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Measurement of the Radiative K^0_{e3} Branching Ratio and Direct Emission contribution in Semileptonic Decay $K_L \to \pi^{\pm} e^{\mp} \nu(\gamma)$

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KLOE measured for the first time the DE contribution for $K^0_{e3\gamma}$, using a $328 pb^{-1}$ data sample, corresponding to about $9,000$ $K^0_{e3\gamma}$ signal events. With the present measurement we find only a 1.2σ significance level for the DE contribution, $\langle X \rangle = -2.3 \pm 1.3(stat) \pm 1.4(syst)$. We also measured the ratio of branching ratio of $K^0_{e3\gamma}$ with respect to the inclusive $K^0_{e3(\gamma)}$ events: R= $\Gamma(K^0_{e3\gamma};\ E^*_\gamma > E^{*min}_\gamma, \theta^*_\gamma > \theta^{*min}_\gamma)/\Gamma(K^0_{e3(\gamma)}) = (924 \pm 23 \pm 16) \times 10^{-5}$, in which E^{*min}_γ= 30 MeV is the minimum photon energy and θ^{*min}_γ= 20° is the minimum angle between photon and electron in the kaon rest frame.

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1. Introduction

The study of radiative K_L decays offers the possibility to obtain information on the kaon structure and the opportunity to test theories describing hadron interactions and decays, like chiral perturbation theory (χPT). Two different components contribute to the photon emission, the inner bremsstrahlung (IB) and the direct emission (DE). The latter describes photon radiation from intermediate hadronic states, giving in this way new information. In the $K^0_{e3\gamma}$ decay the IB component is much larger than the DE one, due also to the smallness of the electron mass. Infact the $K^0_{e3\gamma}$ amplitude in the kaon reference frame has infrared singularity for both $E^*_\gamma \to 0$ and $\theta^*_\gamma \to 0$ (photon angle *w.r.t.* lepton), for a null electron mass. Mainly for historical reasons [1], the applied *standard cuts* to compare results are $E^*_\gamma > 30\,\text{MeV}$ and $\theta^*_\gamma > 20^\circ$. We define R as:

$$R = \frac{\Gamma(K^0_{e3\gamma}; E^*_\gamma > 30\,\text{MeV}, \theta^*_\gamma > 20^\circ)}{\Gamma(K^0_{e3(\gamma)})} \tag{1.1}$$

With these cuts the theoretical predictions for R range between 0.95×10^{-2} and 0.97×10^{-2} [2]. The DE contribution in any case is expected to be less than 1% of IB. Recent experimental measurements of R from NA48 and KTeV [3, 4] are in marginal disagreement, so that new measurements are welcome. Following the authors of Ref. [2], all relevant structure-dependent distributions show a similar and simple photon energy spectrum with a maximum around $E^*_\gamma \sim 100$ MeV. Therefore:

$$\frac{d\Gamma}{dE^*_\gamma} \simeq \frac{d\Gamma_{IB}}{dE^*_\gamma} + \langle X \rangle f(E^*_\gamma) \tag{1.2}$$

where the second term is the structure-dependent (SD) contribution: $f(E^*_\gamma)$, the *distortion function*, represents the deviation from the pure inner bremmstrahlung. All the information on the SD term is contained in the effective strength, $\langle X \rangle$, that multiplies $f(E^*_\gamma)$. Their χPT calculation gives:

$$\langle X \rangle_{theor} = -1.2 \pm 0.4 \quad \mathcal{O}(p^6)@\chi PT \tag{1.3}$$

A first attempt to measure DE contribution has been performed in 2001 by KTeV collaboration [5], but the working hypothesis to neglect two parameters of the model used in their analysis is not correct and this leads to the impossibility to infer definitive conclusions on the $\langle X \rangle$ parameter.

2. Sample selection

Candidate K_L events are tagged by the presence of a $K_S \to \pi^+\pi^-$ decay. The tagging efficiency, about 66%, is almost independent on the photon energy. The K_L vertex is searched along the direction of its momentum (*tagging line*), reconstructed from $K_S \to \pi^+\pi^-$ decay. $K^0_{e3(\gamma)}$ events are then selected using kinematical properties of the decay and electron identification by time of flight (TOF), after track-to-cluster association (TCA). After sample selection we have about $\sim$3 million of $K^0_{e3(\gamma)}$ events with a contamination of 7×10^{-3}, mainly due to $K^0_{\mu3(\gamma)}$ events.
Further details on the selection of $K^0_{e3(\gamma)}$ events, the efficiencies and the control samples used to correct the efficiencies are fully described in Ref. [6].

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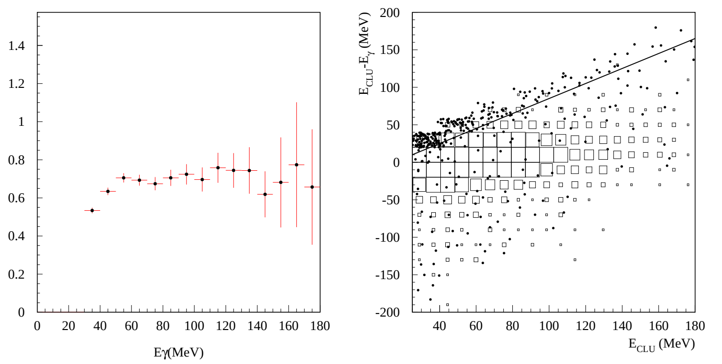
3. Radiative subsample selection

Our signal is a $K^0_{e3\gamma}$ event with $E^*_\gamma > 30\,\text{MeV}$ and $\theta^*_\gamma > 20^\circ$ (*standard cut*). To select the $K^0_{e3\gamma}$ signal we search for a cluster not associated to any track. The cluster time is used to reconstruct a point (neutral vertex, NV) along the K_L flight line under the hypothesis that a photon originated that cluster. NV position, X_N, is then required to be close to the vertex determination from the K_L charged decay tracks, X_C. We apply a 8σ cut on the neutral vertex distance from the charged vertex position, d_{NC}. In case of more than one photon candidate we choose the closest to X_C. To evaluate the photon energy we use only kinematic information, *i.e.*, charged track momenta and photon cluster position. Infact we have $p_\nu = p_K - p_\pi - p_e - p_\gamma$ *and* $\vec{p}_\gamma = E_\gamma \vec{u}$, where $\vec{u}$ is the photon direction. Using the equation above, in the hypothesis of zero mass for the neutrino, the energy of the photon is extracted. The energy resolution is about 1 MeV, a factor ~ 10 better than that obtained using the energy deposit information of the calorimeter. The photon selection efficiency is $\sim 65\%$ on average. The main background contribution comes from $K^0_{e3\gamma}$ events in which the

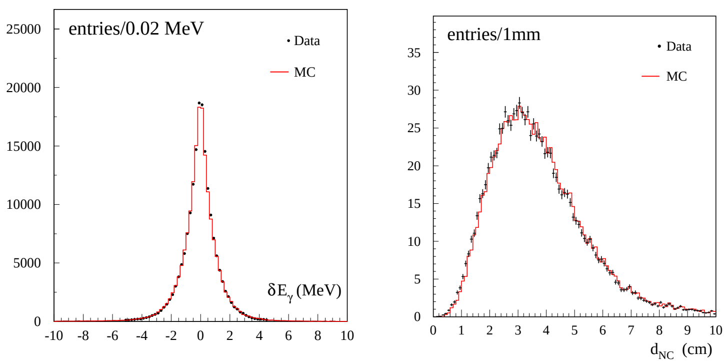


(a) (b)

Figure 1: Monte Carlo simulation: (a) $K^0_{e3\gamma}$ signal efficiency (one period); (b) applied cut to remove accidentals.

emitted photon is soft and goes undetected while a cluster from accidental machine background satisfies the above cuts. This background is strongly reduced by requiring $E_{CLU} > 25$ MeV and $E_{CLU} - E^{lab}_\gamma < E_{CLU} - 15$ MeV where E_{CLU} is the energy of the associated cluster and E^{lab}_γ is the reconstructed photon energy in the laboratory system. This cut is shown in Fig. 1(b). We obtain a factor 10 in background reduction with $\sim$6% loss in signal efficiency. Background from $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi\mu\nu$ events after signal selection is at level of $\sim 6.5\%$. To remove these background contaminations we use a Neural Network (NN) based on photon energy and angle (*w.r.t.* lepton), track momenta, missing momentuma and $M^2_{\gamma\nu}$ (invariant mass of photon-neutrino pair) to remove background from $K_L \to \pi^+\pi^-\pi^0$; we use a NN based on track momenta, calorimetric energy deposit and cluster centroid position to remove background from $K_L \to \pi\mu\nu$. This NN approach allows us to reduce this contribution below a 2% level with a tolerable loss in the efficiency of our signal (10%).

To check the Data-Monte Carlo agreement, to calibrate the Monte Carlo position of NV and correct for the photon selection efficiency we use a control sample of decays $K_L \to \pi^+\pi^-\pi^0$. To select these events we apply a tight kinematic cut in the variable $E^2_{miss} - p^2_{miss} - m^2_{\pi^0}$ in the hypothesis of two pion tracks. Furthermore, we require the presence of a cluster (E>60 MeV) not associated to any track, corresponding to one of the two photons from the π^0 decay. This high energy photon is used to tag the presence of the second photon. We select about 350,000 $K_L \to \pi^+\pi^-\pi^0$ events with a purity of 99.8%. We use this sample to compare the photon energy resolution. The energy of the tagged photon is infact evaluated exactly with the same method used for the $K^0_{e3\gamma}$ signal: there we do not detect the neutrino, here we can ignore the hard photon (the tagging photon). In fact, after squaring the equation $p_{\gamma-hard} = p_K - p_\pi - p_\pi - p_\gamma$, taking into account that $\vec{p}_\gamma = E_\gamma\, \vec{u}$ in which the photon direction, $\vec{u}$, is known, the energy of the tagged photon can be extracted. The energy resolution of this photon (Fig.2) is evaluated with respect to the value computed using the complete hard photon information and closing in this way the kinematics. In the $K^0_{e3\gamma}$ signal



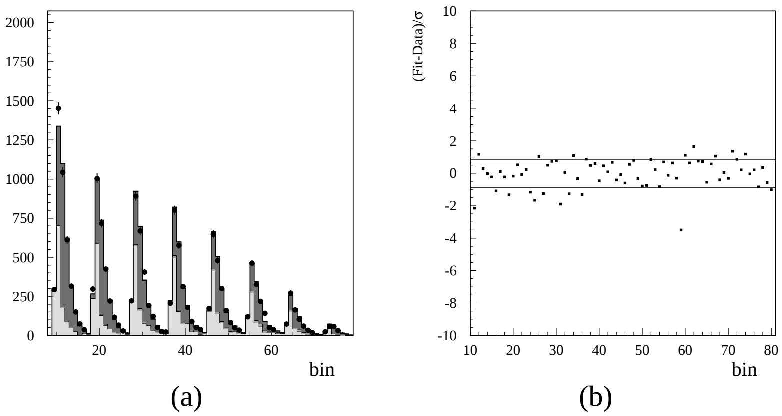
(a) (b)

Figure 2: Control sample from $K_L \to \pi^+\pi^-\pi^0$: (a) resolution of the photon energy; (b) d_{NC} distribution.

selection we search for a photon originating within a defined distance from the charged vertex position, X_c. We use the control sample from $K_L \to \pi^+\pi^-\pi^0$ to evaluate this distance, d_{NC}, and its resolution $\sigma_{d_{NC}}$, in order to correct d_{NC} and $\sigma_{d_{NC}}$ in Monte Carlo simulation. Because of the use of E_{CLU} to remove accidentals, we also use this control sample to check the calorimeter energy response. Finally, using this tagging technique, we evaluate the efficiency from data and Monte Carlo in the control sample and use their ratio to correct the photon selection efficiency in Monte Carlo simulation. The correction is of the order of a few percent.

4. Fit

To count $K^0_{e3\gamma}$ signal events we fit Monte Carlo spectra $f_i(E^*_\gamma, \theta^*_\gamma)$ to the data ($i = 1,2,3,4$ respectively for IB signal, DE signal, $K^0_{e3\gamma}$ out-of-acceptance ($E^*_\gamma < 30$ MeV or $\theta^*_\gamma < 20°$) and physical background from $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi\mu\nu$ events). Free parameters of the fit are the normalizations for IB signal, DE signal and $K^0_{e3\gamma}$ -out-of-acceptance, while we fix the background contribution of $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi\mu\nu$ from Monte Carlo. The two-dimensional 9×9 binned Monte Carlo input shapes are re-arranged into eight $\theta - slices$ energy hystograms, as shown in Fig. 3(a). Each *slice* covers 20 degrees, from 20° to 180°. The result of the fit and the residual are shown in Fig. 3. To check the fit stability as a function of run period we do not use the DE shape (no sensitivity in a single period). The stability is good ($\chi/\mathrm{dof} = 9/13$).



Source	$10^5 \times \Delta R$	$\Delta\langle X \rangle$
Tagging	4.0	0.7
Tracking	1.5	0.8
Clustering	5.5	0.1
Kinematic cuts	∼0	∼0
TOF-cut	1.3	0.5
p-miscalibration	3.5	0.2
p-resolution	7.2	0.4
Fiducial volume	3.0	0.5
Rejection acc.	5.2	0.4
NV acceptance	2.9	0.3
BKG Reject.by NN	9.0	0.1
Total	15.5	1.4

(c)

Figure 3: (a) Fit: dots are data, dark grey is the signal (IB+DE), light grey is the $K^0_{e3\gamma}$ -out-of-acceptance; each θ-slice covers the range $0\div180$ MeV; (b) Fit residual; (c) List of the systematics (absolute values).

5. Results and conclusions

We evaluate the systematics on R and $\langle X \rangle$ with the cut variation method. Systematic errors are summarized in Table 3(c). Taking into account all systematics, the measurements of R and $\langle X \rangle$ yield:

$$R = (924 \pm 23_{\text{stat}} \pm 16_{\text{syst}}) \times 10^{-5} \quad , \quad \langle X \rangle = -2.3 \pm 1.3_{\text{stat}} \pm 1.4_{\text{syst}} \tag{5.1}$$

this last is in agreement with $\mathcal{O}(p^6)$ evaluation [2]. The presence of DE contribution reduces the value of R of about 1%. The correlation between R and $\langle X \rangle$, including also systematics, is 3.9% (Fig. 4). Using the entire KLOE data set will allow us to increase the statistic by a factor of 5. This could confirm at $\sim 3\sigma$ significance level the presence of DE and will improve the accuracy on R measurement. In fact, at this stage, the KLOE measurement of R (3% accuracy) is not sufficient to solve the experimental disagreement between NA48 and KTeV measurement.

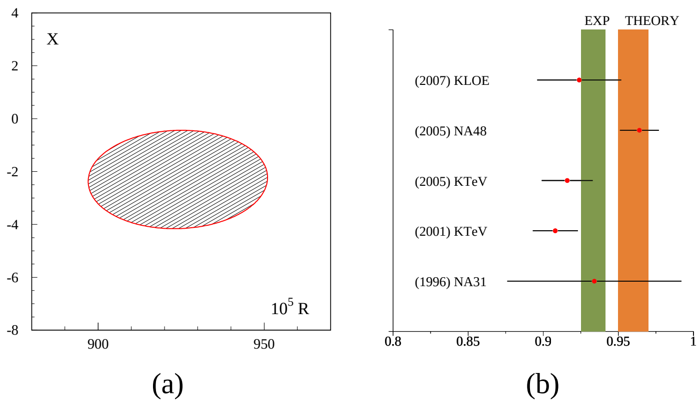


Figure 4: (a) 1-σ confidence level for R and $\langle X \rangle$ measurement; (b) Recent measurements of R with the *standard cut.*

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