Measurement of the K_S lifetime and study of $K \to e\nu\gamma$ at KLOE

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Using a large sample of pure, slow, short lived neutral kaon mesons collected with KLOE at DAFNE, we have measured the K_S lifetime. From a fit to the proper time distribution we find $\tau_S = 89.562 \pm 0.052$ ps, in good agreement with recent measurements.

While measuring the ratio $R_K = \Gamma(K^{\pm}_{e2(\gamma)})/\Gamma(K^{\pm}_{\mu2(\gamma)})$, the KLOE Collaboration has studied the radiative process $K_{e2\gamma}$. The observed radiation spectrum agrees with predictions from chiral perturbation theory. This result reduces the contribution to systematic uncertainties on measurements of R_K.

1. $K^{\pm} \to e^{\pm}\nu(\bar{\nu})\gamma$ $(K_{e2\gamma})$

The K_{e2} decay is strongly helicity suppressed. Its rate is therefore a sensitive probe for minute contributions from physics beyond the Standard Model (SM). This is particularly true of the ratio $R_K = \Gamma(K_{e2(\gamma)})/\Gamma(K_{\mu2(\gamma)})$, which can be calculated in the SM without uncertainties from strong-interaction dynamics. A recent calculation, which includes $\mathcal{O}(e^2p^4)$ corrections in chiral perturbation theory (ChPT), gives $R_K^{\rm SM} = 2.477(1) \times 10^{-5}$ [1]. Deviations of R_K of up to a few percent are possible in minimal supersymmetric extensions of the SM with non-vanishing e-τ scalar-lepton mixing [2].

Additional photons in the K_{e2} final state can be produced via internal bremsstrahlung (IB) or structure-dependent (direct) emission (SD); the spectrum of the latter is sensitive to the structure of the kaon. Interference between the IB and SD processes is negligible [3]. By definition, R_K is IB inclusive and SD exclusive. However, since events with IB photons cannot be distinguished from those with SD photons, to compare data with the SM prediction at the percent level or better, sufficiently precise knowledge of the SD component is required.

Because of the helicity suppression of the IB channel, the contribution from the SD channel to the total width is approximately equal to that from IB [3]. Previous measurements give the SD rate with a relative uncertainty of 15% [4]. The KLOE Collaboration has published a measurement of R_K to within 1.3% [5], obtaining $R_K = 2.493(31) \times 10^{-5}$. The study of the SD radiation in $K_{e2\gamma}$ decay presented here was conducted in order to reduce the contribution to the systematic error on the KLOE measurement of R_K from the uncertainty in the SD rate, from 0.5% to 0.2%. The NA62 Collaboration has recently announced a preliminary measurement of R_K with a 0.5% error [6]. The uncertainty in the SD rate is the second-largest contribution to the overall systematic uncertainty on this result, so that the present study may help to reduce the uncertainty on the NA62 value of R_K as well.

Decays with SD radiation can proceed through vector and axial transitions, with effective couplings V and A, respectively:

$$\frac{d^2\Gamma_{\rm SD}(K_{e2\gamma})}{dx\,dy} = \frac{G_F^2\,|V_{us}|^2\,\alpha_{\rm em}M_K^5}{64\pi^2} \times \left[(V+A)^2 f_{\rm SD+}(x,y) + (V-A)^2 f_{\rm SD-}(x,y)\right]. \tag{1}$$

Here, $x = 2E^*_\gamma/M_K$ and $y = 2E^*_e/M_K$ are the normalized photon and electron energies in the kaon rest frame; both lie between 0 and 1. The form factors $f_{\rm SD+}$ and $f_{\rm SD-}$ describe the hadronic-structure-dependent effects in the contributions to the decay intensity from the channels with positive and negative photon polarization, respectively. In the SD+ channel, the photon is preferentially emitted in the direction opposite to that of the $e^{\pm}$, and the $e^{\pm}$ momentum spectrum is hard, peaking above the endpoint of the p_e^* spectrum in K_{e3} decays at 228 MeV. (p_e^* is the $e^\pm$ momentum in the decay rest frame.) In the SD$-$ channel, the photon is preferentially emitted in the direction parallel to that of the $e^\pm$, and the $e^\pm$ has a softer momentum spectrum. Because the contribution from the SD$-$ channel is completely submersed in $K_{e3(\gamma)}$ background, the present measurement is exclusively focused on the SD+ contribution, and events with $p_e^* < 200$ MeV are eliminated to reduce background.

The starting sample of $K_{e2(\gamma)}$ events (inclusive with respect to the presence of additional photons in the final state) is the same as that used in the KLOE measurement of R_K [5]. Single-prong vertices in the drift chamber are examined if the inbound track originates from the interaction point and has momentum compatible with the two-body decay momentum in $\phi \to K^+K^-$ (127 MeV), and if the outbound track has $p_{\rm lep} > 180$ MeV. The mass of the outbound track (the lepton candidate) is then reconstructed as $M^2_{\rm lep} = (E_K - |\mathbf{p}_{\rm miss}|)^2 - p^2_{\rm lep}$, with E_K the kaon energy and $\mathbf{p}_{\rm miss}$ the missing momentum at the vertex. Stringent track quality cuts on both the inbound and outbound tracks increase the ratio of $K_{e2(\gamma)}$ events to background events from 1/1000 to 1/20. For the analysis of R_K, the lepton-candidate track is extrapolated to the KLOE electromagnetic calorimeter, and a neural network is used to combine E/p, time-of-flight, and longitudinal energy deposition information for the purposes of μ/e separation.

After the above cuts, the dominant backgrounds are from $K_{\mu2(\gamma)}$ events for $M^2_{\rm lep} < 20000$ MeV^2, and from $K_{e3(\gamma)}$ events for $M^2_{\rm lep} > 20000$ MeV^2. $K_{e2\gamma}$ events with $p_e^* < 200$ MeV are submerged in background. For the purposes of this analysis, the signal sample of SD+ events is fiducially defined as the sample of identified $K_{e2\gamma}$ events with $E^*_\gamma > 10$ MeV, $\cos\theta^*_\gamma < 0.9$ (θ^*_γ is the angle of the photon momentum with respect to that of the $e^\pm$), and $p_e^* > 200$ MeV. Simulations indicate that this selection has a 90% acceptance for true SD+ events, a 2% acceptance for SD$-$ events, and contains a 1% background of IB events.

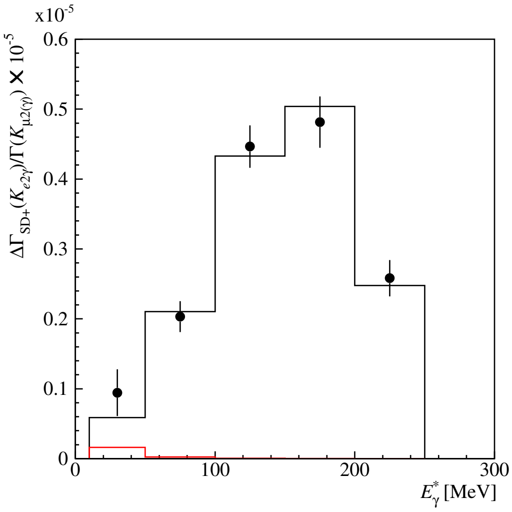

Figure 1. $\Delta\Gamma_{\rm SD+}(K_{e2\gamma})/\Gamma(K_{\mu2(\gamma)})$ for five bins in E^*_γ, with fit to $\mathcal{O}(p^6)$ ChPT model.

An additional variable that is useful in isolating signal events is ΔE_γ, the difference between the energy of the radiative photon as determined by kinematic, and that from the measurement of the calorimeter.

The number of $K_{e2\gamma}$ events in the SD+ sample is determined via log-likelihood fits to the distribution of candidate events in the ($M^2_{\rm lep}$, ΔE_γ) plane in five different bins in E^*_γ. The first bin in E^*_γ extends from 10 to 50 MeV; the remaining four adjacent bins are 50 MeV wide. The fit function is a linear combination of Monte Carlo (MC) distributions for $K_{e2\gamma}$ events with kinematics as generated satisfying the SD+ selection (signal events), $K_{e2\gamma}$ events as generated not satisfying the SD+ selection, $K_{\mu2(\gamma)}$ events, and events from other background sources (mainly $K_{e3(\gamma)}$). The free parameters of the fit are the weights for each distribution.

Figure 1 summarizes the results of this analysis. The points in each panel show the measured values of $\Delta\Gamma_{\rm SD+}(K_{e2\gamma})$, normalized to $\Gamma(K_{\mu2(\gamma)})$, for each of the five bins in E^*_γ. Summed over all bins in E^*_γ, $N_{\rm SD+}(K_{e2\gamma}) = 1378 \pm 63$, which gives $\Gamma_{\rm SD+}(K_{e2\gamma})/\Gamma(K_{\mu2(\gamma)}) = 1.484(66)_{\rm st}(16)_{\rm sy} \times$

10^{-5}. This agrees with the prediction from the KLOE MC, 1.447×10^{-5}, which is based on the $\mathcal{O}(p^4)$ ChPT calculation of Ref. [3].

At $\mathcal{O}(p^6)$, the vector coupling V in Eq. (2) depends linearly on the photon energy x, with $V = V_0[1+\lambda(1-x)]$, $V_0 = 0.082/m_K$ and $\lambda = 0.4$; the axial coupling is constant, $A \approx 0.034/m_K$ [7]. The Fig. 1 shows the data together with the results of a fit using the $\mathcal{O}(p^6)$ prediction. Since there is no sensitivity to the SD− component of the radiation, the quantity $(V - A)$ in Eq. (2) is fixed to its $\mathcal{O}(p^6)$ numerical value, and the fit parameters are $(V_0 + A)$ and λ. The results $(V_0+A) = 0.125(7)/m_K$ and $\lambda = 0.38 \pm 0.21$ with $\rho = -0.93$ and $\chi^2/\mathrm{ndf} = 1.97/3$ are obtained.

2. K_S lifetime

The reaction chain $e^+e^- \rightarrow \phi$, $\phi \rightarrow K_S K_L$(unobserved), $K_S \rightarrow \pi^+\pi^-$, with p_ϕ=13 MeV in the horizontal plane, is geometrically and kinematically overdetermined. We can therefore, event by event, determine the K_S-meson vector momentum p_K, the kaon production point P and its decay point D. From p_K, P and D we obtain the proper time that the kaon survived. A fit to the proper time distribution gives the K_S-meson lifetime. The vast available statistics allows us to select some 20 million $K_S \rightarrow \pi^+\pi^-$ decays with favorable configuration to provide the most accurate and least biased measurement of time. Averaging over the sample gives an accuracy of about 2 μm in the measurement of the kaon path. For consistency we use our value of the kaon mass, M_K=(497.583 ± 0.021) MeV, Ref. [8].

$K_S \rightarrow \pi^+\pi^-$ decays are reconstructed from two opposite sign tracks which must intersect at a point D with $r_\mathrm{D} < 10$ cm and $|z_\mathrm{D}| < 20$ cm, where $x = y = z = 0$ is the e^+e^- average collision point. The invariant mass of the two tracks, assumed to be pions, must satisfy, $|M_{\pi\pi} - M_{K^0}| < 5$ MeV. D is taken as the decay point. The kaon momentum p_K can be obtained from the sum of the pion momenta and also from the kaon direction w.r.t. the known, fixed ϕ momentum p_ϕ. We call the latter value p'_K. The magnitude of the two values of the kaon momentum must agree to within 10 MeV. We refer to the finding of D as vertexing. The above procedure selects a $K_S \rightarrow \pi^+\pi^-$ sample almost 100% pure.

For each event we need the kaon production point P. In fact only the z-coordinate of P is required since the interaction region is 2-3 cm long while the other dimensions are negligible and the x, y coordinates well known. P lies on the beam axis and is taken as the point of closest approach to the K_S path as determined by the $\pi^+\pi^-$ tracks.

We have to discard events with poor vertexing resolution. We therefore retain decays with $\cos\alpha_{\pi\pi} < -0.87$, rejecting large Δp values. We also retain events with $0.5 < |\cos\alpha^\perp_{\pi^+K}| < 2.2$ rad, where $\alpha^\perp_{\pi^+K}$ is the angle between positive pion and kaon projected on the vertical xy plane. All above angles are in the laboratory. We then require $|M_{\pi\pi} - M_K| <$ 2 MeV and retain events with $-0.5 < \cos\theta(\pi^\pm) < +0.5$. Only about 1/3 of the events survive while the rms spread on the time is reduced to 0.63.

A significant improvement is obtained performing a geometrical fit of each event to obtain the production point P and the decay point D. We chose a new point P' on the beam axis and a new decay point D' on a line through P', parallel to the kaon path.

MC and data, studies show that the time resolution is well described by the sum of two gaussians. Allowance must be still be made for small mistakes in the reconstruction of the decay and production points D and P. A shift δ in the proper time is therefore introduced.

The four parameters, σ_1, σ_2, α, δ in $f(t)$ depend on colatitude and azimuth, θ and ϕ, of the kaon and it is not realistic to attempt to obtain them from MC. We divide the data in a 20x18 grid in $\cos\theta, \phi$ and fit each data set for the lifetime τ with the above parameters free. Large values of $|\cos\theta|$ (θ close to 0°and 180°) are rejected since they give the largest error for t. Moreover kaons are produced with a $\sin^2\theta$ distribution which means that only about 8% of the events have $|\cos\theta| > 0.5$. For the weighted average we obtain $\chi^2//\mathrm{dof} = 202/179$ for a confidence level, CL, of 11.4%. Fig. 2 left shows a fit example.

Changes in analysis cuts and FV giving in a ±60% change in efficiency result in a lifetime shift

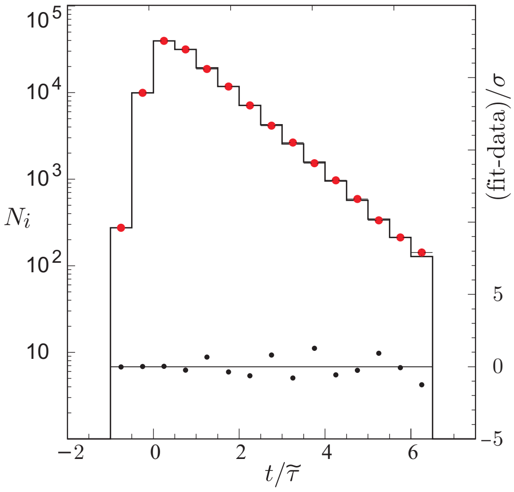

Figure 2. Fit example with χ^2/dof= 8/10 (dots are data).

of 0.024 ps. Varying the fit range gives a shift of 0.012 ps. As mentioned, we use the KLOE value of the kaon mass in the kinematic determination of the K_S momentum and the calculation of β_K. The measurement of β_K and the decay position are independent. The uncertainty on the calibration of p'_K gives a t uncertainty of 0.033 ps. The uncertainty due to K_S mass is 0.004 ps. All fits are performed assuming constant efficiency vs t resulting in an uncertainty of 0.005 ps. Table 1 summarizes all systematic errors. The result

source	absolute value (ps)
cuts & FV	0.024
fit range	0.012
p'_K calibration	0.033
kaon mass	0.004
efficiency	0.005
total	0.043

Table 1
Systematic error contributions.

is stable across the entire run period. Without applying the vertex correction the result still remains within $2\,\sigma$ of the final result, but stability with the run period is lost. Our result for K_S lifetime is:

$$\tau(K_S) = 89.562 \pm 0.029_{\rm stat} \pm 0.043_{\rm syst}\ \ {\rm ps} \qquad (2)$$

REFERENCES

1. V. Cirigliano, I. Rosell, Phys. Rev. Lett 99 (2007) 231801.
2. A. Masiero, P. Paradisi, R. Petronzio, Phys. Rev. D 74 (2006) 011701 (R).
3. J. Bijnens, et al., in: L. Maiani, G. Pancheri, N. Paver (Eds.), Secon d DAΦNE Physics Handbook, Laboratori Nazionali di Frascati, 199 5, p. 315.
4. J. Heintze, et al., Nucl. Phys. B 149 (1979) 365.
5. F. Ambrosino *et al.* [KLOE Collaboration], Eur. Phys. J. C **64**, 627 (2009) [Erratum-ibid. **65**, 703 (2010)] [arXiv:0907.3594 [hep-ex]].
6. E. Goudzovski for the NA62 Collaboration, these proceedings.
7. C.-H. Chen, C.-Q. Geng, C.-C. Lih, Phys. Rev. D 77 (2008) 014004.
8. F. Ambrosino et al., KLOE Coll., JHEP **0712**, (2007) 073. This paper gives the K_S mass value obtained by KLOE and used in the present analysis.