STATUS OF THE KLOE AND DAΦNE PROJECTS

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CP and CPT physics issues at a ϕ-factory are reviewed. The design strategies and the status of the new Frascati ϕ-factory complex, DAΦNE, and of the KLOE detector are discussed.

1 Introduction

The commissioning of the new Frascati ϕ-factory, DAΦNE, and of the KLOE detector is almost completed.

The primary mission of KLOE is to measure the real part of ε'/ε with statistical and systematic accuracy of 10^{-4}. This is mainly motivated by the fact that experimental results to date[1,2], which carry errors $\sim 6\times10^{-4}$, do not allow one to draw firm conclusions on the CP properties of the weak K^0decay; in particular, it is not known yet whether the ε' parameter, describing direct

CP violation, is vanishing or not.

In the present paper, after briefly recalling the main objectives of the KLOE experiment, I will assess the status of DAΦNE and KLOE.

2 DAΦNE

To allow a 10^{-4} measurement of ε'/ε, the DAΦNE luminosity must be $\mathcal{O}(5\times10^{32}$ cm^{-2}s^{-1}), 100 times bigger than the maximum ever obtained at the low energy for ϕ resonant production, where intra-beam instabilities play a significant role. The strategy to achieve such a high luminosity is to circulate up to 120+120 bunches, in two separate rings to minimise beam-beam interactions [3]. The DAΦNE injection system consists of a 60 m LINAC where e^+e^- are accelerated to their nominal energy of 510 MeV, and a 32 m circular accumulator. The particles are then injected in topping up mode (that is, continuously replenishing the lost beam) into the main rings. The projected single beam current is 44 mA, which makes for more than 5 A per ring with 120 bunches. The main technological challenges posed by these huge currents included the design of a vacuum system capable of dynamically maintaining the residual pressure at the 1 nTorr level required for beam life time and background in the detectors, and the design of a feedback system to tame multibunch instabilities.

The maximum current reached in single bunch mode during the machine commissioning has been 110 mA for both positrons and electrons, without any active feedback. In multibunch mode, 120 bunches have been stored, without feedback, with 0.3 A in the positron ring and 0.23 in the electron one. With longitudinal feedback, about 0.5 A have been stored in 25 e^- bunches and in 28 e^+ bunches.

Collisions were first obtained on March 1st this year; the maximum single bunch luminosity was 3×10^{29} cm^{-2}s^{-1}, (to be compared with the design one of 4×10^{30} cm^{-2}s^{-1}). Tuning of the machine parameters is in progress, and expected to reach a reasonably good working point by autumn 1998.

3 Physics issues at a ϕ-factory

At a ϕ-factory, kaons originate from the decay of the ϕ meson, which is resonantly produced in e^+e^- collisions at 1020 MeV centre of mass energy. Kaon beams from two body decays of the ϕ are, except for small effects due to the beam-beam crossing angle monochromatic and back-to-back. Moreover, $K^0\overline{K}^0$ pairs (or, equivalently, $K_{\rm S}K_{\rm L}$ pairs) are produced in a pure antisymmetric superposition, due to conservation of charge conjugation in the strong decay $\phi{\to}K^0\overline{K}^0$. These properties result in two main consequences. First, a very efficient and high purity tag: thanks to the huge difference in the decay lengths, the K_S and K_L fiducial volumes are neatly separated, therefore the detection of a K_S implies the presence of the K_L in the opposite direction and vice-versa, with contaminations $\mathcal{O}(10^{-5})$ at worst.

Second, the coherence of the initial state reflects in the $K_S K_L$ decay products, which exhibit then quantum mechanical interference patterns. This opens up a whole world of measurements which are unique to the ϕ-factory environment.

The gold plated way to study quantum interference at DAΦNE is to consider the probability distribution for finding in the detector two generic final states, f_1 and f_2, at a given proper time difference[4] $\Delta t = t_1 - t_2$:

$$\begin{aligned} I(f_1, f_2; \Delta t > 0) = & \frac{|\langle f_1|K_S\rangle\langle f_2|K_L\rangle|^2}{2\Gamma}\times \\ & \{|\eta_1|^2 e^{-\Gamma_L} + |\eta_2|^2 e^{-\Gamma_S} - 2|\eta_1||\eta_2|e^{-\Gamma|\Delta t|/2}\cos(\Delta m|\Delta t| + \varphi_1 - \varphi_2)\} \end{aligned} \tag{1}$$

with $\Gamma = \Gamma_S + \Gamma_L$, $\eta_j \equiv |\eta_j|e^{i\varphi_j} = \langle K_L|f_i\rangle/\langle K_S|f_i\rangle$. The formula for $\Delta t < 0$ (when state f_2 is is detected before state f_1) reads the same, after interchanging indices 1 and 2.

3.1 Some examples of CP physics

Choosing $f_1 = \pi^+\pi^-$, $f_2 = \pi^0\pi^0$, one has $\eta_1 = \varepsilon(1 + \varepsilon'/\varepsilon)$, $\eta_2 = \varepsilon(1 - 2\varepsilon'/\varepsilon)$, thus $\varphi_1 - \varphi_2 = 3\Im\varepsilon'/\varepsilon$. Since $\eta_1 \simeq \eta_2$, for $\Delta t \sim 0$ a symmetric state is being formed from the initial antisymmetric one, therefore the amplitudes interfere destructively (fig. 1).

For large Δt, we can measure $\Re\varepsilon'/\varepsilon$, while for $\Delta t \sim 0$ the distribution is sensitive to $\Im\varepsilon'/\varepsilon$ (which, if found $\neq 0$, would also be a signal of CPT violation[4]). This approach is unique to a ϕ-factory and is complementary *e.g.* to hadronic machines. However, $\Re\varepsilon'/\varepsilon$ can also be measured via time-integrated quantities, among which is the well known double ratio. In the latter case, assuming we detect $\sim 4\times 10^6$ tagged $K_L \to \pi^0\pi^0$ events (the less abundant decay) in the K_L fiducial volume, corresponding to about 2×10^7 seconds of data taking at the DAΦNE target luminosity, the statistical error on $\Re\varepsilon'/\varepsilon$ will be 10^{-4}.

CP violation can also be observed at DAΦNE in the channel $K_S \to \pi^0\pi^0\pi^0$ although, being the latter decay phase space suppressed, only $\sim$20 events are expected[8]. Finally, interesting limits can be found on direct CP violation of charge kaons in the modes $K^\pm \to \pi^+\pi^-\pi^\pm$, $K^\pm \to \pi^0\pi^0\pi^\pm$.

3.2 CPT, $\Delta S = \Delta Q$

CPT invariance can be studied at DAΦNE using semileptonic decays. Similar to the CP violation case, both time integrated asymmetries and interference

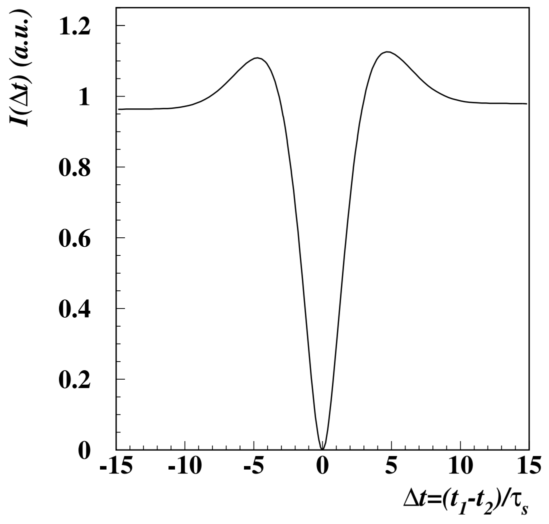

Figure 1: Interference pattern from $\phi \to K_S K_L \to \pi^+\pi^-\pi^0\pi^0$.

patterns can be exploited. In the most general way, semileptonic amplitudes for neutral kaons can be written as [9]:

$$\begin{array}{ll} A(K^0 \to \ell^+) = a + b & A(\overline{K}^0 \to \ell^-) = a^* - b^* \\ A(K^0 \to \ell^-) = c + d & A(\overline{K}^0 \to \ell^+) = c^* - d^* \end{array} \tag{2}$$

where $\Re(a,c) \neq 0$ conserve and $\Im(a,c) \neq 0$ violate both CP and T, $\Re(b,d) \neq 0$ violate CP but conserve T, and $\Im(b,d) \neq 0$ conserve CP and violate T. Consequently, a and c are CPT conserving, while b and d are CPT violating. Moreover, c, d violate the so called $\Delta S = \Delta Q$ rule, which is expected to hold to very good accuracy ($\sim 7 \cdot 10^{-7}$) in the Standard Model [5]. Going back to eqn. 1, the η coefficients read now (δ_k parametrises CPT violation in the mass matrix):

$$\begin{aligned} \eta_{\ell^+} &= 1 - 2\left(\delta_k + \frac{c^*}{a} - \frac{d^*}{a}\right) \\ \eta_{\ell^-} &= -1 - 2\left(\delta_k - \frac{c}{a^*} - \frac{d}{a^*}\right) \end{aligned} \tag{3}$$

i.e. they have nearly opposite signs; for this reason, in the double semileptonic channel (fig. 2) there is constructive interference for $\Delta t \sim 0$. Again, in this time region there is maximal sensitivity to the imaginary part of the CPT

violation parameter ($\varphi_1 - \varphi_2 = \simeq\pi - 4\Im\delta_k - 4\Im c^*/a$), while the real part is measured from the asymmetry at large Δt. In this respect, fully integrated

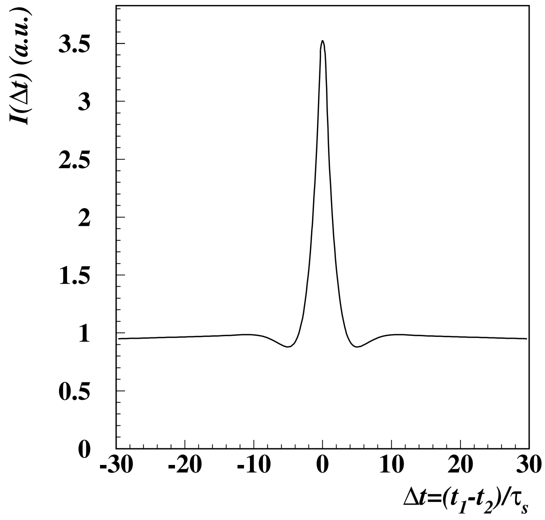

Figure 2: Interference pattern from $\phi\to K_{\rm S}K_{\rm L}\to\pi\ell\nu\pi\ell\nu$.

asymmetries have of course better statistical power. The unique feature of KLOE of having pure tagged $K_{\rm S}$ beams will let us measure the asymmetry of the never observed heretofore semileptonic decay of the $K_{\rm S}$. This in turn will allow us to perform tests of T and CPT violation [6], without assuming CPT conservation in 2 pion decays [7] (as it is done in present CPT analyses), *albeit* assuming $\Delta S{=}\Delta Q$: for example, from the difference of $K_{\rm S}$ and $K_{\rm L}$ semileptonic asymmetries, one has $\mathcal{A}_{\rm S} - \mathcal{A}_{\rm L} = 4\Re\delta_k - 4\Re(d^*/a)$. At present, $\mathcal{A}_{\rm L}{=}(3.30{\pm}0.12){\cdot}10^{-3}$; with $10\,{\rm fb}^{-1}$, KLOE can measure[a] $\mathcal{A}_{\rm L}$ to $\sim2{\times}10^{-5}$ and $\mathcal{A}_{\rm S}$ to $\sim2.5{\times}10^{-4}$. Usually, CPT tests are phrased in terms of the quantity $(m_{K^0} - m_{\overline{K}^0})/\langle m_K\rangle$: using the above measurements, KLOE should reach a sensitivity $(m_{K^0} - m_{\overline{K}^0})/\langle m_K\rangle{\sim}2{\times}10^{-19}$, that is interestingly close to the Planck scale.

Finally, KLOE can test the absence of $\Delta S = -\Delta Q$ transitions, both comparing the total semileptonic rates of $K_{\rm L}$ and $K_{\rm S}$: $\Gamma^\ell_{\rm L}/\Gamma^\ell_{\rm S} - 1 = 4\Re(c^*/a)$, and using tagged K^0 beams from charge exchange of $K^\pm$ on the beam pipe or the

[a] Assuming a $K_{\rm S}$ tagging efficiency of about 70%, obtainable using $K_{\rm L}$ interactions in the e.m. calorimeter: see sec. 4.2

internal wall of the drift chamber.

4 The KLOE detector

4.1 Experimental requirements

The design of the KLOE (K LOng Experiment) detector[8,10] has been optimised to measure $\Re\varepsilon'/\varepsilon$ via the double ratio:

$$\mathcal{R} \equiv \frac{\mathcal{R}^{+-}}{\mathcal{R}^{00}} = \frac{\Gamma(K_{\rm L}\to\pi^+\pi^-)}{\Gamma(K_{\rm S}\to\pi^+\pi^-)} \cdot \frac{\Gamma(K_{\rm S}\to\pi^0\pi^0)}{\Gamma(K_{\rm L}\to\pi^0\pi^0)} = 1 + 6\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \tag{4}$$

with an accuracy of 10^{-4}. KLOE must collect as many as possible of the events delivered by DAΦNE: since $\beta(K) = 0.216$, the mean $K_{\rm L}$ decay length is 3.44 m; this is the parameter driving the scale of KLOE, which is therefore quite a sizeable experiment, despite the fact that DAΦNE is a small, though complex, collider.

On the systematics side, the main challenges KLOE has to face include rejection of the copious non CP violating background, knowledge of the combined – geometric, detection, reconstruction – (in)efficiencies to the percent level, and control of event miscounting in the vicinity of the fiducial volume boundary: in this respect, it is crucial that the distance scales for charged and neutral decays coincide within a fraction of millimetre.

Background rejection at the desired level ($\sim 10^{-4} \div 10^{-5}$, depending on the reaction) is obtained with a careful design and construction of detector components, and exploiting the kinematical constraints of the $\phi\to KK$ events at DAΦNE. The other two requirements are met making use of several reactions, which yield plenty of calibration events. For example, equalisation of the charged/neutral scales can be achieved using $K_{\rm L}\to\pi^+\pi^-\pi^0$ and $K^\pm\to\pi^\pm\pi^0\pi^0$ events; with the same reactions we can also cross-check the photon efficiency with the tracking efficiency, and vice-versa. Finally, Bhabha events can be used to calibrate time and energy scales in the e.m. calorimeter, as well as, together with $\mu^+\mu^-$ events and cosmic muons, t_0's and the drift velocity in the drift chamber. The good point is that these events are so abundant that a calibration to the desired level of accuracy is obtainable in a few minutes of data taking, therefore variations of the running conditions can be easily tracked.

4.2 Status of the detector

The KLOE detector (fig. 3) is about 6 m in diameter and 5 m in length – relatively short: $K\overline{K}$ pairs from ϕ decays have the $\sin^2\vartheta$ angular distribution typical of a $J = 1$ state. The installation of the detector components started from the most external one, the superconducting magnet, which provides a longitudinal field of 6 kG, proceeding inwards with the electromagnetic calorimeter, the drift chamber, the two small calorimeters on the quadrupoles, and the spherical beam pipe.

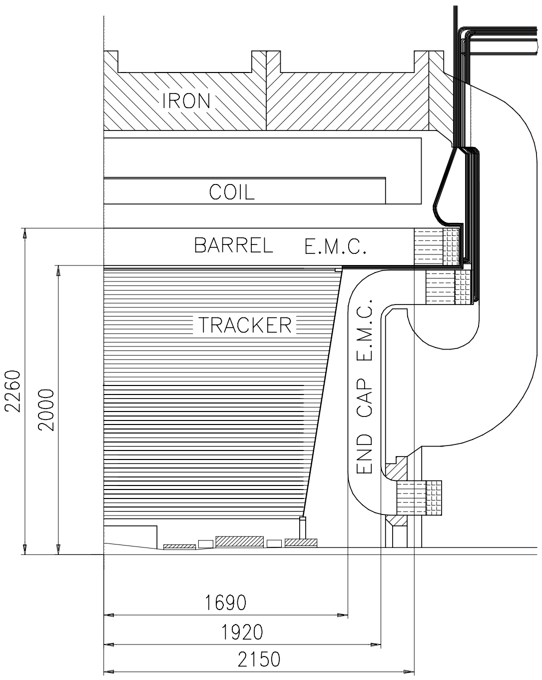

Figure 3: Schematic section of KLOE.

The electromagnetic calorimeter [10] is a fine sampling lead/scintillating fibres calorimeter, with good measured energy response: $\Delta E/E = 4.7\%/\sqrt{E(\mathrm{GeV})}$, and excellent time resolution, $\Delta t = 55ps/\sqrt{E(\mathrm{GeV})}$. The barrel section is subdivided into 24 modules 4.5 m long, while each end cap is composed by 32 C-shaped modules of variable sizes, arranged in such a way as to cover $\simeq 98.5\%$ of the solid angle, to reject $K_L \to \pi^0\pi^0\pi^0$ decays in which some of the photons escape detection. The light is read out from both sides of the modules, by about 5 000 fine mesh photomultipliers, with a granularity of $4.5\times4.5\,\mathrm{cm}^2$. The $K_L \to \pi^0\pi^0$ vertex can be measured in KLOE to a fraction of cm using only one of the 4 γ's, exploiting the low K_L velocity, and the fact that the K_L direction is known with good accuracy from momentum balance in $K_S \to \pi^+\pi^-$. A further crucial property of the electromagnetic calorimeter is its high efficiency for photons of energy down to 20 MeV. The calorimeter has been installed in the fall of 1997 and is being continuously tested with cosmic rays since then.

The tracking detector is a cylindrical single cell drift chamber [11,12]. The exigency of a sizeable decay volume for K_{L}'s and the necessary hit granularity of their decay products required us to design and build the biggest detector of this kind, both for dimensions (3.3 m in length, 4 m in diameter) and number of wires (over 52 000). Other unconventional features comprise: the all stereo geometry of the square drift cells, organised in 58 concentric layers because this configuration optimises the filling of the decay volume; the mechanical structure entirely in carbon fibre/epoxy, to prevent low energy photon conversion; the spherical end plates, to minimise the plate thickness and their deformation under the $\sim$3.5 tons load of the wires; the system of recovery of the plates deformation within $\sim$0.5 mm, with carbon fibre rings which pull the end plates like membranes through a set of radial screws; and the ultra light gas mixture (90%He-10%iC_4H_{10}) to minimise multiple scattering and K_{L} regeneration. The overall radiation length of the gas mixture plus the wires is almost one kilometre, while the total material thickness in front of the calorimeter, including the 8.5 mm C-fibre end plates, the low mass electronics mounted on them, and the cables is $\leq 0.1 X_0$.

The design point space resolution of $\sigma_{R\phi} = 200\,\mu$m allows large rejection factors on the unwanted $K_{\mu 3}$ background through kinematical cuts (for example, the resolution on the reconstructed K_{L} mass is $\sigma_M \simeq 1$ MeV); all the test on prototypes, including one in a magnetic field and one on a 1:1 prototype, yielded a resolution of $\sim 120\,\mu$m on large portions of the drift cell, and efficiencies close to one.

The drift chamber was wired in Frascati using dedicated machineries designed and built for this job, was closed and sealed to helium (the present O_2 contamination is $\sim$40 ppm at 15 slm flux), and $\sim$2000 channels out of the total 12 582 were tested on march with cosmic rays. On April 1st the chamber was then moved inside the rest of the detector, where cabling, installation and test of the remaining electronics proceeded till June. Since July a new, systematic test began. The program is to fully commission the chamber by mid October.

A factor 5 reduction of the $K_{\mathrm{L}} \to \pi^0\pi^0\pi^0$ background has been achieved by equipping the low β permanent quadrupoles inside KLOE with scintillating tiles/lead calorimeters (QCAL). The calorimeters on both quadrupoles have been built and tested with cosmic rays [13]. The data show excellent agreement with simulations and preliminary tests, therefore indicating that the QCAL will detect photons with the required efficiency and time/space resolution.

Peculiar to the KLOE experiment is the spherical shape of the beam pipe at the interaction region; the sphere has a radius of 10 cm, and is designed in order to give negligible regeneration effects. The correct electromagnetic field profile is guaranteed by a straight beryllium section 50 μm thick, while the sphere is a Be-Al composite of 500 μm thickness.

At the expected DAΦNE peak luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the event rate on the KLOE detector will be several hundred kHz, out of which about 5 kHz are due to ϕ decays. The two level trigger system [14] which has been designed and realised is capable of rejecting the unwanted reactions, while keeping a very high efficiency for CP violating events. It is also crucial that such events be selected without any bias, since the latter could influence the measurement of $\Re\varepsilon'/\varepsilon$. The rate after the second level will be of 10 kHz, including some 'prescaled' Bhabha events for calibration purposes.

At an expected average event size of 5 kbytes, this corresponds to a load of 50 Mbytes per second on the data acquisition system. The system which has been realised [15] collects data from some 23 000 FEE channels organised in 10 independents chains composed by 40 9U-VME crates. It sustains rates up to 80 Mbyte/sec, and is scalable to 130 Mbyte/sec. Like the trigger system, it is being extensively tested on the detector since several months, proving it exceeds the design specifications.

5 Prospects and conclusions

The conclusion of the KLOE construction and commissioning phase will coincide with the startup of the exciting data taking period. KLOE is expected to roll in during the fall 1998, it is therefore conceivable to start data taking by early 1999. KLOE's request to collect 100 pb^{-1} of data has been granted by the LNF scientific committee. This corresponds to about two months of run at 1/10 of the design luminosity, but will already let us obtain the first physics results.

We intend to measure $\Re\varepsilon'/\varepsilon$ to a 10^{-3} statistical accuracy, learning how the detector works and to control the systematics. This is a fundamental step towards the 10^{-4} measurement.

With 100 pb^{-1}, the $K_{\ell 3}$ form factors can be measured to an unprecented accuracy, $\sim$10 times better than at present. Even better so ($\times$30 improvement) for various branching ratios of the light scalar mesons f_0 and a_0 from the radiative decays $\phi \to f_0\gamma$, $\phi \to a_0\gamma$.

CP, T and CPT precision measurement together with the test of the $\Delta S = \Delta Q$ rule which all can in principle give clues of new physics beyond the Standard Model, will come (soon) after.

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