The DAΦNE ϕ-factory and the related physics program

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Abstract

Following a glorious tradition, INFN has launched a plan for a ϕ-factory, to be installed at the Frascati National Laboratories. DAΦNE, the new e^+e^- machine, will represent an ideal tool to carry on "nice experiments": at present two collaborations, KLOE and FINUDA, are working to put in operation two apparatuses, aimed, respectively, to precise CP violation measurements in the $K\bar{K}$ system and to high resolution hypernuclear spectroscopy with K^- at rest.

1 The DAΦNE project

The project for the DAΦNE (Double Annular ϕ-factory for Nice Experiments) accelerator complex [1] was approved and funded by the INFN Board of Directors in June 1990. It will consist of a double ring e^+e^- collider with two intersecting regions and of a 510 MeV e^+/e^- injector for topping-up, to be installed at the INFN National Laboratories of Frascati, in the pre-existing buildings housing the former ADONE machine, which has been recently dismantled (see Fig. 1).

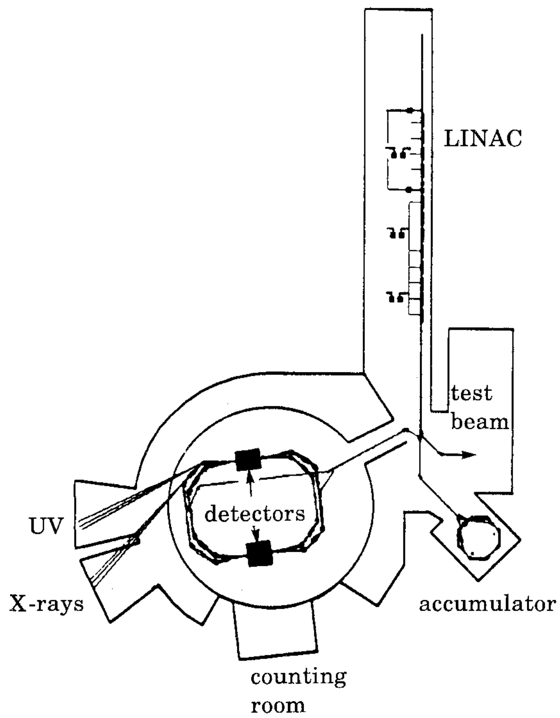

Figure 1: Layout of the DAΦNE complex at INFN National Laboratories of Frascati.

The luminosity is optimized at the ϕ peak ($E = 1019 MeV$): project top luminosity is $10^{33}\ cm^{-2}s^{-1}$, while at the commissioning time, foreseen for mid '96, the luminosity will be in excess of $2.5\times10^{32}\ cm^{-2}s^{-1}$. The strategy followed to reach this ambitious and challenging goal is that of having two long ($\sim 100\ m$) and symmetric rings, in which a high number of electron and positron bunches (~ 120) circulate separately in opposite directions and collide at a horizontal half-angle of $10 \div 15\ mrad$ so as to have a high collisions frequency without parasitic crossing. In addition, the crab-crossing technique will possibly be employed in order to reach the final top luminosity value. These features make DAΦNE the progenitor of a new generation of high-luminosity e^+e^- colliders. Figure 2 shows the layout of the collider magnetic components. A complete description of the machine characteristics can be found in Ref. [2].

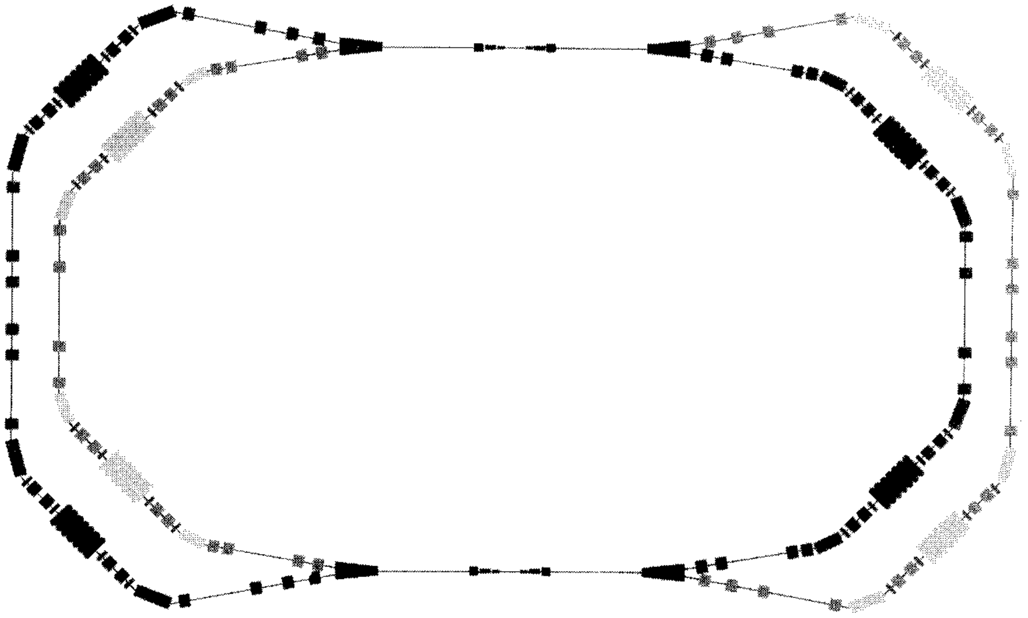

Figure 2: Layout of the magnetic components of the e^+e^- DAΦNE collider.

DAΦNE will be a very powerful ϕ-factory but it can be also regarded as a remarkably good K-factory, a good η-factory and, hopefully an interesting source of η' and gluons. These potentialities can be better appreciate in terms of annual yield of "interesting" particles. Assuming, in fact, a luminosity of $\mathcal{L} = 5 \times 10^{32}\ cm^{-2}s^{-1}$ and integrating the total cross-section at the ϕ resonance

$$\sigma_{peak} = \frac{12\pi}{M^2}\frac{\Gamma_e}{\Gamma} = 4.4\ \mu b \tag{1}$$

over an effective year of $10^7\ s$, we can estimate a production of $\sim 2.2 \times 10^{10}\ \phi$ mesons. Then, considering the ϕ decay modes, with their relative branching ratios, we obtain the following table:

Decay mode	branching ratio	events per year
$\phi \to K^+K^-$	0.495	1.1×10^{10}
$\phi \to K_L K_S$	0.344	7.6×10^9
$\phi \to \gamma\eta$	0.012	2.8×10^8
$\phi \to \gamma\eta'$	$< 10^{-4}$	—

Hence DAΦNE represents a unique opportunity for high-statistics and high-precision experiments on several topics [3]:

- CP, CPT physics
- hypernuclear physics
- K decays
- ϕ decays and quantum mechanics

- one photon processes
- photon-photon processes
- radiative ϕ decays
- spectroscopy issues above ϕ (in the prospect of an energy upgrade of the machine)
- low energy K-$\mathcal{N}$ interactions

2 The KLOE experiment

From the very beginning [1], the physics program of DAΦNE has been focused on the direct observation of CP violation in the $K\bar{K}$ system: the aim is a precise determination of the CP-violating parameters ε and ε', in particular of the ratio ε'/ε, recently measured with a 10^{-3} precision at CERN and at Fermilab by the NA31 [4] and, respectively, by the E731 [5] collaboration.

It is worthwhile to recall that since the experimental observation [6], in 1964, of the long lived K^0 meson decay into two pions, the search for direct CP violation has failed. CP violation remains, hence, one of the most interesting phenomena in the field of particle physics: in fact, even if theoretically allowed (the Cabibbo-Kobayashi-Maskawa quark mixing mechanism provides a home for CP [7]), its origin is not completely clear. In addition theory is not able to predict its existence nor the magnitude of the effect. It is of great relevance to establish whether CP violation is fully explained in the framework of the standard model or whether physics beyond it must be involved. Even the question about the validity of the *super-weak* hypothesis [8] is still open.

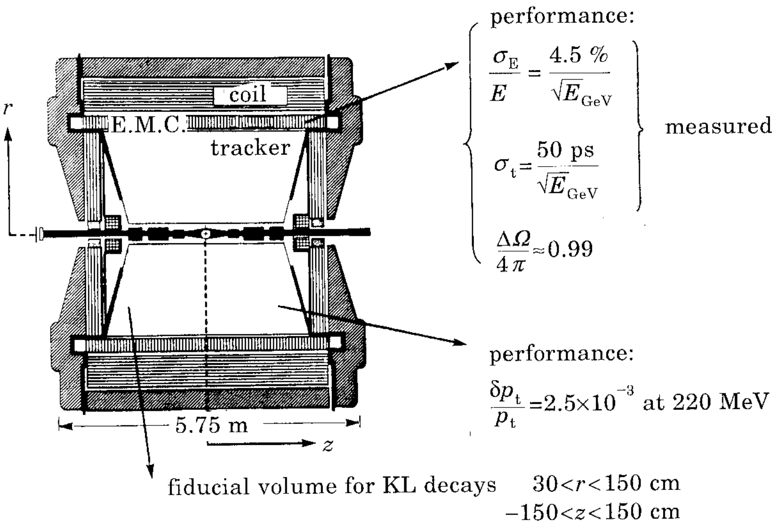

Figure 3: Schematic view of the KLOE detector and expected or measured performances of its components.

These challenging questions represents the main physics program of KLOE (K-Long Observation Experiment) [9][10], the first of the two detectors foreseen at DAΦNE. Figure 3 show a schematic view of the apparatus: it is a standard general purpose collider's apparatus: a cylindrical structure surrounding the beam pipe consisting of a vertex detector, a large tracking device with high efficiency for the K^0 decay products, an electromagnetic calorimeter with exceptional timing ability, also providing some particle identification and a super-conducting solenoidal magnet, generating a 0.6 T field.

The described apparatus will be characterized by a large fiducial volume in which $\sim 35\%$ of the K_L will decay and their decay products will be measured. In fact KLOE will look for CP violation studying the

$K_L, K_S, \to \pi^0\pi^0, \pi^+\pi^-$ decays, exploiting the circumstance that at a ϕ-factory K mesons are produced in a pure, C-odd quantum state. Furthermore $K^0(K^\pm)$ are emitted in collinear pairs, with a momentum of $\sim 110\ MeV/c$, thus detection of one K gives the direction of the other.

Defining the usual amplitudes ratios and ε parameter [11]:

$$\frac{\langle\pi^+\pi^-|K_L\rangle}{\langle\pi^+\pi^-|K_S\rangle} = \eta_{+-} = \varepsilon + \varepsilon' \quad \text{and} \quad \frac{\langle\pi^0\pi^0|K_L\rangle}{\langle\pi^0\pi^0|K_S\rangle} = \eta_{00} = \varepsilon - 2\varepsilon', \tag{2}$$

where η's and ε's are all complex, experimental observation of $\varepsilon' \neq 0$ would be proof that CP is violated in the decay amplitude.

An elegant way to determine the CP-violating parameters is the classical method of the double ratio:

$$\frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} \Big/ \frac{K_L \to \pi^0\pi^0}{K_S \to \pi^0\pi^0} = 1 + 6 \times \Re(\varepsilon'/\varepsilon). \tag{3}$$

$\Re(\varepsilon'/\varepsilon)$ can be obtained also from the the time asymmetry in the K_L decays into $\pi^+\pi^-$ and $\pi^0\pi^0$ or thanks to interference effects sensitive to $\Im(\varepsilon'/\varepsilon)$ in the time evolution of the $K^0\bar{K}^0$ system [12]. Finally, other ways of measuring $\Re(\varepsilon'/\varepsilon)$ from selected final states are [13]:

$$\frac{N(\pi^+\pi^-\pi^+\pi^-)}{N(\pi^0\pi^0\pi^0\pi^0)} \times \left(\frac{BR(K_S \to \pi^0\pi^0)}{BR(K_S \to \pi^+\pi^-)}\right)^2 = 1 + 6 \times \Re(\varepsilon'/\varepsilon); \tag{4}$$

$$\frac{N(\pi^+\pi^-\pi^+\pi^-)}{N(\pi^+\pi^-\pi^0\pi^0)} \times \frac{BR(K_S \to \pi^0\pi^0)}{BR(K_S \to \pi^+\pi^-)} = 1 + 3 \times \Re(\varepsilon'/\varepsilon). \tag{5}$$

It is worthwhile to note that all the method listed, even if are not statistically independent, provide very useful checks because of the very different dependence on all systematic effects.

The ambition of KLOE is that of measuring $\Re(\varepsilon'/\varepsilon)$ in one year of run at the DAΦNE top luminosity, reaching an absolute accuracy of 10^{-4}.

A ϕ-factory like DAΦNE represents also a very powerful tool for hadron spectroscopy: at the ϕ resonance there are, in fact, a number of interesting radiative and non-radiative rare decays. Their observation can shed light on the nature of some elusive scalar meson like, for instance, the $a_0(980)$ and the $f_0(970)$ ones. Various arguments suggest that they are not "usual" $q\bar{q}$ states [14], but $qq\bar{q}\bar{q}$ or $K\bar{K}$ molecules, analogues in the meson world of the baryonic deuteron. The study of the ratio $R = \Gamma(\phi \to a_0\gamma)/\Gamma(\phi \to f_0\gamma)$ could, hopefully, help to discriminate among the different hypotheses.

3 The FINUDA experiment

The FINUDA (FIsica NUcleare at DAΦNE) detector [15][16] looks, at first sight, like a typical collider's apparatus too (see Fig. 4), but it will devoted to nuclear physics and this represents a fact *absolutely new*. The project arose from an original idea of T. Bressani [17], that noticed that the low-energy, background free and tagged K^- from ϕ decays could offer a unique opportunity for high-resolution and high-statistics hypernuclear spectroscopy with K^- at rest. At proton machines, where intense fluxes of kaons are emitted from a production external target, the distance between the source and the experimental area is at least of $10 \div 15\ m$, for radiation safety requirements. $K^\pm$ of less than $400 \div 450\ MeV/c$ cannot obviously survive to such a length in a number suitable to give a reasonable beam intensity. Then experiments with stopped K^- are performed by degrading in momentum a $\sim 500 \div 600\ MeV/c\ K^-$ beam using a moderator just in front of the stopping target. This technique introduces a large uncertainty in the momenta of the degraded K^-, due to the straggling on the energy loss, and a rather thick target ($\geq 1\ g/cm^2$) has to be used to have an acceptable K^- stopping rate. Apart the case of active targets, the uncertainty in the localization of the stopping point leads to an error on the determination of the emitted charged particles, which often make fruitless the designed performances of the magnetic spectrometer.

At DAΦNE, on the contrary, since the K^- are slow ($\sim\ 16\ MeV$), just a very thin target ($\leq 100\ mg/cm^2$) will be necessary to stop them and the uncertainty on the interaction point leads, typically, to a momentum spread, for the outgoing particles, of $\sim 200\ KeV/c$. Thus it made sense to design a spectrometer with a pushed momentum resolution of $\sim 0.2 \div 0.3\%$ $(FWHM)$, that represents the figure of merit of the FINUDA apparatus.

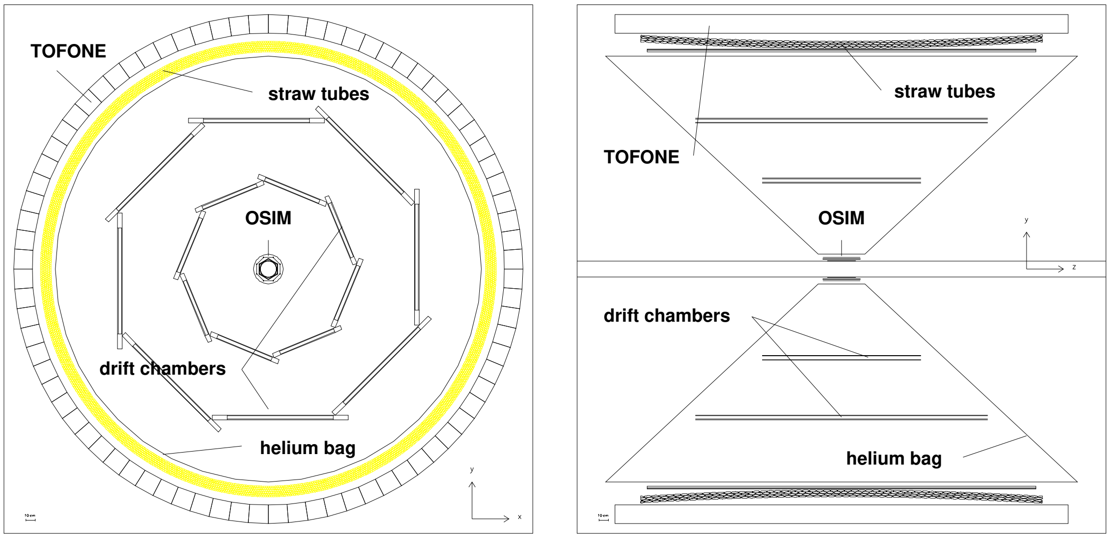

Figure 4: Schematic frontal and lateral views of the FINUDA apparatus.

FINUDA is a non focusing magnetic spectrometer with cylindrical geometry, consisting essentially of an interaction/target region, an external tracking system and an outer scintillator array. The full apparatus is immersed into a solenoidal field of 1.1 T, homogeneous within 1% over the volume used for the tracking of charged particles.

The initial research program will be focused on hypernuclear physics. With K^- at rest it is possible to populate many different hypernuclear state, in contrast to what happens with K^- in flight around the "magic moment". The energy spectrum of the hypernuclear levels can be determined by accurate measurements of the energy of the π^- emitted in the two-body reaction:

$$K^-_{stop} + {}^AX_Z \rightarrow {}^A_\Lambda X_Z + \pi^- \tag{6}$$

π^- from (6) carry a momentum ranging from ~ 250 to ~ 280 MeV/c, depending on the target nucleus and on the produced hypernuclear final state. A production mechanism similar to that of (6) holds for Σ-hypernuclei, noticing that the Σ-hyperon has three states of charge and therefore a π^+ can be emitted in case of Σ^--hypernuclei formation. $\pi^\pm$ following Σ-hypernuclei production would have typical momenta in the range $180 \div 200$ MeV/c, again depending on the target nucleus and on the reached final state. However it is worthwhile to recall that experiments at KEK [18] using stopped K^- have reported no clear evidence of the existence of narrow Σ-hypernuclei, previously claimed by experiments with K^- in flight. So it may be very challenging to try to solve this intriguing puzzle. Last but not least, the decay of hypernuclei plays a crucial role in understanding the behaviour of elementary particles embedded in a nuclear medium. A free Λ-hyperon decays mostly via the weak non leptonic decay $\Lambda \rightarrow N + \pi$, with a lifetime of 2.63×10^{-10} s, the energy release being 37 MeV. The situation changes completely when the Λ is embedded in the nuclear medium: in the nucleus, in fact, it is bound up to 25 MeV (for heavy nuclei), so the phase space for mesonic decay of the free Λ is greatly reduced. An even further suppression of this decay is due to the fact that the produced final-state nucleon has a very low momentum (< 100 MeV) and it is, consequently, Pauli blocked. In other words, the nuclear medium affects the weak decay mode of the Λ-hyperon, by introducing a new non-mesonic decay mode $\Lambda + N \rightarrow N + N$. The corresponding energy release is approximately 176 MeV, leaving each of the final nucleons with a momentum of 417 MeV/c. This channel has a much larger phase space (compared to the mesonic one) and the outgoing nucleons are no more Pauli blocked: hence it dominates largely the weak decay process in medium or heavy hypernuclei.

However very poor experimental data exist on this subject, due to the difficulty of producing hypernuclei in their ground states and of detecting the (n,p) and (n,n) pairs from non-mesonic decays. A recent analysis of data on light hypernuclei indicated, at a 1.6 σ level, a violation of the $\Delta I = 1/2$ rule for non mesonic decays of hypernuclei. It is of paramount importance to confirm, eventually, this result [19], studying the behaviour of the ratio of the relative amplitude for the np and nn non-mesonic decay.

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