$ hypotheses are tested defining two χ^2-like variables. The events are counted in the signal box in the plane defined by these two variables. KLOE finds 2 events with 3 background events expected, leading to the following 90% limits on the branching ratio and on the module of η_{000}:

$$\begin{aligned} BR(K_S \to 3\pi^0) &\leq 1.2 \times 10^{-7} \\ |\eta_{000}| &\leq 0.018 \end{aligned} \quad (20)$$

The comparison of NA48 and KLOE results is shown in Fig. 3.

The K_L decays to three pions have been measured by KLOE and KTeV, and a preliminary result for the $3\pi^0$ decay has been also presented by NA48. These measurements are described in [12].

4. Results

Following the method outlined in Secs. 2 and 3 and the values in Tab. 1 the KLOE Collaboration together with G. Isidori and G. D'Ambrosio obtained the following results:

$$\Re\epsilon = (161.0 \pm 1.0) \times 10^{-5}$$
$$\Im\delta = (1.3 \pm 2.0) \times 10^{-5} \quad (21)$$

and from Eq. (1):

$$\Gamma_{K^0} - \Gamma_{\bar{K}^0} = (5 \pm 4) \times 10^{-18} \text{ GeV}$$
$$m_{K^0} - m_{\bar{K}^0} = (-2.2 \pm 2.0) \times 10^{-18} \text{ GeV} \quad (22)$$

The 90% and 68% C.L. regions are shown in Fig. 4.

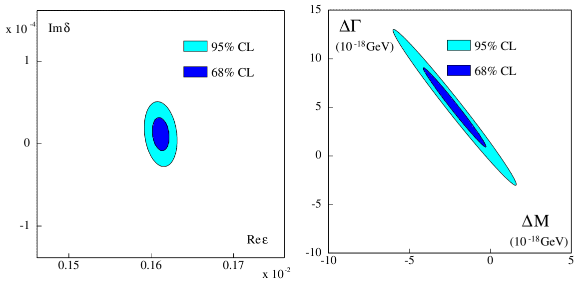

Figure 4. Allowed region at 68% and 95% C.L. in the $\Re\epsilon$, $Im\delta$ plane, and in the $\Gamma_{K^0} - \Gamma_{\bar{K}^0}$, $m_{K^0} - m_{\bar{K}^0}$ plane.

Assuming no CPT violation in the decay width ($\Gamma_{K^0} - \Gamma_{\bar{K}^0} = 0$), they find the 95% C.L.:

$$-4 \times 10^{-19} < m_{K^0} - m_{\bar{K}^0} < 7 \times 10^{-19} \text{ GeV} \quad (23)$$

to be compared with the previous determination due to the CPLEAR Collaboration:

$$-10 \times 10^{-19} < m_{K^0} - m_{\bar{K}^0} < 17 \times 10^{-19} \text{ GeV} \quad (24)$$

Eq. (23) is at present the most stringent test of CPT symmetry. The uncertainty is dominated by the knowledge of the phases ϕ_{+-} and ϕ_{00}, and of the parameter $\Im x_+$. Further improvements are expected from the analysis of the complete data sample of KLOE (~ 2.5 fb^{-1}), in particular for what concerns the K_S rare decays. However, there are no plans to further improve the determination of $\phi_{+-,00}$.

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