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The first data taking with KLOE: measuring CP and testing CPT using leptonic decays

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Abstract

CP and CPT violation are the main physics issues of the KLOE experiment at the Frascati ϕ–factory DAΦNE. The detector has two main subsystems: the large cylindrical He–based drift chamber, with a r/ϕ resolution better than 200 μm which ensures a very good momentum resolution of $\sigma_{p_\perp}/p_\perp \simeq 0.5\%$ in a magnetic field of ≈ 0.6 T, surrounded by the fine sampling lead/scintillating fibers electromagnetic calorimeter with an excellent time resolution of 55 ps$/\sqrt{E(\text{GeV})}$ and good energy resolution of $4.7\%/\sqrt{E(\text{GeV})}$, high hermeticity and full efficiency for photons down to 20 MeV.

The data taking will start with a RUN I in Spring 1999 at the initial luminosity of 5×10^{31} cm^{-2} s^{-1}; in the first few months the KLOE detector will collect 5×10^8 ϕ decays, corresponding to $\simeq 7\times10^6$ reconstructed $K_{\mu3}$ and K_{e3} decays. The two years long RUN II at the design luminosity of 5×10^{32} cm^{-2} s^{-1} will increase this statistics by a factor 100.

If CPT invariance is assumed, CP violation in the mass matrix can be measured by the leptonic asymmetries in K_L decays, $2\Re e(\bar\varepsilon) \simeq A_L^\ell = (\Gamma_L^{\ell^+} - \Gamma_L^{\ell^-})/(\Gamma_L^{\ell^+} + \Gamma_L^{\ell^-})$, $\ell = \mu,e$. The uniqueness of the ϕ–factory is that the K_LK_S pairs are produced in a pure antisymmetric superposition, moreover the two fiducial volumes are completely separated due to the large difference in decay lengths.

An efficient and high purity tagged K_S beam gives the opportunity to measure the A_S^ℓ asymmetry in the semileptonic decays. Since the expected number of reconstructed $K_S \to \pi\ell\nu$ decays for RUN I is 6×10^4 $\pi e\nu$ and 4×10^4 $\pi\mu\nu$, the expected statistical uncertainty is $< 1\%$. CPT invariance can thus be tested at KLOE, assuming $\Delta S = \Delta Q$, by measuring the difference $A_S^\ell - A_L^\ell = 4\Re e(\delta)$.

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1 The KLOE Experiment

The main physics aim of the KLOE experiment [1] is the measurement of the CP violation parameters to an accuracy of $\mathcal{O}(10^{-4})$. This will be done both with the double ratio method and kaon interferometry experiments [2].
The KLOE detector is optimised for the rejection of the background from the kaon decays other than $\pi\pi$, and for an excellent control of efficiencies in order to keep systematic errors at the level of the statistical accuracy [3].
The large drift chamber [4] with its 12 582 square cells ($2 \times 2\pi/3$ cm^2 in the first 12 layers, $3 \times \pi$ cm^2 in the 46 outer layers) in an all stereo configuration, ensures a single point resolution better than 200 μm in the transverse plane and high and uniform track and vertex reconstruction efficiency. A fractional transverse momentum resolution of 0.5% is achieved with a $\approx$0.6 T field, provided by a superconducting solenoid. Low Z and density materials and gas mixtures (He 90% - iC$_4$H$_{10}$ 10%) have been used to minimise multiple scattering for low momentum particles (50-300 MeV/c) and to ensure high transparency for low energy photons.
The fine sampling lead/scintillating fibers calorimeter [5] with its 15 X_0 thick modules (24 4.3 m long barrel modules and the 2×32 C-shaped end-cap modules) covers $\approx$ 98% of the solid angle. Its hermeticity, together with a good energy resolution of $4.7\%/\sqrt{E(\mathrm{GeV})}$ and full efficiency for photons down to 20 MeV, ensures the rejection of the 3 π^0 background, while its excellent time resolution of 55 ps$/\sqrt{E(\mathrm{GeV})}$ results in an accuracy of in 1 cm in the determination of the decay point for $K \to 2\pi^0 \to 4\gamma$.

2 CP, CPT and Semileptonic Kaon Decays

The K_S and K_L states can be written in general, to lowest order in ε, as:

$$\begin{aligned} |K_S\rangle &\simeq 1/\sqrt{2}[(1+\varepsilon_S)|K^0\rangle + (1-\varepsilon_S)|\bar{K}^0\rangle] \\ |K_L\rangle &\simeq 1/\sqrt{2}[(1+\varepsilon_L)|K^0\rangle + (1-\varepsilon_L)|\bar{K}^0\rangle] \end{aligned}$$

and if CPT holds $\varepsilon_S = \varepsilon_L = \varepsilon$. More generally if CPT invariance is not imposed two parameters can be defined by the identities:

$$\varepsilon_S \equiv \tilde{\varepsilon} + \delta, \quad \varepsilon_L \equiv \tilde{\varepsilon} - \delta$$

The δ parameter is related to the CPT violation assuming the $\Delta S = \Delta Q$ rule, while

$$\tilde{\varepsilon} - \delta = \varepsilon + \Re e(B_0/A_0)$$

is related to CP violation in $K \to \pi\pi$ and the CPT odd amplitude B, where the $K \to \pi\pi$ amplitude general expression is:

$$A(K^0 \to \pi\pi, I) = \sqrt{2/3}(A_I + B_I).$$

A sector in which the CPT violation can be studied is the semileptonic kaon decay; the $\Delta S = \Delta Q$ amplitudes are in general:

$$\begin{aligned} A(K^0 \to \ell^+) &= a + b \\ A(\bar{K}^0 \to \ell^-) &= a^* - b^* \end{aligned}$$

where $b \neq 0$ implies "direct" CPT violation.
The integrated leptonic asimmetries

$$\begin{aligned} A_{\ell,S} &= \frac{\Gamma(K_S \to \ell^+\nu_\ell\pi^-) - \Gamma(K_S \to \ell^-\bar{\nu}_\ell\pi^+)}{\Gamma(K_S \to \ell^+\nu_\ell\pi^-) + \Gamma(K_S \to \ell^-\bar{\nu}_\ell\pi^+)} \\ A_{\ell,L} &= \frac{\Gamma(K_L \to \ell^+\nu_\ell\pi^-) - \Gamma(K_L \to \ell^-\bar{\nu}_\ell\pi^+)}{\Gamma(K_L \to \ell^+\nu_\ell\pi^-) + \Gamma(K_L \to \ell^-\bar{\nu}_\ell\pi^+)} \end{aligned}$$

are connected to the $\tilde{\varepsilon}$ and δ and the CPT violation in the semileptonic amplitudes [6]:

$$A_{\ell,S} = 2\left(\Re e\tilde{\varepsilon} + \Re e\delta + \Re e\frac{b}{a}\right)$$
$$A_{\ell,L} = 2\left(\Re e\tilde{\varepsilon} - \Re e\delta + \Re e\frac{b}{a}\right)$$

In the most general framework in which $\Delta S = \Delta Q$ is no longer assumed, the two violations can not be disentagled with $K_{S,L}$ decays alone [6]; anyhow $\Delta S = -\Delta Q$ transitions in the Standard Model are forbidden at the tree level, and expected at the level of $\mathcal{O}(10^{-7})$. The asymmetries difference, in absence of $\Delta S = \Delta Q$ violation, can be written as:

$$A_{\ell,S} - A_{\ell,L} = 4\Re e(\delta)$$

since the "direct" CPT term cancels out.
Only the asymmetry in K_L semileptonic decays has been so far measured, A_L=$(3.27 \pm 0.12)\ 10^{-3}$ [7], in good agreement with $\Re e\varepsilon \sim \sqrt{2}\varepsilon$, which is what one expects from CP violation coming from the mass term.

3 Leptonic Asymmetries with KLOE

The uniqueness of the ϕ–factory is that the K_LK_S pairs are produced in a pure anti-symmetric superposition, moreover the two fiducial volumes are completely separated due to the large difference in decay lengths:

$$\lambda_S = 5.6 \text{ mm}, \qquad \lambda_L = 3.43 \text{ m}.$$

The huge amount of kaon decays that can be observed at KLOE will allow a much more accurate determination of A_L, while the efficient and high purity tagged K_S beam will give the opportunity to measure for the first time both the branching ratio of $K_S \to \ell\nu\pi$ and the A_S asymmetry. The measurement of the two asymmetries will thus allow a test of CPT by measuring the δ parameter.
The K_L decays are tagged by $K_S \to \pi^+\pi^-$, which have a branching ratio of 66%; the number of fully reconstructed K_L semileptonic decays are:

$$\begin{aligned} N_{L,\ell} &= N_\phi \times BR(\phi \to K_SK_L) \times BR(K_S \to \pi^+\pi^-) \times \\ &\times BR(K_L \to \ell\nu_\ell\pi) \times \epsilon_{geo} \times \epsilon_{id} \times \epsilon_{rec} \end{aligned}$$

where the geometric acceptance in the fiducial volume is $\epsilon_{geo} \sim 28\%$, the identification has an efficiency of $\epsilon_{id} \sim 68\%$ [8] and a conservative estimate of the reconstruction efficiency is $\epsilon_{rec} \sim 50\%$. The contamination coming from $\phi \to 2$ charged particles (such as K^+K^- and $\rho\pi$) is $\mathcal{O}(10^{-5})$, while the tagging efficiency can be increased from 66% to almost 100% using also $K_S \to \pi^0\pi^0$ decays.
The K_S decays are tagged by $K_L \to \pi\ell\nu_\ell$ and $K_L \to \pi^+\pi^-\pi^0$, which have a total branching ratio of 78%. Taking into account the geometric acceptance inside the drift chamber of about 40%, the tagging efficiency $\sim 30\%$, while the reconstruction efficiency of the K_L is $\epsilon_{id} \sim 50\%$. The contamination is at the level of $\mathcal{O}(10^{-6})$ coming essentially from $\phi \to K^+K^-$ [9]. The tagging efficiency can be increased using also the fraction of K_L's which escape the drift chamber without decaying, $f_{geo} \sim 51\%$, and interact in the calorimeter producing at least one cluster with probability $p_{interact} \sim 85\%$: we call this a K_L "crash" [10]. Assuming to recognize the "crash" with an efficiency of $\epsilon_{crash} \sim 70\%$ [10], the overall tagging efficiency is doubled, so that the number of fully reconstructed K_S semileptonic decays are:

$$\begin{aligned} N_{S,\ell} &= N_\phi \times BR(\phi \to K_S K_L) \times \\ &\times [BR(K_L \to \text{charged}) \times \epsilon_{geo} \times \epsilon_{id} + f_{geo} \times p_{interact} \times \epsilon_{crash}] \times \\ &\times BR(K_S \to \ell\nu_\ell\pi) \times \epsilon_{rec} \end{aligned}$$

where ϵ_{rec} is the identification and recostruction efficiency for the K_S leptonic decay.
At the initial luminosity of DAΦNE of $\mathcal{L} = 5{\times}10^{31}$ cm^{-2}s^{-1}, in the first months of data taking 5 $\times 10^8$ ϕ events will be collected, corresponding to an integrated luminosity of 100 pb^{-1}. The branching ratio for K_S leptonic decays can be estimated from the K_L decays:

$$BR(K_S \to \ell^\pm\nu_\ell\pi^\mp) = BR(K_L \to \ell^\pm\nu_\ell\pi^\mp) \times \tau_{K_S}/\tau_{K_L}$$

so that the number of fully reconstructed K semileptonic decays is:

$$\begin{aligned} N_{L,\mu} &\simeq 3 \times 10^6, \quad & N_{L,e} &\simeq 6 \times 10^6 \\ N_{S,\mu} &\simeq 4 \times 10^4, \quad & N_{S,e} &\simeq 6 \times 10^4 \end{aligned}$$

which is 1/100 of the full statistics of the two years long run at $\mathcal{L} = 5{\times}10^{32}$ cm^{-2} s^{-1}. The measurements on the K_S BR's will be by itself a test of the Standard Model, which predictions have uncertainties of the order of $\mathcal{O}(10^{-2})$, due to the present error on $BR(K_L)$, while the only measurement performed so far [11] has an accuracy of $\sim$ 20%. If $N_{id,\ell}$ is the number of decays identified as $K_S \to \ell\nu_\ell\pi$, and $N_{B,\ell}$ is the estimated number of background decays, the branching ratio is measured by:

$$BR_\ell = \frac{N_{id,\ell} - N_{B,\ell}}{N(\phi \to KK)\epsilon_{tot}}$$

where ϵ_{tot} is the overall identification efficiency. The statistical accuracy that can be reached, neglecting the contribution of the error on the background estimate, is $\sim 10^{-2}$ with 100 pb^{-1} and will reach $\sim 10^{-3}$ with the full statistics.
For the measurement of $A_{\ell,S}$ the main task is to determine the lepton sign, i.e. the correct lepton-pion assignment to the two charged tracks connected to the K_S vertex. Different strategies are available at KLOE:

- the "neutrino mass" method;
- $\pi/\mu/e$ discrimination using the time of flight tecnique;
- other discriminant methods (neural net).

The "neutrino mass" method consists in evaluating the neutrino mass using 4-momentum convervation in the two possible π/ℓ track combinations, and choosing the one with the smallest value. This requires to estimate the K_S momentum components, which are measured with poor accuracy because of the small K_S fligth path. The determination can be improved by using the K_L measured vertex and momentum components, by applying 4-momentum conservation.
The main background for the $A_{S,e}$ and $A_{S,\mu}$ measurements comes from the CP-allowed $K_S \to \pi^+\pi^-$ decays, which are 10^3 more abundant than the $\pi\ell\nu$. This background can be rejected by a kinematical cut on the estimated "neutrino mass". Further kinematical cuts can be used in the $M_{\pi\pi}$-p_{tot} plane in the $\pi\pi$ hypothesis: the two pion decays should reconstruct the kaon mass and momentum.
Cuts in the "neutrino mass" at 50 MeV/c^2 and in the invariant mass/total momentum plane for the $\pi\pi$ hypothesis result in an $\epsilon_{kine} \simeq 52\%$ with a contamination of $\simeq 5\%$ [12]. While the main contribution to the inefficiency is the wrong lepton sign assignment $1 - \epsilon_{sign}$, where $\epsilon_{sign} \simeq 83\%$, the $\pi\pi$ contamination comes essentially from the long tails in the $\pi\pi$ invariant mass distribution [12].
The statistical accuracy on the measurement of $A_{S,e}$ is given by:

$$\delta A_{S,e} = 1/\sqrt{\epsilon(2\epsilon_{sign} - 1)^2 N_{S,e}} \times \sqrt{1 + B/S}$$

where ϵ takes also into account the tagging and vertex efficiency:

$$\epsilon = \epsilon_{tag} \times \epsilon_{vtx} \times \epsilon_{kine}$$

and B/S is the backgroung to signal ratio.
Since the background has a branching ratio 1000 bigger than the signal, after the kinematical cuts we have $\sqrt{1 + S/B} \sim 7$, even with a contamination as low as $\sim 5\%$. The statistical error on $A_{S,e}$ can be estimated at the level of 8×10^{-3} with 100 pb^{-1} integrated luminosity, which corresponds to an error on δ of 2×10^{-3}; these errors will be decreased by a factor 10 with the full statistics.
Improvements on the S/B ratio could result in significantly better limits on δ, for istance using the electromagnetic calorimeter timing or adding dE/dx measurements in order to discriminate leptons from pions.

4 Conclusions

The possibility of having a clean, tagged, intense beam of K_S's and the excellent performances of the KLOE detector will allow many measurements in the leptonic sector, which were not available so far, such as the $K_S \to \ell\nu_\ell\pi$ branching ratio measurement, to an accuracy of 10^{-3}, and the $A_{S,\ell}$ charge asymmetry to a level of 8×10^{-4}. Together

with the $A_{L,\ell}$ determination this will allow to test CPT violation by measuring the δ parameter to an accuracy of 2×10^{-4}, albeit assuming the $\Delta S = \Delta Q$ rule[2].
The first months of running of KLOE at the initial DAΦNE luminosity will already give preliminary results with 1/100 of the full statistics, i.e. with a factor 10 in the statistical error.

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