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

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Abstract. The decay $K_S \to 3\pi^0$ is forbidden by CP conservation. Using a sample of more than 6 million $K \to 3\pi^0$ decays, the NA48 Collaboration has improved the limit on $\eta_{3\pi^0} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0)$ and on the branching ratio $Br(K_S \to 3\pi^0)$ 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.

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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 also been used to perform a variety of other measurements of CP violation ($\eta_{3\pi^0}$ and $K_{\Sigma^3}$ charge asymmetry), mass and lifetime ($K$ and $\eta$ 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 $\sim 95 \mu m$ and the momentum resolution is $\sigma(p)/p = 0.48\% \pm 0.009\% * p[GeV]$ (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 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, Tab. 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 $K \to 3\pi^0$. Let’s calculate the P, C and I values of a $|3\pi^0 >$ state. The parity is given by $P|3\pi^0 > = (-1)^l(-1)^3|3\pi^0 >$ where $l$ is the angular momentum of a pair of $\pi^0$, $L$ is the angular momentum of the third $\pi^0$ with respect of this pair and $(-1)^3$ is the intrinsic parity of a $|3\pi^0 >$ state. Since the total angular momentum is $J = 0$ then $l = L$ and $P|3\pi^0 > = (-1)^2(-1)^3|3\pi^0 > = -|3\pi^0 >$. The charge conjugation operation on a $\pi^0$ does not change its state,
Table 1. Kaon Eigenstates

| Eigenstate | expression | CP value |
|------------|------------|----------|
| Strong     | $K^0 (d_s), K^0 (d)$ |            |
| CP         | $K_1 \propto (K^0 + K^0)$ | $+1$ |
| CP         | $K_2 \propto (K^0 - K^0)$ | $-1$ |
| Mass       | $K_3 \propto K_1 + \epsilon K_2$ | Almost $+1$ |
| Mass       | $K_L \propto \epsilon K_1 + K_2$ | Almost $-1$ |

$K_S$ (almost CP $= +1$) = $K_1 + \bar{\epsilon} K_2$

CP violating decay

CP conserving decay

$I = 1, 3$

$K_L$ (almost CP $= -1$) = $\bar{\epsilon} K_1 + K_2$

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

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

$\eta_{oo}$

In order to quantify the strength of CP violation in the $K_S \to 3\pi^0$ decay the following quantity has been introduced [1]:

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

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

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

where $a_1$ is the weak amplitude for $K^0$ to decay into I=1 final states and $\epsilon$ can be derived from the $K_L \to \pi\pi$ decay. In eq. 2 $Re(\eta_{oo}) = Re(\epsilon)$ so it’s only the immaginary 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 $K_S \to 3\pi^0$. However, it’s possible to see it’s presence since it interferes with the much larger decay $K_L \to 3\pi^0$: given a $K_S + K_L$ beam, the intensity of $3\pi^0$ decay is given by

$$I_{3\pi^0}(t) \propto e^{-\Gamma_L t} + |\eta_{oo}|^2 e^{-\Gamma_S t} + 2D(p)|Re(\eta_{oo})\cos \Delta m t - Im(\eta_{oo})\sin \Delta m t|e^{0.5(\Gamma_L + \Gamma_L)t}$$

interference $K_S - K_L$

where $D(p) = N(K^0 - K^0)/N(K^0 + K^0) \sim 0.35$, 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 $K_L \to 3\pi^0$ signal and it can be positive or negative depending on the value of $\eta_{oo}$, Fig. 3. The technique used for the measurement is therefore the following: 1) measure the intensity of $K \to 3\pi^0$ 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 has been performed using the data taken during the 2005 run. A sample of $6 \cdot 10^6 K_S + K_L \to 3\pi^0$ decays from the NEAR target and $\sim 10^7 K_L \to 3\pi^0$ decays from the FAR target have been collected, Fig. 4. To extract $\eta_{oo}$ a fit to the ratio of the NEAR/FAR samples is performed in kaon energy bins ($75 < E_K < 150$ GeV).
Table 2. Source of systematic errors

| Source of systematic errors | Re $\eta_{o0}$($10^{-2}$) | Im $\eta_{o0}$($10^{-2}$) |
|----------------------------|---------------------------|---------------------------|
| Accidents                  | $\pm 0.1$                 | $\pm 0.6$                 |
| Energy scale               | $\pm 0.1$                 | $\pm 0.1$                 |
| Dilution                   | $\pm 0.3$                 | $\pm 0.4$                 |
| Acceptance                 | $\pm 0.3$                 | $\pm 0.8$                 |
| Binning                    | $\pm 0.1$                 | $\pm 0.2$                 |
| Total                      | $\pm 0.5$                 | $\pm 1.1$                 |

7 Results and discussion

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

$$Re(\eta_{o0}) = -0.026 \pm 0.01 stat$$

$$Im(\eta_{o0}) = -0.034 \pm 0.01 stat$$

$$Br(K_S \rightarrow 3\pi^0) < 1.4 \times 10^{-9} 90\% CL.$$  

The values of $Re(\eta_{o0})$ and $Im(\eta_{o0})$ have a correlation coefficient of 0.8. According to eq. 2 the constrain $Re(\epsilon) = Re(\eta_{o0})$ can be used in the fit changing the results to:

$$Im(\eta_{o0}) = -0.012 \pm 0.007 stat \pm 0.011 sys$$

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

Fig. 4 shows these numbers while Tab. 3 lists the results of other experiments. NA48 has improved the precision of both $\eta_{o0}$ and $Br(K_S \rightarrow 3\pi^0)$ by an order of magnitude.

7.1 The Bell-Steinberger relation

Consider a kaon state, superposition of $K_S$ and $K_L$,

$$|K(t)\rangle = a_S|K_S\rangle + a_L|K_L\rangle.$$  

Conservation of probability requires that the time derivative of this state is equal to the sum of the decay rates:

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

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