Recent results from KLOE at DAΦNE

The KLOE Collaboration*
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The KLOE experiment at the DAΦNE e^+e^- collider and its physics program is presented. The most recent results obtained using the data collected during the year 2000 (about 20 pb^{-1}) are presented, in particular the ratio of branching ratios BR($K_S \to \pi^+\pi^-$)/BR($K_S \to \pi^0\pi^0$), the branching ratio for the K_{e3} decay of the K_S, the ratio BR($\phi \to \eta'\gamma$)/BR($\phi \to \eta\gamma$) and the pseudoscalar mixing angle φ_P, and the branching ratios for the decays $\phi \to f_0\gamma$ and $\phi \to a_0\gamma$.

1. INTRODUCTION

DAΦNE, the Frascati ϕ-factory [1], is an e^+e^- collider working at the ϕ resonance peak. The ϕ meson, produced practically at rest, decays with a probability of 33.8% into a K_SK_L pair. DAΦNE collisions are thus a source of nearly monochromatic, back-to-back K_S-K_L beams.

The KLOE experiment [2] is primarily designed to study CP and CPT violation in the K^0-$\overline{K}^0$ system. The unique feature of KLOE is the possibility to perform these studies by measuring the interference patterns in the relative time distributions of the K_SK_L pair decays (the pair is produced in a $J^{PC} = 1^{--}$ quantum state) into various final states [3]. Another complementary and more traditional way to measure $\Re(\epsilon'/\epsilon)$ at KLOE is the double ratio method based on the relation:

$$\frac{R_L}{R_S} \simeq 1 + 6\Re(\epsilon'/\epsilon) \tag{1}$$

where

$$R_{S,L} = \frac{BR(K_{S,L} \to \pi^+\pi^-)}{BR(K_{S,L} \to \pi^0\pi^0)} \tag{2}$$

As an example of the statistics needed for these studies, the measurement of $\Re(\epsilon'/\epsilon)$ with an accuracy $O(10^{-4})$, considering the double ratio method for simplicity, requires an integrated luminosity of about 10 fb^{-1}. This corresponds, at the design luminosity $L = 5 \cdot 10^{32}$ cm^{-2} s^{-1}, to about two years of running.

In 1999 the KLOE integrated luminosity was $\sim$ 2pb^{-1}, while during year 2000 was more than 20pb^{-1}. In year 2001 the DAΦNE luminosity reached $5 \cdot 10^{31}$ cm^{-2} s^{-1} and KLOE collected $\sim$ 180pb^{-1}, the vast majority of which in the last three months. In year 2002 further progress in the luminosity is expected.

Even though the statistics of the current data set is not adequate for the precision studies of

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fundamental symmetries, however it is suitable for the study of other topics, which are part of the KLOE physics program. In fact a sample of about 17pb^{-1} of good data, collected during the year 2000, has been used to obtain the results on K_S decays and on radiative decays of the ϕ meson presented in this report.

2. THE KLOE DETECTOR

The KLOE detector, shown in Fig.1, consists mainly of a large volume drift chamber surrounded by an electromagnetic calorimeter. A superconducting coil provides a 0.52 T solenoidal magnetic field.

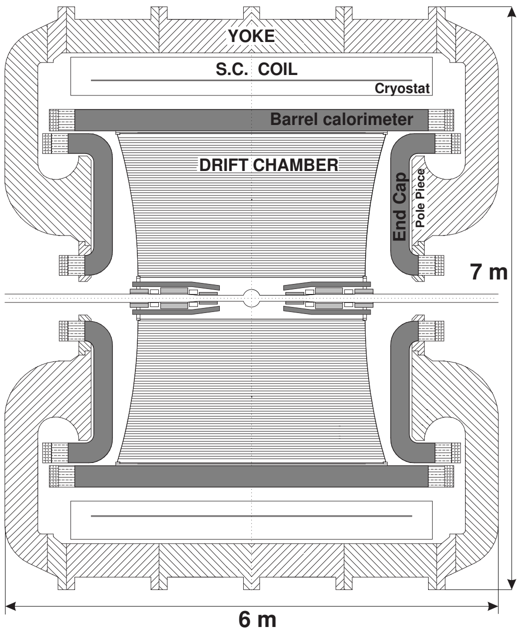

Figure 1. Schematic view of the KLOE detector.

The fine sampling lead-scintillating fiber calorimeter [4] consists of 24 barrel modules with 4.3 m active length and 23 cm thickness ($\sim 15X_0$) and 2×32 C-shaped end-cap modules of various lengths and same thickness as barrel modules, with photomultiplier read-out at both sides. The solid angle coverage is 98%. The energy resolution measured using $e^+e^- \to e^+e^-\gamma$ events is $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$. The time resolution measured using $e^+e^- \to e^+e^-\gamma$ and $e^+e^- \to 2\gamma$ events is $\sigma_t = 54$ ps$/\sqrt{E(\mathrm{GeV})} \oplus 50$ ps, after the subtraction of the finite bunch-lenght effect.

The tracking detector is a 4 m diameter and 3.3 m long cylindrical drift chamber [5] with a total of ~ 52000 wires, of which ~ 12000 are sense wires, in an all-stereo geometry. In order to minimize multiple scattering and K_L regeneration and to maximize detection efficiency of low energy photons, the chamber works with a helium based gas mixture and its walls are made of light materials (mostly carbon fiber composites). The momentum resolution for tracks produced at large polar angle is $\sigma_p/p \leq 0.4\%$ while spatial resolutions are $\sigma_{r,\phi} \approx 150\mu$ m and $\sigma_z \approx 2$mm.

3. TAGGING OF K_S DECAYS

At KLOE a K_S is tagged by identifying the interactions of the K_L in the calorimeter. In fact about 50% of the produced K_L's in $\phi \to K_SK_L$ events reach the calorimeter before decaying; their associated interactions (called "K_L-crash") are identified by a high-energy ($E \geq 200$ MeV), neutral (i.e. not associated to any track in the event) and delayed (the interaction time of a K_L with $\beta \sim 0.218$ is delayed of ≈ 30 ns with respect to the one due to a $\beta = 1$ particle coming from the interaction region) cluster in the calorimeter.

The position of the K_L-crash, exploiting the two body decay kinematics, provides the momentum of the K_S. Moreover in about 40% of the events the K_L-crash alone indipendently satisfies the trigger conditions, thus facilitating the trigger efficiency studies.

4. BR($K_S \to \pi^+\pi^-$)/BR($K_S \to \pi^0\pi^0$)

The measurement of R_S constitutes a part of the double ratio method for measuring $\Re(\epsilon'/\epsilon)$.

In the sample of K_L-crash events the $K_S \to \pi^+\pi^-$ decay is identified by requiring the presence of two tracks of opposite charge coming from the interaction region (IR) which satisfy loose cuts on momentum, p, and polar angle, θ. These cuts define the acceptance for the decay; the corresponding efficiency is obtained from Monte Carlo simulation (MC). The single-track reconstruction efficiency in bins of (p, θ) is obtained directly from subsamples of $K_S \to \pi^+\pi^-$ events themselves.

The $K_S \to \pi^0\pi^0$ decay is identified by requiring the presence of at least three "prompt" clusters (i.e. originated by photons coming from the IR: $|T_{cl} - R/c| \leq 5\sigma_t$, where R and T_{cl} are the measured distance from the IR and the time of the cluster, respectively) which satisfy cuts on energy and polar angle.
The photon detection efficiency is evaluated from a sample of $\phi \to \pi^+\pi^-\pi^0$ events, in which the kinematic variables of one photon can be constrained by the detection of the two pions and the other photon in the event.

In both $\pi^+\pi^-$ and $\pi^0\pi^0$ cases, the probability that the K_S (K_L-crash) detection fully or partially satisfies the trigger conditions can be evaluated using events in which the K_L-crash (K_S) alone triggers. Thus the trigger efficiency is evaluated as the combined probability of K_S and K_L-crash to satisfy the trigger conditions.

The preliminary KLOE result is:

$$R_S = 2.192 \pm 0.003_{\mathrm{stat}} \pm 0.016_{\mathrm{syst}} \tag{3}$$

This result has a statistical significance never reached before by a single measurement and has to be compared to the world average [6] $2.197 \pm 0.026_{\mathrm{stat}} \pm 0.013_{\mathrm{syst}}$. The systematic error will be further reduced in the analysis of 2001 data, partly because the error on some efficiencies are currently dominated by the statistics of control samples, and partly because of an improved selection of K_L-crash events in 2001 data.

5. BR($K_S \to \pi e \nu$)

Assuming CPT and the $\Delta S = \Delta Q$ rule, the $K_S \to \pi e \nu$ branching ratio is calculated from the equality $\Gamma(K_S \to \pi e \nu) = \Gamma(K_L \to \pi e \nu)$. Using the measured values of $\mathrm{BR}(K_L \to \pi e \nu)$ and τ_S/τ_L [6], $\mathrm{BR}(K_S \to \pi e \nu) = (6.70 \pm 0.07) \cdot 10^{-4}$ is obtained. At present only one direct measurement exists [7] obtained with 75 ± 13 observed events: $\mathrm{BR}(K_L \to \pi e \nu) = (7.2 \pm 1.4) \cdot 10^{-4}$.

At KLOE the $K_S \to \pi e \nu$ events are selected in the sample of K_L-crash events by requiring the presence of a vertex with two tracks of opposite charge in the IR. The observation of the K_L-crash determines the momentum of the K_S. The invariant mass at the vertex is calculated assuming both tracks are from pions, and the total momentum at the vertex is calculated in the K_S rest frame. Loose preselection cuts, which mainly eliminate $K_S \to \pi^+\pi^-$ events, are imposed on these quantities. The preselection efficiency is evaluated by the MC.

The $K_S \to \pi e \nu$ decay is identified by making the correct π/e assignment to the two tracks. In order to use time-of-flight π/e identification, both tracks from the vertex must be associated to calorimeter clusters. The difference $\delta_t(m) = T_{cl} - L/c\beta(m)$ is calculated for each track by using the measured cluster time, the track length L, and by applying the mass hypotheses $m = m_e$ or $m = m_\pi$ to derive the velocity β from the track momentum. In order to be independent from the absolute time zero determination, the difference $\Delta = \delta_t(m)_1 - \delta_t(m)_2$ is evaluated. For the correct mass assignment, this difference is expected to be around zero. Therefore a cut at $|\Delta| \leq 1$ ns is applied to select the signal. In the end, events are kinematically constrained at the K_S vertex finding the neutrino energy E_{miss} and momentum P_{miss}. The difference of these two variables is plotted in Fig. 2. The observed peak around zero is due to the $K_S \to \pi e \nu$ decays, while the residual $K_S \to \pi^+\pi^-$ background populates the region above zero. The histogram corresponds to $\sim 17\mathrm{pb}^{-1}$ of data of year 2000, while crosses are the results of a fit to the sum of the MC spectra for signal and background events. The free parameters of the fit are the independent normalizations of the signal and background distributions, and the finite MC statistics has been taken into account in the likelihood function. As a result of the fit, 627 ± 30 signal events are observed.

The vertex reconstruction, π/e identification and trigger efficiencies can be evaluated from a clean and unbiased sample of $K_L \to \pi e \nu$ events in which the K_L decays near the IR, thus simulat-

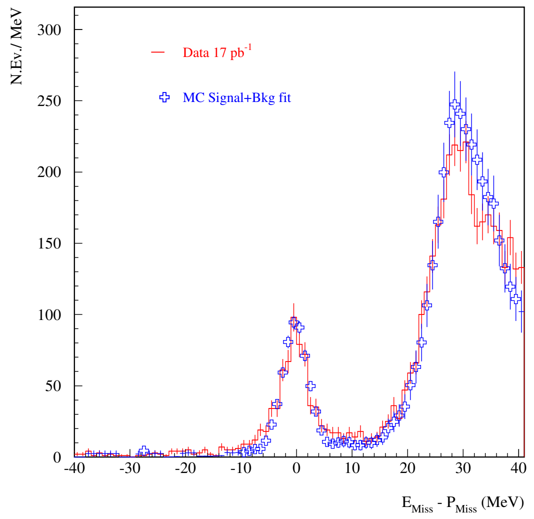

Figure 2. Spectrum of $E_{miss} - P_{miss}$ for $K_S \to \pi e \nu$ candidate events; data (histogram) are compared to MC (crosses).

ing a $K_S \to \pi e \nu$ decay. The track-cluster association efficiency is evaluated using proper samples of $\phi \to \pi^+\pi^-\pi^0$, $K_S \to \pi^+\pi^-$ and $K_L \to \pi e \nu$ events. Therefore from these events the probability that a given particle (π^+, π^-, $\mu^\pm$ or $e^\pm$) reaching the calorimeter deposits enough energy to register a cluster and that the track and cluster are then correctly associated can be obtained.

The result:

$$\mathrm{BR}(K_S \to \pi e \nu) = (6.79 \pm 0.33_{\mathrm{stat}} \pm 0.20_{\mathrm{syst}}) \cdot 10^{-4} \quad (4)$$

is obtained by normalizing the number of signal events to the number of $K_S \to \pi^+\pi^-$ events in the same data set and using the present experimental value for $\mathrm{BR}(K_S \to \pi^+\pi^-)$. This result is in agreement with the expectation of the $\Delta S = \Delta Q$ rule. The relative uncertainty on the KLOE measurement is less than a third of that on the only existing measurement [7]. From the analysis of year 2001 data both the statistical and systematic errors should be reduced and a competitive test of the $\Delta S = \Delta Q$ rule could be performed.

6. BR($\phi \to \eta' \gamma$)

The branching ratio of the decay $\phi \to \eta'\gamma$ is particularly interesting since its value can probe the $|s\bar{s}\rangle$ and gluonium content of the η' [8–10]. In particular, the ratio of its value to the one of $\phi \to \eta\gamma$ can be related to the $\eta - \eta'$ mixing parameters and determine the mixing angle in the flavor basis φ_P, offering an important point of comparison for the description of the $\eta - \eta'$ mixing in chiral perturbation theory [11].

The decay chains considered are:

- $\phi \to \eta'\gamma$ with $\eta' \to \pi^+\pi^-\eta$ and $\eta \to \gamma\gamma$
- $\phi \to \eta\gamma$ with $\eta \to \pi^+\pi^-\pi^0$ and $\pi^0 \to \gamma\gamma$

In both cases the final state is $\pi^+\pi^-\gamma\gamma\gamma$, resulting in several systematic errors cancellation in the measurement of the ratio $\mathrm{BR}(\phi \to \eta'\gamma)/\mathrm{BR}(\phi \to \eta\gamma)$. For both channels events are selected requiring the presence of three prompt photons and two tracks of opposite charge with a vertex near the IR. Then a preliminary kinematic fit is performed requiring total energy and momentum conservation, the constraint $\beta = 1$ for all photons, without any invariant mass constraint on intermediate particles. Simple kinematic cuts eliminate the background mainly due to $\phi \to \pi^+\pi^-\pi^0$ events in which a spurious cluster is present, and to $\phi \to K_S K_L \to \pi^+\pi^-\pi^0\pi^0$ events in which one photon is lost.

The energy spectrum of the photons gives no combinatorial problem: the radiative photon is the hardest one in $\phi \to \eta\gamma$ events ($E_{rad} \simeq$ 363 MeV), while is the softest in $\phi \to \eta'\gamma$ events ($E_{rad} \simeq 60$ MeV), the other two photons being generated in π^0 and η decays, respectively. Hence η' events are disentangled from η background by proper cuts on the energy spectrum of the two hardest photons γ_1 and γ_2.

The distribution of the invariant mass of $\pi^+\pi^-\gamma_1\gamma_2$ for the $\phi \to \eta'\gamma$ events is shown in Fig.3, where a small residual background is observed in the η' peak region. The shape of the background is obtained from sidebands of the signal region in the γ_1 and γ_2 energy distribution. The number of signal events, as obtained from the simple fit shown in Fig.3, is $124 \pm 12_{\rm stat} \pm 5_{\rm syst}$. The ratio BR($\phi \to \eta'\gamma$)/BR($\phi \to \eta\gamma$) is obtained by normalizing to the number of $\phi \to \eta\gamma$ observed events and correcting for detection efficiency taken from MC.

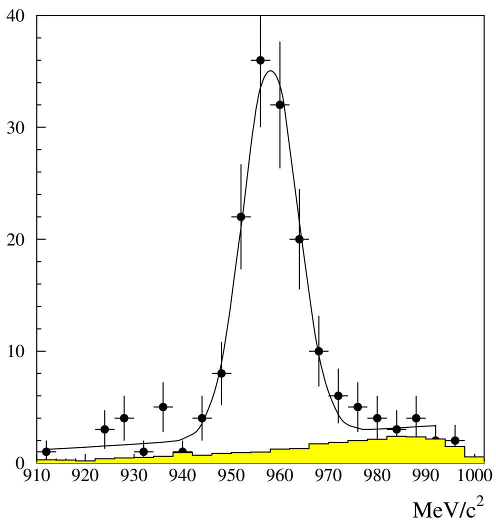

Figure 3. The $\pi^+\pi^-\gamma_1\gamma_2$ invariant mass distribution for candidate events $\phi \to \eta'\gamma$. The shaded area represents the residual background. The continuous line is the result of a gaussian plus linear fit.

The KLOE preliminary result is:

$$\frac{\mathrm{BR}(\phi \to \eta'\gamma)}{\mathrm{BR}(\phi \to \eta\gamma)} = (5.3 \pm 0.5_{\rm stat} \pm 0.4_{\rm syst}) \cdot 10^{-3} \quad (5)$$

from which the corresponding value for the mixing angle can be extracted [9,11]:

$$\varphi_P = (40^{+1.7}_{-1.5})^\circ \quad (6)$$

Making use of BR($\phi \to \eta\gamma$) value from Ref.[6], it is obtained:

$$\mathrm{BR}(\phi \to \eta'\gamma) = (6.8 \pm 0.6_{\rm stat} \pm 0.5_{\rm syst}) \cdot 10^{-5} \quad (7)$$

which is the most accurate measurement to date. The value obtained disfavours a very large gluonium content of η', while leaves still room for an $O(10\%)$ admixture.

7. BR($\phi \to f_0\gamma$) AND BR($\phi \to a_0\gamma$)

Several models proposed to explain the nature of the f_0 and a_0 mesons: ordinary $q\bar{q}$ meson, $q\bar{q}q\bar{q}$ state, $K\overline{K}$ molecule, make different predictions of BR($\phi \to f_0\gamma$), BR($\phi \to a_0\gamma$) and their ratio [12]. Therefore a precise measurement of BR($\phi \to f_0\gamma$) and BR($\phi \to a_0\gamma$) would clarify the interpretation on the nature of these mesons. Up to now only the VEPP-2M experiments have studied these decays [13,14].

At KLOE the following decay chains are considered:

- $\phi \to f_0\gamma$ with $f_0 \to \pi^0\pi^0$
- $\phi \to a_0\gamma$ with $a_0 \to \eta\pi^0$ and $\eta \to \gamma\gamma$

In both cases the final state is 5γ's. Several backgrounds are present: the main contributions come from the resonant process $\phi \to \rho^0\pi^0$ with $\rho^0 \to \pi^0\gamma$ or $\rho^0 \to \eta\gamma$, and the continuum process $e^+e^- \to \omega\pi^0$ with $\omega \to \pi^0\gamma$ or $\omega \to \eta\gamma$. There are also contributions from the 3γ's final states in which two clusters are spurious, and from 7γ's final state in which two clusters are lost.

The events are identified by requiring five prompt photons within loose acceptance cuts. Then a preliminary kinematic fit is performed requiring total energy and momentum conservation with the additional constraint $\beta = 1$ for all photons, thus refining the measured cluster positions, energies, and times. The best photon pairing is then obtained assuming each one of the possible decays, e.g. $\phi \to \pi^0\pi^0\gamma$, $\phi \to \eta\pi^0\gamma$, and $e^+e^- \to \omega\pi^0$. For each of them, a second kinematic fit is then performed with additional constraints on the masses of intermediate η's and π^0's. Finally the $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \eta\pi^0\gamma$ events are isolated by means of cuts on kinematic variables and on the χ^2 probability values obtained in the second series of kinematic fits.

The overall detection efficiency is obtained by tuning the MC to reproduce the observed $M_{\pi^0\pi^0}$ and $M_{\eta\pi^0}$ invariant mass distributions in case of $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \eta\pi^0\gamma$ events, respectively. The background in the $M_{\pi^0\pi^0}$ and $M_{\eta\pi^0}$ distributions is estimated using the MC and the cross section values for various processes directly measured by KLOE. The $\phi \to \rho^0\pi^0$ background rate is estimated from Ref.[6,15] (the interference between this process amplitude and the signal amplitude is neglected). The background from misreconstructed 3γ's final state events is estimated by embedding accidental cluster distributions obtained directly from data into MC generated events.

The preliminary KLOE measurements are:

$$\mathrm{BR}(\phi \to f_0\gamma \to \pi^0\pi^0\gamma) = (7.9 \pm 0.2_{\mathrm{stat}}) \cdot 10^{-5} \quad (8)$$

obtained for $M_{\pi^0\pi^0} \geq 700$ MeV, and

$$\mathrm{BR}(\phi \to a_0\gamma \to \eta\pi^0\gamma) = (5.8 \pm 0.5_{\mathrm{stat}}) \cdot 10^{-5} \quad (9)$$

Assuming $\mathrm{BR}(f_0 \to \pi^+\pi^-) = 2\mathrm{BR}(f_0 \to \pi^0\pi^0)$, and full decay of the f_0 and a_0 in the $\pi\pi$ and $\eta\pi$ channels, the following value is obtained for the ratio of branching ratios:

$$\frac{\mathrm{BR}(\phi \to f_0\gamma)}{\mathrm{BR}(\phi \to a_0\gamma)} = 4.1 \pm 0.4_{\mathrm{stat}} \quad (10)$$

This value seems to favour the interpretation of f_0 and a_0 as compact $q\bar{q}q\bar{q}$ states surrounded by a virtual $K\overline{K}$ cloud [12].

The systematic error on the previous results is under study and it should not exceed 10%. Detailed analyses to fit the $M_{\pi^0\pi^0}$ and $M_{\eta\pi^0}$ distributions and to extract the f_0 and a_0 resonance parameters, also studying the contribution of the background due to $\phi \to \rho^0\pi^0$ decay (and of a possible $\phi \to \sigma\gamma$ decay with $\sigma \to \pi^0\pi^0$) with its interference with the signal are in progress.

REFERENCES

1. S. Guiducci et al, Proceedings of PAC99, New York, March 1999
2. KLOE collaboration, *KLOE: a general purpose detector for DAΦNE*, LNF-92/019 (IR) (1992); KLOE collaboration, *The KLOE detector - technical proposal*, LNF-93/002 (IR) (1993)
3. G. D'Ambrosio, G. Isidori and A. Pugliese, "CP and CPT measurements at DAΦNE", in L. Maiani, G. Pancheri and N. Paver eds., *The second DAΦNE physics handbook*, LNF, Frascati, 1995
4. M. Adinolfi et al., *The KLOE electromagnetic calorimeter*, submitted to Nucl. Instr. Meth. A (2001)
5. M. Adinolfi et al., *The tracking detector of the KLOE experiment*, submitted to Nucl. Instr. Meth. A (2001)
6. Particle Data Group, D.E. Groom et al., Eur. Phys. J. C 15 (2000) 1
7. R. R. Akhmetshin et al., Phys. Lett. B456 (1999) 90
8. J. L. Rosner, Phys. Rev D27 (1983) 1101
9. A. Bramon, R. Escribano and M.D. Scadron, Eur. Phys. J. C7 (1999) 271
10. E. Kou, contributed paper to these proceedings (see also E. Kou, Phys. Rev. D63 (2001) 054027)
11. T. Feldmann, Int. J. Mod. Phys. A15 (2000) 159
12. F. E. Close and A. Kirk, Phys. Lett. B515 (2001) 13 and references therein
13. R. R. Akhmetshin et al., Phys. Lett. B462 (1999) 380
14. M. N. Achasov et al., Phys. Lett. B479 (2000) 53; M. N. Achasov et al., Phys. Lett. B485 (2000) 349
15. M. N. Achasov et al., JETP Lett. 72 (2000) 282 ; R. R. Akhmetshin et al., Phys. Lett. B509 (2001) 217