K$^\pm$e$^2$ search and Lepton Flavor Violation at KLOE

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This paper is devoted to the first analyses based on the complete data sample collected by the KLOE detector at DAΦNE, the Frascati φ-factory. The result for the BR($K_S \to \gamma\gamma$) and the search for the decay $K_S \to e^+e^-$ are presented. Particular emphasis is put on the measurement of the ratio of $K_{e2}$ and $K_{\mu2}$ BR’s.

1. EXPERIMENTAL SETUP

DAΦNE, the Frascati φ factory, is an $e^+e^-$ collider working at $\sqrt{s} \sim m_\phi \sim 1.02$ GeV. φ mesons are produced nearly at rest, with a visible cross section of $\sim 3.1 \mu b$ and decay into $K_S K_L$ (BR~34%) or $K^+ K^-$ (BR~49%). Neutral and charged kaons have momenta of 110 and 127 MeV, respectively.

The kaon pairs from φ decay are produced in a pure $J^{PC} = 1^{--}$ quantum state, so that the detection of a $K_S(K_L)$ thus signals, or tags, the presence of a $K_L(K_S)$. This in effect creates pure $K_S$ and $K_L$ beams of precisely known momenta (event by event, from kinematic closure) and flux, which can be used to measure absolute $K_S$ and $K_L$ BR’s. Similar arguments hold for $K^+$ and $K^-$ as well. $K_S$ and $K_L$ can be distinguished by their mean decay lengths: λ$S \sim 0.6$ cm and λ$L \sim 340$ cm.

The analysis of kaon decays is performed with the KLOE detector $^1$, consisting essentially of a drift chamber, DCH, surrounded by an electromagnetic calorimeter, EMC. A superconducting coil provides a 0.52 T magnetic field. The DCH is a cylinder of 4 m in diameter and 3.3 m in length, which constitutes a fiducial volume for $K^\pm$ thus allowing clean and efficient tagging.

In KLOE, the identification of $K_L$-interaction in the EMC ($K_{\text{crash}}$ events in the following) is used to tag the presence of $K_S$ mesons. $K^+$ and $K^-$ decay with a mean length of $\lambda_{\pm} \sim 90$ cm and can be distinguished from their decays in flight to one of the two-body final states $\mu\nu$ or $\pi\pi^0$. The c.m. momenta reconstructed from identification of 1-prong $K^\pm \to \mu\nu, \pi\pi^0$ decay vertices in the DC peak around the expected values with a resolution of 1–1.5 MeV, thus allowing clean and efficient tagging.

In early 2006, the KLOE experiment completed data taking, having collected $\sim 2.5$ fb$^{-1}$ of integrated luminosity at the φ peak, corresponding to $\sim 3.8$ billion $K^+K^-$ pairs, and to $\sim 2.6$ billion $K_LK_S$ pairs.

2. MEASUREMENT OF BR($K_S \to \gamma\gamma$)

In ChPT calculations of the amplitude for $K_S \to \gamma\gamma$ process, since all particles involved are neutral, there are non tree-level contributions. Moreover, at $O(p^4)$, only finite chiral-meson loops contribute. BR($K_S \to \gamma\gamma$)) is predicted unambiguously at this level in terms of the couplings $G_S$ and $G_{27}$, giving $2.1 \times 10^{-6}$ $^2$. The most precise published

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measurement of this BR is from NA48: \( BR = 2.78(6)(4) \times 10^{-6} \) [3]. This result would suggest the need for a significant \( O(p^6) \) correction in the ChPT calculation of the BR.

KLOE searched for the decay \( K_S \to \gamma\gamma \) in a sample of \( \sim 2 \times 10^9 \phi \to K_S K_L \) decays which corresponds to an integrated luminosity of 1.9 fb\(^{-1}\). Two prompt photons must be detected, and \( K_S \to 2\pi^0 \) decays counted in the same sample, are used as normalization sample. KLOE measured [4]: \( BR(K_S \to \gamma\gamma) = (2.26 \pm 0.12^{\text{stat}} \pm 0.06^{\text{syst}}) \times 10^{-6} \). This result deviates by 3 \( \sigma \)'s from the previous best determination, as shown in Fig. 1, left panel. While the number of \( K_S \to \gamma\gamma \) observed by KLOE is \( \sim 700 \), as compared to the \( \sim 7500 \) observed by NA48, KLOE profits from the use of a tagged \( K_S \) beam and does not have to contend with irreducible background from \( K_L \to \gamma\gamma \).

Precise ChPT theory calculation for this decay are done at \( O(p^4) \). Higher order effects are predicted to be at most of the order of \( \sim 20\% \) of the \( O(p^4) \) decay amplitude. Our measurement is consistent with negligible higher order corrections.

3. SEARCH FOR THE DECAY \( K_S \to e^+e^- \)

The decay \( K_S \to e^+e^- \), like the decay \( K_L \to e^+e^- \) or \( K_L \to \mu^+\mu^- \), is a flavour-changing neutral-current process, suppressed in the Standard Model and dominated by the two-photon intermediate state [6]. For both \( K_S \) and\( K_L \), the \( e^+e^- \) channel is much more suppressed than the \( \mu^+\mu^- \) one (by a factor of \( \sim 250 \)). Using Chiral Perturbation Theory (\( \chi PT \)) to order \( O(p^4) \), the SM prediction for \( BR(K_S \to e^+e^-) \) is evaluated to be \( \sim 2 \times 10^{-14} \). A value significantly higher than expected would point to new physics. The best experimental limit for \( BR(K_S \to e^+e^-) \) has been measured by CPLEAR [6], and it is equal to \( 1.4 \times 10^{-7} \), at 90% CL.

\( \sim 650 \) million \( K_{\text{crash}} \) events are used as a starting sample for the \( K_S \to e^+e^- \) search. \( K_S \to e^+e^- \) events are selected by requiring the presence of two tracks of opposite charge with their point of closest approach to the origin inside a cylinder 4 cm in radius and 10 cm in length along the beam line. The track momenta and polar angles must satisfy the fiducial cuts \( 120 \leq p \leq 350 \) MeV and \( 30^\circ \leq \theta \leq 150^\circ \). The tracks must also reach the EMC without spiralling, and have an associated cluster.
The two-track invariant mass is evaluated in electron hypothesis \((M_{ee})\). A preselection cut requiring \(M_{ee} > 420\,\text{MeV}\) has been applied, which rejects most of \(K_S \rightarrow \pi^+\pi^-\) events, for which \(M_{ee} \sim 409\,\text{MeV}\). The residual background has two main components: \(K_S \rightarrow \pi^+\pi^-\) events, populating the low \(M_{ee}\) region, and \(\phi \rightarrow \pi^+\pi^-\pi^0\) events, spreading over the whole spectrum. The \(K_S \rightarrow \pi^+\pi^-\) events have such a wrong reconstructed \(M_{ee}\) because of track resolution or one pion decaying into a muon. The \(\phi \rightarrow \pi^+\pi^-\pi^0\) events enter the preselection because of a machine background cluster, accidentally satisfying the \(K_{\text{crash}}\) algorithm. After preselection we are left with \(\sim 5 \times 10^5\) events. To have a better separation between signal and background, a \(\chi^2\)-like variable is defined, collecting information from the clusters associated to the candidate electron tracks. A signal box to select the \(K_S \rightarrow e^+e^-\) events can be conveniently defined in the \(M_{ee} - \chi^2\) plane.

The \(\chi^2\) cut for the signal box definition has been chosen to remove all MC background events: \(\chi^2 < 70\). The cut on \(M_{ee}\) is practically set by the \(p_T^*\) cut, which rules out all signal events with a radiated photon with energy greater than 20\,MeV, corresponding to an invariant mass window: \(477 < M_{ee} < 510\,\text{MeV}\). The signal box selection on data gives \(N_{\text{obs}} = 0\). The upper limit at 90\% CL on the expected number of signal events is \(UL(\mu_S) = 2.3\).

The total selection efficiency on \(K_S \rightarrow e^+e^-\) events is evaluated by MC, and includes contribution from radiative corrections. The number of \(K_S \rightarrow \pi^+\pi^-\) events \(N_{\pi^+\pi^-}\) counted on the same sample of \(K_S\) tagged events is used as normalization. The upper limit on \(BR(K_S \rightarrow e^+e^-)\) is evaluated as follows:

\[
UL(BR(K_S \rightarrow e^+e^-)) = UL(\mu_s) \times \frac{\epsilon_{\pi^+\pi^-}(\text{sel}|K_{\text{crash}})}{\epsilon_{\text{sig}}(\text{sel}|K_{\text{crash}})} \times \frac{BR(K_S \rightarrow \pi^+\pi^-)}{N_{\pi^+\pi^-}}.
\]

Using \(\epsilon_{\text{sig}}(\text{sel}|K_{\text{crash}}) = 0.480(4)\), \(\epsilon_{\pi^+\pi^-}(\text{sel}|K_{\text{crash}}) = 0.6102(5)\) and \(N_{\pi^+\pi^-} = 217, 422, 768\), we obtain

\[
UL(BR(K_S \rightarrow e^+e^-(\gamma))) = 9 \times 10^{-9}, \text{ at 90\% CL}.
\]

Our measurement improves by a factor of \(\sim 15\) on the CPLEAR result \(\bar{\text{6}}\), for the first time including radiative corrections in the evaluation of the upper limit.

4. MEASUREMENT OF \(R_K\)

A strong interest for a new measurement of the ratio \(R_K = \Gamma(K^\pm \rightarrow e^\pm\nu_e)/\Gamma(K^\pm \rightarrow \mu^\pm\nu_\mu)\) has recently arisen, triggered by the work of Ref. \(\bar{\text{7}}\). The SM prediction of \(R_K\) benefits from cancellation of hadronic uncertainties to a large extent and therefore can be calculated with high precision. Including radiative corrections, the total uncertainty is less than 0.5 per mil \(\bar{\text{8}}\). Since the electronic channel is helicity-suppressed by the \(V-A\) structure of the charged weak current, \(R_K\) can receive contributions from physics beyond the SM, for example from multi-Higgs effects inducing an effective pseudoscalar interaction. It has been shown in Ref. \(\bar{\text{1}}\) that deviations from the SM of up to few percent on \(R_K\) are quite possible in minimal supersymmetric extensions of the SM and in particular should be dominated by lepton-flavor violating contributions with taunonic neutrinos emitted. Using the present KLOE dataset of \(\sim 2.5\,\text{fb}^{-1}\) of luminosity integrated at the \(\phi\)-meson peak, we show that an accuracy of about 1\% in the measurement of \(R_K\) might be reached.

In order to compare with the SM prediction at this level of accuracy, one has to treat carefully the effect of radiative corrections, which contribute several percent to the \(K_{ee}\) width. In particular, the SM prediction of Ref. \(\bar{\text{8}}\) is made considering all photons emitted by the process of internal bremsstrahlung (IB) while ignoring any contribution from structure-dependent direct emission (DE). Of course both processes contribute, so in the analysis we will consider DE as a background which can be distinguished from the IB width by means of a different photon energy spectrum.

Given the \(K^\pm\) decay length of \(\sim 90\,\text{cm}\), the selection of one-prong \(K^\pm\) decays in the DC required to tag \(K^\pm\) has an efficiency smaller than 50\%. In order to keep the statistical uncertainty on the number of \(K^\pm \rightarrow e^\pm\nu_e\) counts below 1\%, we decided to perform a “direct search” for \(K^\pm \rightarrow e^\pm\nu_e\) and \(K^\pm \rightarrow \mu^\pm\nu_\mu\) decays, without tagging. Since we measure a ratio of BR’s for two channels with similar topology and kinematics, we expect to benefit from some cancellation of the uncertainties on tracking, vertexing, and kinematic identification efficiencies. Small deviations in the efficiency due to the different masses of \(e^\pm\)’s and \(\mu^\pm\)’s can be evaluated using MC.
A powerful kinematic variable used to distinguish $K^\pm \rightarrow e^\pm \nu_e$ and $K^\pm \rightarrow \mu^\pm \nu_\mu$ decays from the background is calculated from the momenta of the kaon and the secondary particle measured in DC: assuming zero neutrino mass one can obtain the squared mass of the secondary particle, or lepton mass ($M^2_{lep}$). While the one-prong selection is enough for clean identification of a $K^\pm \rightarrow \mu^\pm \nu_\mu$ sample, further rejection is needed in order to identify $K^\pm \rightarrow e^\pm \nu_e$ events: the background, which is dominated by badly reconstructed $K^\pm \rightarrow \mu^\pm \nu_\mu$ events, is reduced by a factor of $\sim 10$ by the quality cuts, but still remains $\sim 10$ times more frequent than the signal in the region around the electron mass peak. Information from the EMC is used to improve background rejection: Electron clusters can be further distinguished from $\mu$ (or $\pi$) clusters by exploiting the granularity of the EMC, in particular using the spread of energy deposits on each plane ($E_{RMS}$). The PID technique described above selects $K^\pm \rightarrow e^\pm \nu_e$ events with an efficiency $\epsilon_{PID}^{K^\pm} \sim 64.7(6)%$ and a rejection power for background of $\sim 300$. These numbers have been evaluated from MC. A likelihood fit to the two-dimensional $E_{RMS}$ vs $M^2_{lep}$ distribution was performed to get the number of signal events. Distribution shapes for signal and background were taken from MC, the normalizations for the two components are the only fit parameters. The number of signal events obtained from the fit is $N_{K^\pm e^\pm} = 8090 \pm 156$. Projections of the fit results onto the $M^2_{lep}$ axes is compared to real data in Fig. 1 right panel.

The primary generators for $K^\pm \rightarrow e^\pm \nu_e$ and $K^\pm \rightarrow \mu^\pm \nu_\mu$ decays include radiative corrections and allow for the emission of a single photon in the final state $[e]$. $K^\pm \rightarrow e^\pm \nu_e + \gamma$ events with photon energy in the kaon rest frame $E_\gamma < 20$ MeV (where the DE contribution is indeed negligible) were considered as signal.

The number of $K^\pm \rightarrow \mu^\pm \nu_\mu$ events in the same data set is extracted from a similar fit to the $M^2_{lep}$ distribution. The fraction of background events under the muon peak is estimated from MC to be less than one per mil. The number of observed $K^\pm \rightarrow e^\pm \nu_e$ and $K^\pm \rightarrow \mu^\pm \nu_\mu$ events and all corrections, we get the preliminary result $[10]$

$$R_K = (2.55 \pm 0.05 \pm 0.05) \times 10^{-5}.$$  

(3)

This value is compatible within the error with the SM prediction, $R_K = (2.477 \pm 0.001) \times 10^{-5}$, and with other recent measurements by NA48 $[11]$. Three sources contribute to the present statistical uncertainty of 1.9%: fluctuation in the signal counts (1.1%), fluctuation in the background to be subtracted (0.7%), and statistical error on the MC estimate of the background (1.4%). The total error on $R_K$ should be reduced to $\sim 1.3%$ after analysis completion.

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