Recent KLOE results on rare $K_SK_L$ processes

Matteo Martini
For the KLOE collaboration
INFN, Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati (Rm), Italy.
E-mail: matteo.martini@lnf.infn.it

Abstract. We present the measurements of the branching ratio for the $K_S \to \gamma\gamma$ and $K_S \to \pi\nu\bar{\nu}$ decays, and a direct search for the $K_S \to e^+e^-$ decay carried out with the KLOE detector at DAΦNE. Using the latest KLOE results on kaon decays, we have also increased the accuracy of the CPT test made with the Bell-Steinberger relation.

1. Measurement of $\text{BR}(K_S \to \gamma\gamma)$
A precise measurement of the $K_S \to \gamma\gamma$ decay rate is an important test of the predictions of Chiral Perturbation Theory ($\chi PT$). The decay amplitude of $K_S \to \gamma\gamma$ has been evaluated at the leading $O(p^4)$ order of $\chi PT$ with a few percent precision [1] giving $\text{BR}(K_S \to \gamma\gamma) = 2.1 \times 10^{-6}$. The more recent measurement of this decay, published from NA48 [2], indicates a branching ratio of $2.78 \times 10^{-6}$ with a total uncertainty below 3%. This result differs from $\chi PT O(p^4)$ prediction of about 30% suggesting the presence of important contributions from higher order corrections.

In KLOE, $K_S$ mesons are clearly tagged with an efficiency of $\sim 30\%$ by identifying a $K_L$ interaction in the calorimeter ($K_L$-crash in the following) which has a very distinctive signature given by a delayed ($\beta_K = 0.2$) energy cluster not associated to any track.

The main source of background for the $K_S \to \gamma\gamma$ decay is due to $K_S \to 2\pi^0$ events where two photons are not detected, either because outside the acceptance, or not reconstructed by the calorimeter. For the Monte Carlo simulation, MC, of the background, we use a production of $\phi \to K_SK_L$ decays corresponding to an equivalent luminosity of $\sim 1.1$ fb$^{-1}$. For the signal MC we use a production equivalent to $\sim 18$ fb$^{-1}$. The data sample analyzed for this measurement corresponds to 1.6 fb$^{-1}$.

To reject the main background from $K_S \to 2\pi^0$ decays, we count the number of prompt photons, $N_\gamma$ with energy above 7 MeV produced in a large angular acceptance, $|\cos(\theta)| < 0.93$. To improve the background rejection we also veto events from the small angle calorimeter, QCAL [3].

To improve the signal over background ratio we apply a kinematic fit ($N_{dof} = 7$) which imposes 4-momentum conservation on $\phi \to K_SK_L$ and $K_S \to \gamma\gamma$ decays, and $\beta = 1$ for each energy cluster. We reject events with $\chi^2_{fit} < 20$. To estimate the signal, we look at the two-dimensional distribution of the two-photon invariant mass, $M_{\gamma\gamma}$, and the opening angle between the two photons in the $K_S$ center of mass system, $\theta_{\gamma\gamma}$. A binned max-likelihood fit to the $M_{\gamma\gamma} - \theta_{\gamma\gamma}$ 2D distribution on data is done by using the MC shapes for signal and background.
and $M_{\gamma\gamma}$. Solid line: data, red area: MC signal, blue area: MC background, dashed line: MC signal+background. The MC shapes have been scaled with the weights determined by the fit.

Fig. 1 shows the fit result for the two-photon invariant mass and the angle distributions. The angle distribution for the signal has a shape more peaked around $\cos\theta^*_\gamma = -1$ than for the background. The $M_{\gamma\gamma}$ distribution shows a gaussian shape around the $K_S$ mass for the signal, while the background populates the low mass values. We count $N(2\gamma|\text{tag}) = 600 \pm 35$ signal events in a total of 2280 events. The branching ratio is normalized to the number of $K_S \rightarrow 2\pi^0$ events recorded in the same data sample by counting the $K_S$ tagged events with $N_e = 4$.

The signal efficiency is the product of the efficiencies for the acceptance selection, the QCAL veto and the $\chi^2$-cut: $\varepsilon(2\gamma|\text{tag}) = (50.8 \pm 0.6^{+0.5}_{-0.4})\%$. The number of $K_S \rightarrow 2\pi^0$ events after correcting for the selection efficiency is $(159.8 \pm 0.5) \times 10^6$. Using $\text{BR}(K_S \rightarrow 2\pi^0) = (30.69 \pm 0.05)\%$ [4], we obtain:

$$\text{BR}(K_S \rightarrow \gamma\gamma) = (2.27 \pm 0.13(\text{stat.})^{+0.03}_{-0.04}(\text{syst.})) \times 10^{-6}$$

where the second error includes the systematics due to fit procedure and to the small difference in energy scale between data and MC.

2. Direct search for $K_S \rightarrow e^+e^-$

The $K_S \rightarrow e^+e^-$ decay, like $K_L \rightarrow e^+e^-$ or $K_L \rightarrow \mu^+\mu^-$, is a flavour-changing neutral-current process, suppressed in the Standard Model and dominated by the two-photon intermediate state [5]. Using $\chi^PT$ to order $O(p^4)$, Ecker and Pich evaluated the ratio $\Gamma(K_S \rightarrow e^+e^-)/\Gamma(K_S \rightarrow \gamma\gamma) = 8 \times 10^{-3}$ with 10% uncertainty [5]. Using the present average, $\text{BR}(K_S \rightarrow \gamma\gamma) = (2.71 \pm 0.06) \times 10^{-6}$ [4], the Standard Model prediction is $\text{BR}(K_S \rightarrow e^+e^-) \simeq 10^{-15}$.

$K_S$ decays are tagged using the $K_L$-crash algorithm. $K_S \rightarrow e^+e^-$ events are selected requiring the presence of two tracks of opposite charge forming a vertex inside a cylinder centered on the origin of 4 cm radius and 10 cm length along the beam line. The track momenta and polar angles must satisfy the cuts ($120 < p < 350$) MeV/c and $30^\circ < \theta < 150^\circ$. The tracks must also reach the calorimeter without spiralling, and have an associated cluster with $E > 50$ MeV.

The main backgrounds are $K_S \rightarrow \pi^+\pi^-$ decays where two pions are misidentified, and $\phi \rightarrow \pi^+\pi^0\pi^0$ decays where one prompt photon simulates $K_L$-crash and the other goes undetected. For the first, the $M_{ee}$ invariant mass is peaked at low values: a cut $M_{ee} > 420$ MeV/$c^2$ rejects most of the background. After preselection we are left with $\sim 10^6$ events. To improve the signal and background separation, a $\chi^2$-like variable is defined, which uses information from the clusters associated to the two tracks.

After applying few kinematical cuts to reduce the background contamination, we normalize the relative fraction of background using the side bands. A signal box to select $K_S \rightarrow e^+e^-$ events can be conveniently defined in the $\chi^2$-$M_{ee}$ plane.
The signal box is chosen with an optimization procedure based on MC only. The boundaries are \((492 < M_{ee} < 504)\) MeV/\(c^2\) and \(\chi^2 < 20\), corresponding to a total signal efficiency of 55.8%.

Applying this selection to the data sample we obtain \(N_{obs} = 3\). The background estimated from MC is \(\mu_B = 7.1 \pm 3.6\), the value takes into account events fluctuations and normalization factors. Using a bayesian approach [6], we evaluate the upper limit on the expected number of signal events \(S < 4.3\) at 90% CL. The chosen interval for \(M_{ee}\) selects \(K_S \rightarrow e^+ e^- (\gamma)\) events with \(E_{\gamma} < 6\) MeV. Then we derive an upper limit for the branching ratio \(BR(K_S \rightarrow e^+ e^- (\gamma); E_{\gamma} < 6\) MeV) < 2.1 \times 10^{-8}\) at 90% CL.

3. Measurement of \(BR(K_L \rightarrow \pi ev\gamma)\)

The experimental measurements of this decay show a marginal disagreement from theoretical expectation. The ratio: \(R = BR(Ke3\gamma, E_\gamma^* > 30\) MeV, \(\theta_{lep-\gamma}^*)/BR(Ke3(\gamma))\) has two possible components: radiation from electron bremsstrahlung, IB, and from weak vertex, DE. Due to the small electron mass, IB is dominant. The separation between IB and DE has never been measured before. Using a sample of \(2 \times 10^6\) \(K_{e3}\) decays, KLOE obtain a preliminary result: \(R = BR(K_L \rightarrow \pi ev\gamma)/BR(K_L\pi ev) = 0.924 \pm 0.023_{\text{stat}} \pm 0.016_{\text{syst}}\), so confirming the disagreement with theory. According to [7], the spectrum can be parametrized as:

\[
\frac{d\Gamma}{dE_\gamma} = \left( \frac{d\Gamma}{dE_\gamma^*} \right)_{IB} + \left[ \langle X \rangle f \left( E_\gamma^* \right) \right]
\]

We obtain: \(\langle X \rangle = (2.3 \pm 1.3)_{\text{stat}} \pm 1.4_{\text{syst}}\)

4. CPT test with Bell-Steinberger relation

The CPT test from unitarity relation is based on \(K_S K_L\) observables [8]:

\[
(1 + i \tan \phi_{SW}) [\Re \varepsilon - i3\delta] = \frac{1}{\Gamma_S} \sum_f A^* (K_S \rightarrow f) A (K_L \rightarrow f) = \sum_f \alpha_f
\]

The most important contribution from KLOE are: measurement of \(K_S\) semileptonic asymmetry, upper limit on \(BR(K_S \rightarrow 3\pi^0)\) and the evaluation of \(3\pi^+\) from a combined fit of KLOE and CPLEAR data. The main uncertainty on \(3\delta\) comes now from \(\eta_{++}\) trough \(\phi_{++}\).

Using KLOE results we obtain: \(\Re \varepsilon = (159.6 \pm 1.3) \times 10^{-5}\) and \(3\delta = (0.4 \pm 2.1) \times 10^{-5}\). Assuming \(\Delta \Gamma = 0\) (i.e. no CPT violation in decay), the result on \(3\delta\) can be converted in a limit for:

\[
\left( -5.3 \times 10^{-19} < \Delta M(K^0 - \bar{K}^0) < 6.3 \times 10^{-19} \right)
\]

at 95% C.L.

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