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A DIRECT SEARCH FOR $K_S \to 3\pi^0$ DECAY AT KLOE.

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ABSTRACT

We have searched for $K_S \to 3\pi^0$ decay in a sample of $\sim$450 pb^{-1} of electron-positron collisions collected at the Frascati ϕ-factory DAΦNE. A direct observation of this decay is a sign of CP violation and a stringent limit on its

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branching ratio, BR, helps on improving the accuracy on the CPT violation parameter of the mixing matrix δ. The most stringent limit on $BR(K_S \to 3\pi^0)$ is obtained.

1 The KLOE experiment

The data were collected with the KLOE [1, 4] detector at DAΦNE [5], the Frascati ϕ-factory. DAΦNE is an e^+e^- collider which operates at a center of mass energy W of $\sim$ 1020 MeV, the mass of the ϕ-meson [6]. ϕ mesons are produced, essentially at rest, with a visible cross section of ~ 3.2 μb and decay into K^+K^- ($K_S K_L$) pairs with BR of $\sim$ 49% ($\sim$ 34%). All of the above implies that the detection of a K_L guarantees the presence of a K_S of given momentum and direction. We refer to this technique as K_S *tagging*.

The KLOE detector consists of a large cylindrical drift chamber, DC [1], surrounded by a lead-scintillating fiber electromagnetic calorimeter, EMC [2]. A superconducting coil around the EMC provides a 0.52 T field.

The drift chamber is 4 m in diameter and 3.3 m long. The position resolutions are σ_{xy} $\sim$150 μm and σ_z $\sim$ 2 mm. The momentum resolution is $\sigma(p_\perp)/p_\perp \approx 0.4\%$. Vertices are reconstructed with a spatial resolution of $\sim$3 mm.

The calorimeter is divided into a barrel and two endcaps and covers 98% of the solid angle. The arrival times of particles and the positions in three dimensions of the energy deposits are obtained from the signals collected at the two ends. Energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E\ (\mathrm{GeV})}$ and $\sigma_t = 57\ \mathrm{ps}/\sqrt{E\ (\mathrm{GeV})} \oplus 50$ ps, respectively.

During 2002 data taking, the maximum luminosity reached by DAΦNE was $7.5 \cdot 10^{31}$ cm^{-2} s^{-1} ($\sim$ 160 ϕ/s) and at the end of 2002, we collected ~ 4.5 pb^{-1}/day. The entire collected sample (2001-2002) amounts to 450 pb^{-1}, equivalent to 1.4 billion (450 million) ϕ decays (K_S,K_L pairs).

The mean decay lengths of the K_S and K_L are $\lambda_S \sim 0.6$ cm and $\lambda_L \sim 340$ cm. The K_L interaction in the calorimeter (K_L-crash) is identified by requiring a cluster of energy above 100 MeV, which is not associated to any track, and whose time corresponds to a velocity $\beta = R/cT$ compatible with that one of the K_L, $\beta_k \sim 0.2$. The K_L-crash provides a clean K_S tagging. Reconstruction of one kaon establishes the trajectory of the other one with an angular resolution of 1° and a momentum resolution of ~ 2 MeV.

2 Introduction

The decay $K_S \to 3\pi^0$ is a pure CP violating process. The related CP violation parameter is defined as the ratio of K_S to K_L decay amplitudes: $\eta_{000} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0) = \varepsilon + \varepsilon'_{000}$ where ε describes the CP violation in the mixing matrix and ε'_{000} is a direct CP violating term. In the Standard Model we expect η_{000} to be similar to η_{00}. The expected branching ratio, BR, of this decay, is therefore $\sim 2 \cdot 10^{-9}$ The best upper limit on the BR has been set to $1.5 \cdot 10^{-5}$ by SND [7] The weighted average of the best published values [8, 9] gives: $\eta_{000} = (0.08 \pm 0.11) + i \cdot (0.07 \pm 0.16)$. Study this decay is also important because the uncertainty on η_{000} limits the precision on CPT test via the unitarity relation [10]. A neutral kaon state [6] can be expressed as: $K_{S,L} = K_{1,2} + (\varepsilon \pm \delta)K_{2,1}$ where K_1 and K_2 are the two CP eigenstates and δ is a CPT violation parameter in mixing. A possible form of the unitarity relation is:

$$(1 + i\tan(\phi_{sw}))(\Re(\varepsilon) - i\Im(\delta)) = \sum(A^*(K_S \to f)A(K_L \to f)/\Gamma_S) \qquad (1)$$

where the sum runs over all the possible decay channels f, and $\tan(\phi_{sw}) = 2\Delta m_{S,L}/(\Gamma_S - \Gamma_L)$. According to ref. [11], the value of $\Im(\delta) = (2.4 \pm 5.0) \cdot 10^{-5}$ is limited by the measurement on η_{000}. Neglecting this term, the same analysis yields $\Im(\delta) = (-0.5 \pm 2.0) \cdot 10^{-5}$; an improvement of around a factor 2.5 on the accuracy.

3 The direct search of $K_S \to 3\pi^0$

In this analysis we have used the whole sample of 450 pb^{-1}, and we expect 0.9 standard model $K_S \to 3\pi^0$ events produced.

Our selection starts by requiring a K_L-crash tag and six neutral clusters coming from the interaction point, IP. A tight constraint on β and moderate requirements on energy and angular acceptance are applied in order to have a large control sample for the background, while retaining a large selection efficiency for the signal. Applying this selection we have an initial sample of $\sim$39000 events. To get the branching ratio we then normalize the final event counting to the rate of $K_S \to 2\pi^0$.

Since $K_S \to 3\pi^0$decay has 6 photons in the final state, the major expected background in this search is $K_S \to 2\pi^0$ +2 fake photons coming from shower fragments, machine background clusters in overlap with the events or both possibilities.

The first step to reduce the background is the application of a kinematic fit procedure which imposes K_S mass, K_L 4-momentum conservation and $\beta = 1$ for each γ. By cutting at reasonable χ^2_{fit} value (ndf=11, $\chi^2_{\rm fit}/\text{ndf} < 3$) we retain 70% of the signal and reduce of a factor ~ 3 the background.

To further improve the rejection and disentangle $3\pi^0$ from $2\pi^0$ final states, we define 2 pseudo-χ^2, $\chi^2_{3\pi}$ and $\chi^2_{2\pi}$. The $\chi^2_{3\pi}$ is based only on the 3 best reconstructed pion masses, while the $\chi^2_{2\pi}$ selects 4 out of the 6 photons providing the best kinematic agreement with the $K_S \to 2\pi^0$ decay. By studying the correlation between $\chi^2_{3\pi}$ and $\chi^2_{2\pi}$ we define a signal box and five surrounding control boxes. To determine how well the data-MC normalization holds in different scatter-plot regions we have projected $\chi^2_{3\pi}$ in bands of $\chi^2_{2\pi}$. All bands show a reasonable data-MC agreement. Studying these comparison, we found a large peak near our signal box, due to fake K_L-crash tags given mostly by $K_S \to \pi^+\pi^-$, $K_L \to 3\pi^0$ events. For this background, the K_S charged pions interact on the quadrupoles creating late clusters which simulates the K_L-crash, while part of the K_L's decay close to the IP thus mimicking our signal. Our Monte Carlo simulates well the shapes of the fake K_L-crash background and we have calibrated its amount fitting data with a linear combination of MC with and without K_L-crash fakes.

Although by cutting on χ^2_{fit} we have a good handle on the fake K_L-crash background we reduce it to a negligible amount by vetoing events with tracks coming from the IP (see Fig. 1). Moreover, in order to enforce the $\chi^2_{2\pi}$ selection of photons we add a cut on the variable $\Delta E = M_\phi/2 - \sum E_i$, where the sum runs over the four γ's chosen by the $\chi^2_{2\pi}$ algorithm. For a $K_S \to 2\pi^0 + 2\gamma$ fake events $\Delta E \sim 0$ MeV, while for a signal event the missing π^0 mass reflects in a larger ΔE value (~ 135 MeV).

Before opening the signal-box we have optimized the limit [12] by varying the cuts on χ^2_{fit}, $\chi^2_{2\pi}$, $\chi^2_{3\pi}$ and ΔE on the MC samples. As a result of this procedure the final cuts have been set to: $\chi^2_{fit} < 31$, $\Delta E > 37$ MeV and we have defined the following signal box region ($14 < \chi^2_{2\pi} < 60$ and $\chi^2_{3\pi} <3.7$).

With an efficiency, after tagging, of $\varepsilon_{3\pi} = (22.6\pm0.8)\%$, we count 4 events

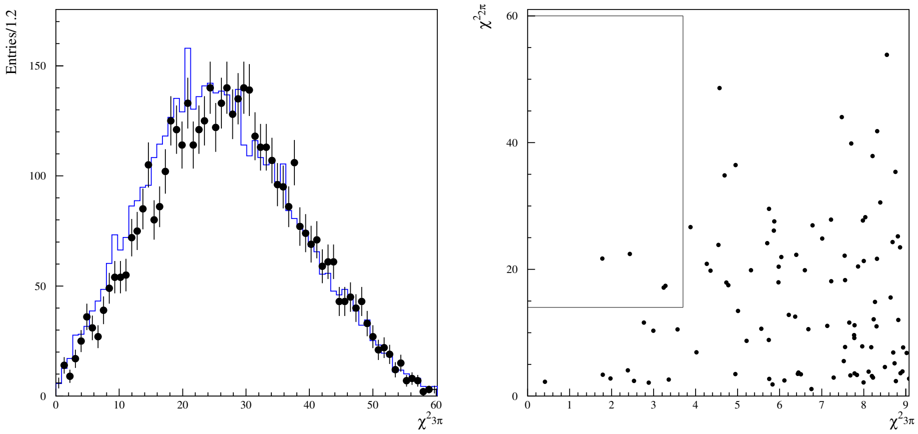

Figure 1: *(left) $\chi 2_{3\pi}$ distribution in the band of $\chi 2_{2\pi}$ which contain the signal box for DATA (●●) and Monte Carlo (–) after track veto; (right) candidates from data in the signal box, at the end of the analysis chain.*

(See Fig. 1) for an expected background $N_b = 3.2 \pm 1.4_{MCstat} \pm 0.5_{syst}$. The systematic error on the background is evaluated by comparing, data and MC expectations, in the five control boxes while varying the analysis cuts. Folding a gaussian behavior to the background uncertainty, we quote the number of $K_S \to 3\pi^0$ decay to be below 5.8 at 90% C.L. In the same tagged sample, we count $3.8 \cdot 10^7$ $K_S \to 2\pi^0$ events to normalize the counting to the BR($K_S \to 2\pi^0$). By this normalization we finally derive BR($K_S \to 3\pi^0$) $\leq 2.1 \cdot 10^{-7}$ at 90% C.L. which improves of a factor ~ 70 the previous measurement.

4 Related physical results

Our result on the upper limit can be used to calculate other parameters directly related to CPT test. From relation:

$$|\eta_{000}| = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)} = \sqrt{\frac{\tau_S}{\tau_L} \frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}} \tag{2}$$

we obtain $|\eta_{000}| \leq 0.024$ at 90 % C.L. which reduces of a factor ~ 5 the uncertainty on this parameter [7, 8, 9].

We can also set a conservative limit on the contribution of the $K_S \to 3\pi^0$decay to $\Im(\delta)$ ($\Im(\delta_{000})$). From eq. 1 we obtain:

$$\Im(\delta_{000}) = -\Im\left[\frac{1}{1+i\tan(\phi_{SW})}\alpha_{000}\right] \quad (3)$$

where $\alpha_{000} = \tau_S/\tau_L BR(K_L \to 3\pi^0)\eta_{000}$ [10]. We finally derive:

$$\Im(\delta_{000}) = BR(K_L \to 3\pi^0)\frac{\tau_S}{\tau_L}|\eta_{000}|cos(\phi_{SW})sin(\phi_{SW} - \phi_{000}) \quad (4)$$

where ϕ_{000} is the η_{000} complex-phase. For any possible value of ϕ_{000} our limit on $|\eta_{000}|$ bounds $|\Im(\delta_{000})| < 6.34 \cdot 10^{-6}$ at 90 % C.L.

Our measurement makes η_{000} comparable to the existing measurement of $\eta_{+-0} = [(-2 \pm 8) + i(-2 \pm 9)] \times 10^{-3}$. Hence, following the analysis of CPLEAR [11] we conclude that the accuracy on $\Im(\delta)$ is now reduced to $2.5 \cdot 10^{-5}$ without any further assumption.

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