

Search for CP-violation in $K_S \rightarrow 3\pi^0$ decays with the NA48 detector

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Received: 13 October 2003 / Accepted: 6 January 2004 /
 Published Online: 6 February 2004 – © Springer-Verlag / Società Italiana di Fisica 2004

Abstract. The decay $K_S \rightarrow 3\pi^0$ is forbidden by CP conservation. Using a sample of more than 6 million $K \rightarrow 3\pi^0$ decays, the NA48 Collaboration has improved the limit on $\eta_{000} = A(K_S \rightarrow 3\pi^0)/A(K_L \rightarrow 3\pi^0)$ and on the branching ratio $Br(K_S \rightarrow 3\pi^0)$ by about one order of magnitude. Using this result and the Bell-Steinberger relation, a new limit on the equality of the K^0 and \bar{K}^0 masses is obtained improving by about 40% the test of CPT conservation in the mixing of neutral kaons.

1 Introduction

The NA48 experiment was optimized to measure the value of $Re(\epsilon/\epsilon)$, i.e. the ratio of *direct* over *indirect* CP violation in the kaon sector [1,2]. It took data between 1997 and 2001. The data taken during this period have been also used to perform a variety of other measurements of CP violation (η_{000} and K_{e3} charge asymmetry), mass and lifetime (K and η mass, K lifetime) and kaon and hyperon rare decays [3].

2 The NA48 detector

The NA48 experiment is a fixed target experiment which uses two concurrent and quasi overlapping beams of kaons, Fig. 1. One kaon beam (called FAR beam) is produced 126 m upstream the other beam and by the time it reaches the decay region all its K_S mesons have decayed away. The second kaon beam (called NEAR beam) is produced only 6 m before the decay region and therefore contains both K_S and K_L . The kaons are produced by a primary 450 GeV (400 GeV in 2001) proton beam ($\sim 1.5 \cdot 10^{12}$ per spill on the FAR target and $\sim 3 \cdot 10^7$ on the NEAR target) impinging on a 400 mm long, 2 mm diameter rod of beryllium. Charged particles from decays are measured by a magnetic spectrometer composed by four drift chambers with a dipole magnet between the second and third one which introduces a momentum kick of 265 MeV/c in the horizontal plane. The space point resolution is $\sim 95\mu\text{m}$ and the momentum resolution is $\sigma(p)/p = 0.48\% \oplus 0.009\% * p[\text{GeV}]$ (2001 values). The spectrometer is followed by a liquid krypton calorimeter 27 radiation length long with an energy resolution of $\sigma(E)/E = (3.2 \pm 0.2)\%/\sqrt{E} \oplus (9 \pm 1)\%/E \oplus (0.42 \pm 0.05)\%$. The detector is complemented by an hadronic calorimeter, a muon detector, fast hodoscopes for triggering, a proton

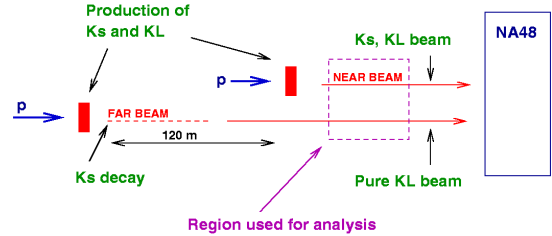


Fig. 1. The beam structure of the NA48 experiment

tagging system, beam monitors. A full description can be found in [1,2].

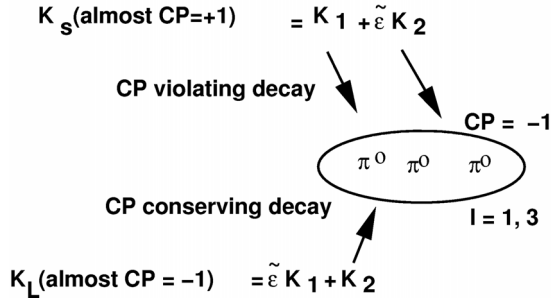
3 The kaon system

The K^0 , \bar{K}^0 flavour eigenstates are created by strong interaction. These states mix and propagate as mass eigenstates, K_S and K_L , which are a superposition of CP eigenstates: K_S is a quasi pure $CP = 1$ state and K_L a quasi pure $CP = -1$ state, Table 1. There is therefore a mismatch between the CP and the mass eigenstates which allows both K_S and K_L to decay into states of opposite CP.

Consider now the decay $K \rightarrow 3\pi^0$. Let's calculate the P, C and I values of a $|3\pi^0\rangle$ state. The parity is given by $P|3\pi^0\rangle = (-1)^l(-1)^L(-1)^3|3\pi^0\rangle$ where l is the angular momentum of a pair of π^0 , L is the angular momentum of the third π^0 with respect of this pair and $(-1)^3$ is the intrinsic parity of a $|3\pi^0\rangle$ state. Since the total angular momentum is $J = 0$ then $l = L$ and $P|3\pi^0\rangle = (-1)^{2l}(-1)^3|3\pi^0\rangle = -|3\pi^0\rangle$. The charge conjugation operation on a π^0 does not change its state, $C|\pi^0\rangle = |\pi^0\rangle$ so we have $C|3\pi^0\rangle = (+1)^3|3\pi^0\rangle = +|3\pi^0\rangle$. The isospin values of a $|3\pi^0\rangle$ state are $I=1$

Table 1. Kaon Eigenstates

Eigenstate	expression	CP value
Strong	$\bar{K}^0 (\bar{d}s), K^0 (d\bar{s})$	
CP	$K_1 \propto (K^0 + \bar{K}^0)$	+1
CP	$K_2 \propto (K^0 - \bar{K}^0)$	-1
Mass	$K_S \propto K_1 + \epsilon K_2$	Almost +1
Mass	$K_L \propto \epsilon K_1 + K_2$	Almost -1

**Fig. 2.** $K_S \rightarrow 3\pi^0$ and $K_L \rightarrow 3\pi^0$ decay mode

and $I=3$, which are both symmetric. The total wavefunction $|3\pi^0\rangle = |spin\rangle |space\rangle |isospin\rangle$ must be symmetric (three identical bosons) so both isospin values are allowed (the $|spin\rangle |space\rangle$ component, with $S=0$ and $l+L=0$ is of course symmetric). We have then: $CP|3\pi^0\rangle = -|3\pi^0\rangle$ with $K_L \rightarrow 3\pi^0$ a CP conserving decay and $K_S \rightarrow 3\pi^0$ a CP violating decay, both with $\Delta I = 1/2, 5/2$, Fig. 2.

4 η_{000}

In order to quantify the strength of CP violation in the $K_S \rightarrow 3\pi^0$ decay the following quantity has been introduced [4]:

$$\eta_{000} = \frac{A(K_S \rightarrow 3\pi^0)}{A(K_L \rightarrow 3\pi^0)}. \quad (1)$$

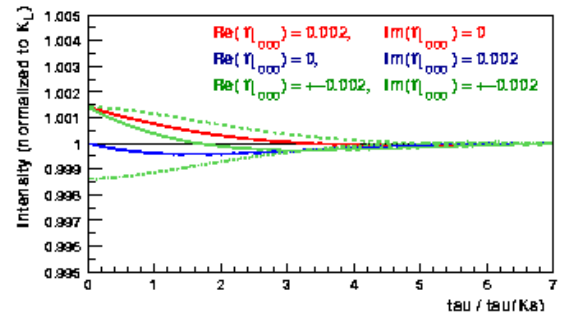
Assuming CPT invariance, using the Wu-Yang phase convention ($Im(a_0) = 0 \rightarrow \epsilon = \tilde{\epsilon}$) and ignoring transition into $I=3$ final states η_{000} can be rewritten as:

$$\eta_{000} = \epsilon + i \frac{Im(a_1)}{Re(a_1)} \quad (2)$$

where a_1 is the weak amplitude for K^0 to decay into $I=1$ final states and ϵ can be derived from the $K_L \rightarrow \pi\pi$ decay. In 2 $Re(\eta_{000}) = Re(\epsilon)$ so it's only the imaginary part which is sensitive to direct CP violation.

5 The method

Given the very small (still unknown) branching fraction it's very hard to measure directly the decay $K_S \rightarrow 3\pi^0$. However, it's possible to see it's presence since it interferes

**Fig. 3.** Interference pattern for different values of η_{000} normalized to $K_L \rightarrow 3\pi^0$

with the much larger decay $K_L \rightarrow 3\pi^0$: given a $K_S + K_L$ beam, the intensity of $3\pi^0$ decay is given by

$$I_{3\pi^0}(t) \propto \underbrace{e^{-\Gamma_L t}}_{K_L \text{ decay}} + \underbrace{|\eta_{000}|^2 e^{-\Gamma_S t}}_{K_S \text{ decay}} + \underbrace{+2D(p)[Re(\eta_{000})\cos\Delta mt - Im(\eta_{000})\sin\Delta mt]e^{0.5(\Gamma_S + \Gamma_L)t}}_{\text{interference } K_S - K_L}$$

where $D(p) = N(K^0 - \bar{K}^0)/N(K^0 + \bar{K}^0) \sim 0.35$, the dilution factor, parametrizes the K^0, \bar{K}^0 production asymmetry as a function of the kaon momentum. The maximum interference is at the target and most of the effect is contained within the first 2 K_S lifetime. The interference pattern is superposed over a large $K_L \rightarrow 3\pi^0$ signal and it can be positive or negative depending on the value of η_{000} , Fig. 3. The technique used for the measurement is therefore the following: 1) measure the intensity of $K \rightarrow 3\pi^0$ decay in the $K_S + K_L$ beam as a function of proper K_S time, 2) measure the same intensity for a pure K_L beam, 3) correct the two intensities for small differences between beams and systematic effects, 4) calculate the ratio of intensities and fit the interference term.

6 Data sample

This analysis have been performed using the data taken during the 2000 run. A sample of $6 \cdot 10^6 K_S + K_L \rightarrow 3\pi^0$ decays from the NEAR target and $\sim 10^7 K_L \rightarrow 3\pi^0$ decays from the FAR target have been collected, Fig. 4. To extract η_{000} a fit to the ratio of the NEAR/FAR samples is performed in kaon energy bins ($75 < E_K < 150$ GeV). Table 2 shows the sources of systematic errors. The systematics are dominated by uncertainties in the detector acceptance, accidental activity and the K^0, \bar{K}^0 dilution.

7 Results and discussion

The result of the simultaneous fit to all energy bins is:

$$Re(\eta_{000}) = -0.026 \pm 0.01_{stat}$$

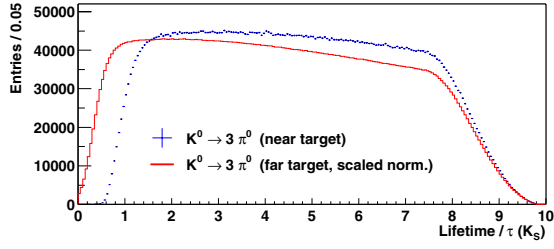


Fig. 4. $K \rightarrow 3\pi^0$ decays from the FAR and NEAR target in unit of K_S proper time

Table 2. Source of systematic errors

	$\text{Re } \eta_{000} (10^{-2})$	$\text{Im } \eta_{000} (10^{-2})$
Accidentals	± 0.1	± 0.6
Energy scale	± 0.1	± 0.1
Dilution	± 0.3	± 0.4
Acceptance	± 0.3	± 0.8
Binning	± 0.1	± 0.2
Total	± 0.5	± 1.1

$$\text{Im}(\eta_{000}) = -0.034 \pm 0.01_{\text{stat}}$$

$$\text{Br}(K_S \rightarrow 3\pi^0) < 1.4 \cdot 10^{-6} \text{ 90\%CL.}$$

The values of $\text{Re}(\eta_{000})$ and $\text{Im}(\eta_{000})$ have a correlation coefficient of 0.8. According to 2 the constrain $\text{Re}(\epsilon) = \text{Re}(\eta_{000})$ can be used in the fit changing the results to:

$$\text{Im}(\eta_{000}) = -0.012 \pm 0.007_{\text{stat}} \pm 0.011_{\text{syst}}$$

$$\text{Br}(K_S \rightarrow 3\pi^0) < 3.0 \cdot 10^{-7} \text{ 90\%CL.}$$

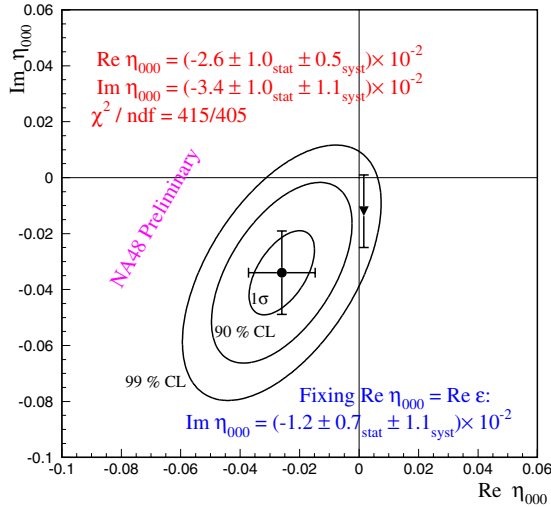


Fig. 5. Fit results for η_{000} assuming or not $\text{Re}(\epsilon) = \text{Re}(\eta_{000})$

Table 3. Results from other experiments

Exp.	Year	Technique	Result
FNAL-E621	1994	$K^0 - \bar{K}^0$ incoherent	$\text{Im } \eta_{+-0} = -1.5 \pm 1.7 \pm 2.5 \cdot 10^{-2}$
CERN	1998	$p - \bar{p} \rightarrow K^- \bar{K}^0 \pi^+$	$\text{Re } \eta_{+-0} = -2 \pm 7^{+4}_{-1} \cdot 10^{-3}$
CPLEAR		$\rightarrow K^+ \bar{K}^0 \pi^-$	$\text{Im } \eta_{+-0} = -2 \pm 9^{+2}_{-1} \cdot 10^{-3}$
Barmin et al.	1983	Bubble ch.	$\text{Re } \eta_{000} = -8 \pm 18 \cdot 10^{-2}$ $\text{Im } \eta_{000} = -5 \pm 27 \cdot 10^{-2}$
CERN	1998	$p - \bar{p} \rightarrow K^- \bar{K}^0 \pi^+$	$\text{Re } \eta_{000} = 18 \pm 14 \pm 6 \cdot 10^{-2}$
CPLEAR		$\rightarrow K^+ \bar{K}^0 \pi^-$	$\text{Im } \eta_{000} = 15 \pm 20 \pm 3 \cdot 10^{-2}$
Novosibirsk	1999	Tagged K_0	$\text{Br}(K_S \rightarrow 3\pi^0) < 1.4 \cdot 10^{-5}$
SND		$e e \rightarrow \phi \rightarrow K_S K_S$	

Figure 5 shows these numbers while Table 3 lists the results of other experiments. NA48 has improved the precision of both η_{000} and $\text{Br}(K_S \rightarrow 3\pi^0)$ by an order of magnitude.

7.1 The Bell-Steinberger relation

Consider a kaon state, superposition of K_S and K_L , $|K(t)\rangle = a_S K_S + a_L K_L$. Conservation of probability requires that the time derivative of this state is equal to the sum of the decay rates [5]:

$$-\frac{d}{dt} | \langle K(0) | K(0) \rangle |^2 = \sum |a_S A(K_S \rightarrow f) + a_L A(K_L \rightarrow f)|^2.$$

This relation can be rewritten as:

$$(1 + i \tan(\phi_{SW})) [\text{Re}(\epsilon) - i \text{Im}(\Delta)] = \sum \alpha_f$$

with $\tan(\phi_{SW}) = 2\Delta m / (\Gamma_S - \Gamma_L)$, $\alpha_f = 1/\Gamma_S A^*(K_S \rightarrow f) A(K_L \rightarrow f)$ the possible decays ($K_L \rightarrow \pi\pi$, $K_S \rightarrow 3\pi^0 \dots$) and Δ the magnitude of CP violation with CPT violation. This identity therefore constrains CPT via the value of $\text{Im}(\Delta)$ which, with the new value of $\alpha_{000} = \frac{\tau_S}{\tau_L} \eta_{000} \text{Br}(K_L \rightarrow 3\pi^0)$, is reduced by almost 40%:

$$\text{Im}\Delta = (2.4 \pm 5.0) \cdot 10^{-5} \rightarrow \text{Im}\Delta = (-1.2 \pm 3.0) \cdot 10^{-5}.$$

$\text{Im}(\Delta)$ is now limited by the knowledge of η_{+-} . Assuming CPT this result can be converted into a new limit on the K^0, \bar{K}^0 mass difference:

$$m_{K^0} - m_{\bar{K}^0} = (-1.7 \pm 4.2) \cdot 10^{-19} \text{ GeV}/c^2.$$

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