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J. Lee-Franzini:

PHYSICS AT DAΦNE

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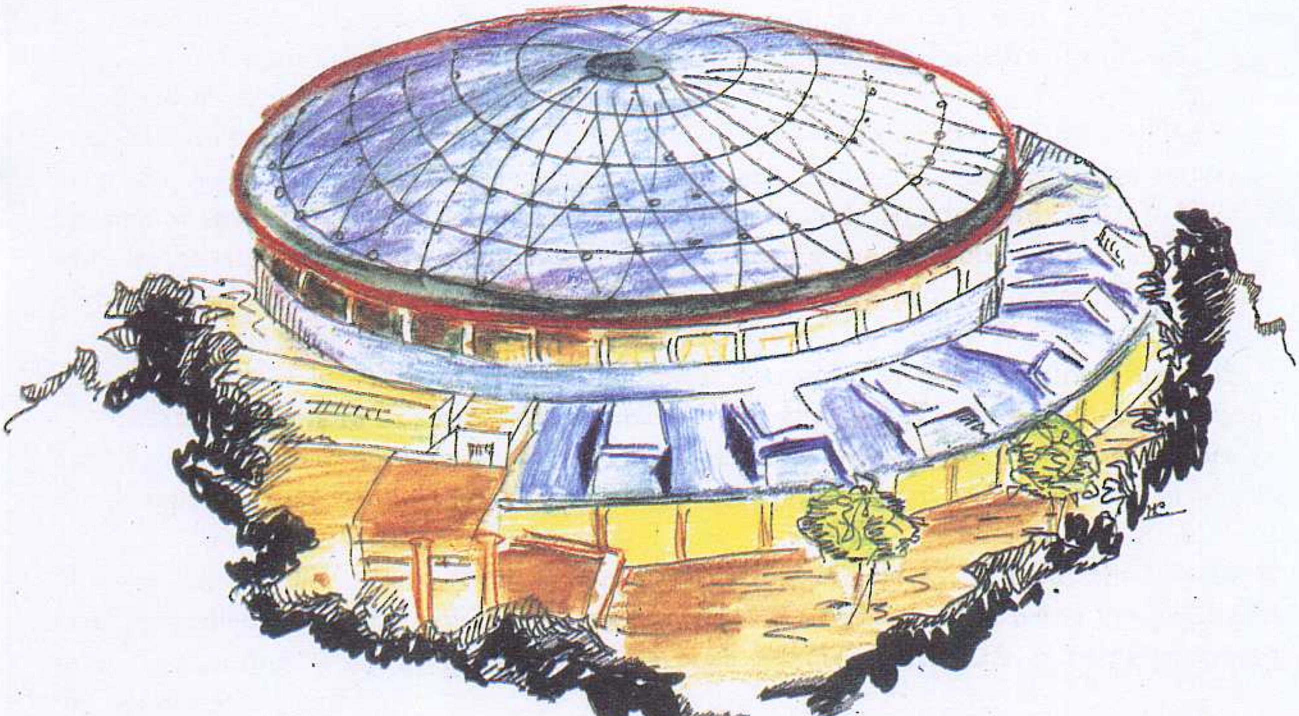

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PHYSICS AT DAΦNE

Juliet Lee-Franzini
Laboratori Nazionali di Frascati dell'INFN
SUNY at Stony Brook, Stony Brook, New York, 11794

ABSTRACT

We describe the physics which can be done at DAΦNE, the ϕ factory under construction at the *Laboratori Nazionali di Frascati dell'INFN*, which includes: (1) The complete determination of 16 independent parameters which describe the K_S-K_L system, mostly through precision interferometry between pairs of same, different, and one versus sum of the other (inclusive) final states. These measurements allow independent determinations of the five (CPT) violating parameters, as well as high precision determinations of three (CP) violation parameters, which include $\Re(\epsilon'/\epsilon)$ and $\Im(\epsilon'/\epsilon)$. $\Re(\epsilon'/\epsilon)$ can also be determined to an equivalent accuracy using the "double ratio" method, and ϵ from precision measurements of asymmetries in K_L semileptonic decays. (2) The first probable observation of CP violation in the K_S system by seeing $K_S \to \pi^0\pi^0\pi^0$ events, and asymmetries in rates of K_S semileptonic decays. (3) Searches for other direct CP violating effects in asymmetries in neutral and charged $K \to 3\pi$ decay distributions and in $K^\pm \to \pi^\pm\pi^0\gamma$ decay rates. (4) Precision measurements of the form factors in Ksemileptonic decays and tests of Chiral Perturbation Theory. (5) Studies of radiative ϕ decays to resolve puzzles in light meson spectroscopy. (6) The study of K-nucleon interaction. (7) The study of hypernuclei formation and decay. All but the last topic can be studied using the general purpose detector KLOE, which is being designed and built for running at DAΦNE. A special purpose detector, FINUDA, is being proposed for hypernuclei physics.

1. Introduction

DAΦNE,[1] an e^+e^- collider optimized to operate at center-of-mass (c.o.m) energy W=M_ϕ, will begin delivering a luminosity of $\mathcal{L}\sim10^{32}$cm^{-2}s^{-1} in late 1995. The target luminosity of DAΦNE is ~10 times larger, which, given that the cross section for $e^+e^-\to\phi$ at the ϕ resonance peak is ~5μb, implies 5000 ϕ's are produced per second. Adopting the canonical definition in high energy physics of one machine year equals 10^7 seconds, which generously takes into account the various integrated luminosity degradation factors, such as peak versus average luminosity, loss due to machine study and maintenance periods, and possible detector down times, the production rate for ϕ's is still $\sim5\times10^{10}$ per year!

The vector meson ϕ, whose quantum numbers are $J^{PC} = 1^{--}$, with mass $M = 1019.412 \pm 0.008$ MeV, total width $\Gamma = 4.41$ MeV and leptonic width $\Gamma_{ee} = 1.37$ keV, decays into other mesons with branching ratios, BR, as given in table 1 .[2] Included therein are also some relevant kinematical quantities.

Table 1. ϕ decays.

Mode	BR %	β_K	$\gamma\beta c\tau]_K$ cm	$p_{\max}$ MeV/c
K^+K^-	49	0.249	95.4	127
K_S, K_L	34	0.216	343.8	110
$\rho\pi$	13	–	–	182
$\pi^+\pi^-\pi^0$	2	–	–	462
$\eta\gamma$	1.3	–	–	362
other	~1	–	–	–

One notes therefore that DAΦNE is indeed a "factory" of neutral K's which are in a well prepared quantum state, of charged K pairs, as well as of ρ's, η's and the rarer η''s. The high luminosity of DAΦNE will also allow measurements of rare ϕ radiative decays.

Another feature at DAΦNE is that, because the ϕ's decay at rest, neutral kaons are produced in collinear pairs, with momenta of 110 MeV/c. The observation of one K guarantees the existence of the other, with determined direction and identity, *i.e.*, K's can be "tagged". Assuming a detector of a reasonable size, a very large numbers of tagged K mesons can be collected per year, as shown in table 2. We choose as our example the KLOE detector proposed for DAΦNE,[3] approximately 4 m in diameter and 4 m long, with a magnetic field B=6 kG, a K_S decay fiducial volume of radius

~8 cm, and K_L decay fiducial volume of radius ~150 cm. This availability of tagged kaons is central to DAΦNE's ability for performing experiments not possible elsewhere, and enables KLOE to be essentially a "self-calibrating" detector, and have an absolute normalization of the K_S, K_L fluxes.

Table 2. Useful, tagged K meson decays

Mode	Tagged decays§
K_S	0.6×10^{10}
K_L	0.4×10^{10}
K^+ or K^-	2.0×10^{10}†
K^+ or K^-	4.0×10^{9}‡

§Detector efficiencies are approximately included.
†Using all $K^\pm$ decays, a good tag.
‡Using only $K^\pm \rightarrow \pi^0\pi^\pm$ decays, for a precision tag.

2. The Neutral K Mesons

K mesons have been responsible for the introduction of a new quantum number, the *strangeness* S. The K mesons contain a strange quark or antiquark, s or $\bar{s}$, and are composed of two isospin doublets: $K^0 = d\bar{s}$, $K^+ = u\bar{s}$, $S = +1$; $\bar{K}^0 = \bar{d}s$, $K^- = \bar{u}s$, $S = -1$. The K^0 and $\bar{K}^0$ are eigenstates of the strong interactions. Parity violation was in fact first observed through the θ–τ decay modes of K's.[4] C is also violated in weak interactions, but CP was believed to be conserved. C violation allows $K^0 \rightleftharpoons \bar{K}^0$ transitions without violating CP. In 1955 Gell-Mann and Pais predicted[5] that there should be two physical neutral K meson states of different lifetimes, which were supposed to be eigenstates of CP. Lederman and his group observed the existence of the long lived neutral K_L in 1956.[6] In 1964 $K_L \rightarrow 2\pi$ decays were observed,[7] giving the first unambiguous proof of CP violation. To date the only other evidence of CP violation is the charge asymmetry in the K_L semileptonic decays, $\delta = (3.3 \pm 0.12)\times10^{-3}$.[2]

Diagonalizing the K^0-$\bar{K}^0$ mass matrix with non-diagonal elements from $K^0 \rightleftharpoons \bar{K}^0$, we find the physical states K_S and K_L, which we can write (adopting the notation of Ref. 8), without assuming CPT, as

$$|\,K_S\,\rangle \propto \left((1+\epsilon_K+\delta_K)|\,K^0\,\rangle + (1-\epsilon_K-\delta_K)|\,\bar{K}^0\,\rangle\right)/\sqrt{2}$$

$$|\,K_L\,\rangle \propto \left((1+\epsilon_K-\delta_K)|\,K^0\,\rangle - (1-\epsilon_K+\delta_K)|\,\bar{K}^0\,\rangle\right)/\sqrt{2}$$

where the (small) complex ϵ_K and δ_K characterize respectively the CP violating and CPT violating parameters in the effective Hamiltonian.

3. CP VIOLATION IN $K^0 \to \pi^0\pi^0$ AND $\pi^+\pi^-$

One of the main targets of the physics program at DAΦNE is centered around the study of CP violation in the decays K_L, $K_S \to \pi^0\pi^0$, $\pi^+\pi^-$. The small CP impurity of the K_L state allows for $K_L \to 2\pi$ decays, due to second order weak $K \Leftrightarrow \bar{K}$ transitions. However, 28 years later, we still do not know whether there is a direct, $\Delta S = 1$, CP violating amplitude.

Defining the usual amplitude ratios and epsilon parameters:[9]

$$\frac{\langle \pi^+\pi^- | K_L \rangle}{\langle \pi^+\pi^- | K_S \rangle} = \eta_{+-} = \epsilon + \epsilon', \quad \frac{\langle \pi^0\pi^0 | K_L \rangle}{\langle \pi^0\pi^0 | K_S \rangle} = \eta_{00} = \epsilon - 2\epsilon' \tag{3.1}$$

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

Many experiments have attempted to measure $\Re(\epsilon'/\epsilon)$ with continuously improving sensitivity. The most recent results have reached precisions of the order of 1×10^{-3} and the results[10,11] can be summarized as $\Re(\epsilon'/\epsilon) = (0 - 3) \times 10^{-3}$ at an 80% confidence level.

The standard model, in the context of the CKM quark mixing mechanism,[12] predicts $\Re(\epsilon'/\epsilon) \sim 10^{-3}$, independently of whether the scale factors (which measure the deviation of the true matrix element from the one computed in the vacuum insertion approximation) are calculated with lattice QCD, QCD sum-rules or the $1/N_c$ expansion.[13-16] Smaller values are possible, especially for $M_{\mathrm{top}} \sim 150$ GeV, see figures 3.1 and 3.2, which are taken from reference 15. Figure 3.1 shows the upper and lower limits of $\Re(\epsilon'/\epsilon)$ versus m_{top}, in the first and second quadrant of the CP-violating phase, δ, from ref. 14. Parameter ranges used are: $0.09 \leq |V_{ub}/V_{cb}| \leq 0.17$, $0.036 \leq |V_{cb}| \leq 0.046$, $0.1\ \mathrm{GeV} \leq \Lambda_{QCD} \leq 0.3$ GeV, $125 \leq m_s \leq 200$ MeV. Other quantities are taken in the leading 1/N expansion.

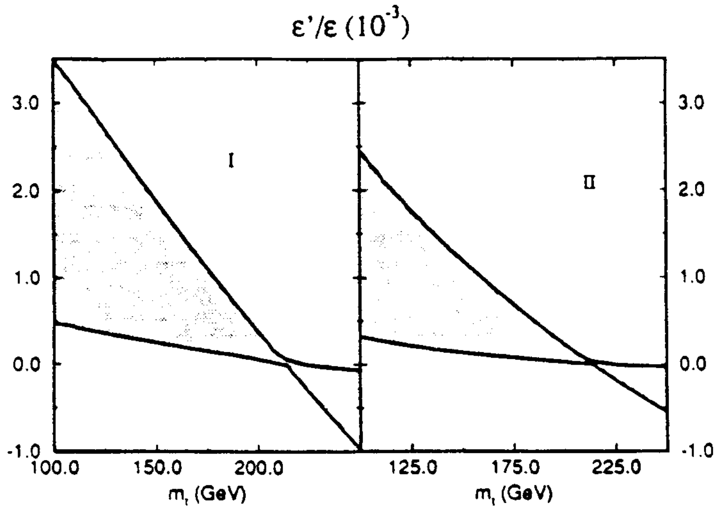

Fig. 3.1. Upper and lower limits of $\Re(\epsilon'/\epsilon)$ versus m_{top},[14] .

Figure 3.2 shows the upper and lower limits of $\Re(\epsilon'/\epsilon)$ versus m_{top}, in the first and second quadrant of the CP–violating phase, δ, from ref. 13. Parameter ranges used are: $0.08 \leq |V_{ub}/V_{cb}| \leq 0.14, 0.042 \leq |V_{cb}| \leq 0.051, 0.1$ GeV$\leq \Lambda_{QCD} \leq 0.3$ GeV, $140 \leq m_s \leq 200$ MeV. Other quantities are taken from lattice QCD calculations.

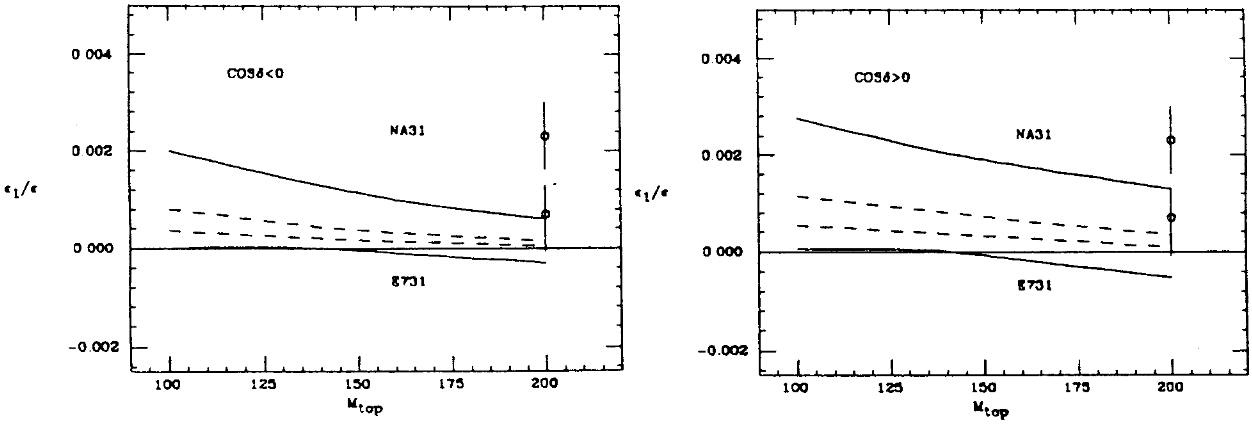

Fig. 3.2. Upper and lower limits of $\Re(\epsilon'/\epsilon)$ versus m_{top},[13] .

Actually, if $\Re(\epsilon'/\epsilon)$ were to be identically zero, it could be a signal of physics beyond the SM,[17] but it might take another 28 years to reach that kind of accuracy, thus it behooves us to search for some other independent ways to test CP–violation, as will be discussed in chapter 6.

The relationships between $\eta_{\pm}$, η_{00} and ϵ, ϵ', when one allows CPT violation, remain as in eq. (3.1), since it depends only on isospin decomposition. *Albeit* both ϵ, ϵ' each acquire terms which violate CP and CPT separately.[8]

4. $\phi \; \longrightarrow \; K^0\bar{K}^0 \; \longrightarrow \; K_S,\; K_L$

At DAΦNE, in the reaction

$$e^+e^- \longrightarrow \text{“}\gamma\text{”} \longrightarrow \phi \longrightarrow K^0\bar{K}^0,$$

$$C(K^0\bar{K}^0) = C(\phi) = C(\gamma) = -1.$$

The initial state

$$|\,i\,\rangle = |\,K\bar{K},\; t=0,\; C=-1\,\rangle$$

is given by:

$$\begin{aligned} |\,i\,\rangle =& \frac{|\,K^0,\mathbf{p}\,\rangle|\,\bar{K}^0,-\mathbf{p}\,\rangle - |\,\bar{K}^0,\mathbf{p}\,\rangle|\,K^0,-\mathbf{p}\,\rangle}{\sqrt{2}} \\ \simeq& \frac{1}{\sqrt{2}}\left(|\,K_S,-\mathbf{p}\,\rangle|\,K_L,\mathbf{p}\,\rangle - |\,K_S,\mathbf{p}\,\rangle|\,K_L,-\mathbf{p}\,\rangle\right). \end{aligned} \tag{4.1}$$

for which $e^+e^- \longrightarrow \text{“}\gamma\text{”} \longrightarrow \phi \longrightarrow K^0\bar{K}^0 \longrightarrow K_S,\; K_L$ at $t=0$. In vacuum the pair of K's remain in a state of pure K_S, K_L.

Defining $\eta_i = \langle\, f_i|\,K_L\,\rangle/\langle\, f_i|\,K_S\,\rangle$, $\Delta t = t_1 - t_2$, $t = t_1 + t_2$, $\Delta\mathcal{M} = \mathcal{M}_L - \mathcal{M}_S$ (where $\mathcal{M}_{S,L} = M_{S,L} - i\Gamma_{S,L}/2$ are the complex masses of K_S and K_L), and $\mathcal{M} = \mathcal{M}_L + \mathcal{M}_S$, the amplitude for decay to states f_1 at time t_1 and f_2 at time t_2, without identification of K_S or K_L is:

$$\begin{aligned} &\langle\, f_1,\, t_1,\, \mathbf{p};\; f_2,\, t_2,\, -\mathbf{p}|\,i\,\rangle \simeq 1/\sqrt{2}\times \\ &\langle\, f_1|\,K_S\,\rangle\langle\, f_2|\,K_S\,\rangle e^{-i\mathcal{M}t/2}\left(\eta_1 e^{i\Delta\mathcal{M}\Delta t/2} - \eta_2 e^{-i\Delta\mathcal{M}\Delta t/2}\right). \end{aligned} \tag{4.2}$$

5. KAON-INTERFEROMETRY

The decay intensity $I(f_1, f_2, \Delta t = t_1 - t_2)$ to final states f_1 and f_2 is obtained from eq. (4.2) above by integrating over all t_1, t_2, with Δt constant. For $\Delta t > 0$:

$$\begin{aligned} I(f_1,\; f_2;\; \Delta t) =& \frac{1}{2}\int_{\Delta t}^{\infty} |A(f_1,\; t_1;\; f_2,\; t_2)|^2 \mathrm{d}t = \\ &\frac{1}{2\Gamma}|\langle f_1|\,K_S\,\rangle\langle f_2|\,K_S\,\rangle|^2\Big(|\eta_1|^2 e^{-\Gamma_L\Delta t} + |\eta_2|^2 e^{-\Gamma_S\Delta t} \\ &- 2|\eta_1||\eta_2| e^{-\Gamma\Delta t/2} cos(\Delta m\Delta t + \phi_1 - \phi_2)\Big), \end{aligned} \tag{5.1}$$

with $\eta_i = A(K_L \rightarrow f_i)/A(K_S \rightarrow f_i) = |\eta_i|e^{i\phi_i}$, exhibiting interference terms sensitive to phase differences.

The idea of studying correlation in decays of prepared $K^0\overline{K}^0$ pairs has been around since 1958, having a continuous history for over 25 years.[18-22] The prospect of building ϕ–factories inspired a whole group of new studies,[23,24] with increasing relaxing of symmetry violations, for example from ref. 8, which relaxes CPT conservation while retaining the $\Delta S = \Delta Q$ rule in semileptonic decays, to ref. 15 where the last assumption is also relaxed, even though this rule, in the standard model (SM), is violated to only 10^{-7} (in amplitude).[25]

Specifically, if both CP and CPT are violated, there are eight parameters which describe these violations in the neutral K meson system. All eight are separately measurable at DAΦNE. This is to be contrasted with the situation in fixed target experiments, where the CPT violation parameters occur in differences of specific combinations of certain of the 21 parameters which describe neutral K decays, so that a "fortuitous" cancellation between certain of such combinations might indicate overall CPT conservation while individual CPT violating parameters could in fact be not small.[8]

DAΦNE is the only particle factory funded and under construction. We are currently designing a "general purpose" detector, capable of performing most of the physics at DAΦNE: KLOE,[3] which is shown schematically in figure 5.1. The fiducial volumes for K_S and K_L decays were already stated in the Introduction. Specifically, the features of the detector are:

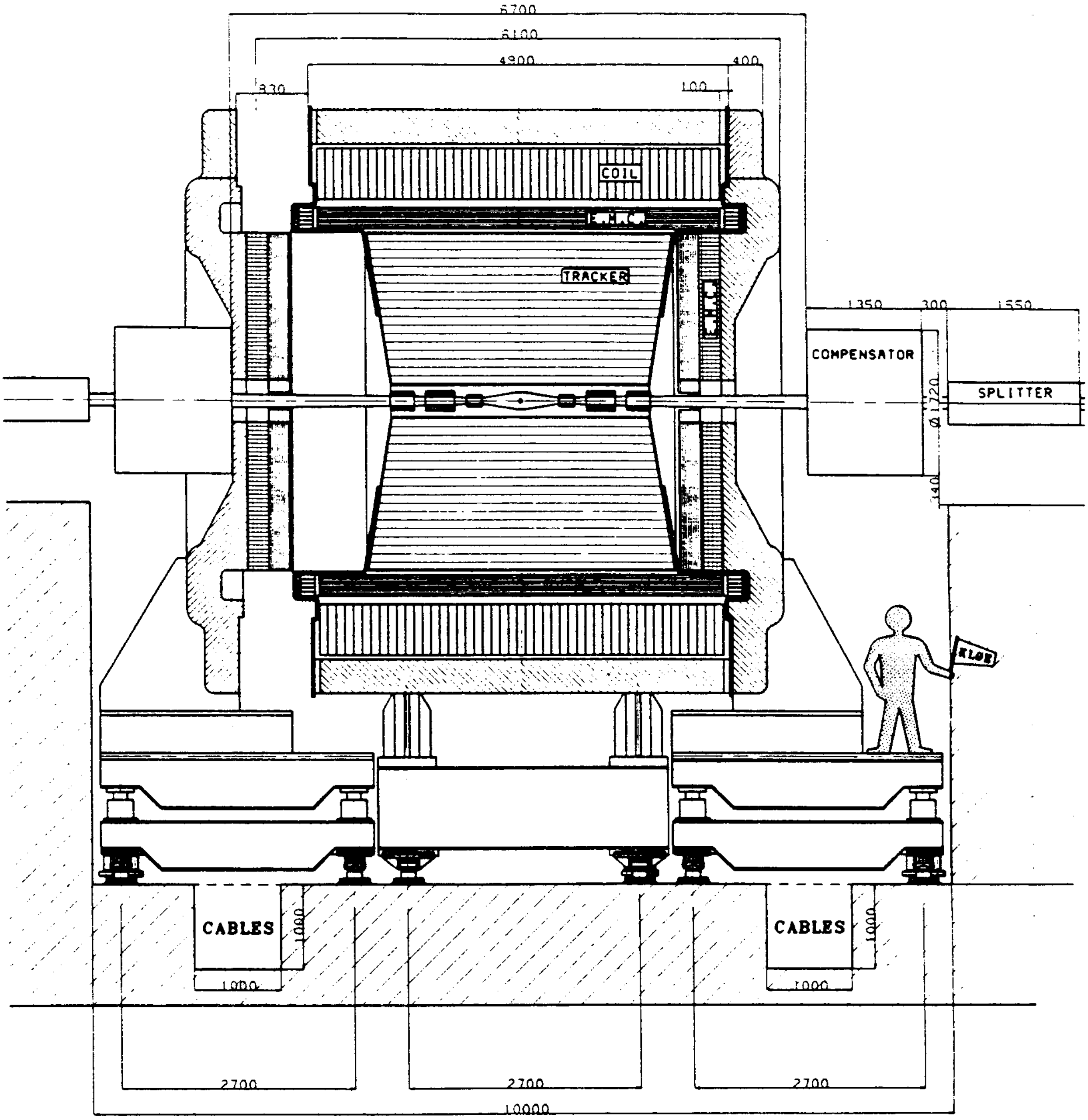

Fig. 5.1. The KLOE Detector.

a cylindrical structure surrounding a thin, 10 cm radius beam pipe, which defines the K_S decay fiducial volume. The detector consists of a drift chamber with a helium-based gas mixture, of 2 m radius and 4 m length, surrounded by a hermetic (solid angle coverage about 99%) electromagnetic calorimeter with three-dimensional readout. The

EM calorimeter consists of sandwiches of very thin (0.5mm) lead foils, grooved, and 1 mm dia. scintillating fibers. Its energy resolution is $5\%/\sqrt{(E/1\text{GeV})}$, with full efficiency for 20 MeV photons, and has exceptional timing performance, $300\ \text{ps}/\sqrt{(E/20\text{MeV})}$, necessary for measuring the decay path of neutral K's decaying to $\pi^0\pi^0$ and photons.[3]

We can perform precision "kaon-interferometry" by using the decay intensity of eq. (5.1) with appropriate choices of the final states f_1, f_2. For example:

1. f_1=f_2: we can measure Γ_S, Γ_L and Δm, since all the phases disappear. Rates can be measured to ×10 improvement in accuracy and Δm to ×2.
2. $f_1 \neq f_2$:
   (a) with f_1=$\pi^+\pi^-$, f_2=$\pi^0\pi^0$, we can measure $\Re(\epsilon'/\epsilon)$, and $\Im(\epsilon'/\epsilon)$. The former by concentrating on large time differences, the latter for $|\Delta t| \leq 5\tau_s$.
   (b) with $f_1 = \pi^+\ell^-\nu$ and $f_2 = \pi^-\ell^+\nu$, we can measure the CPT–violation parameter δ_K, the real part by concentrating on large time difference regions; and the imaginary part for $|\Delta t| \leq 10\tau_s$.
3. If $f_1 = 2\pi$, $f_2 = K_{\ell 3}$, this leads to measurements of CP and CPT violation parameters at large time differences, since we measure the asymmetry in K_L semileptonic decays. At small time differences, we obtain Δm, $|\eta_{\pi\pi}|$ and $\phi_{\pi\pi}$.

Figures 5.2–5.4 give sample interference patterns and the physical quantities measured.

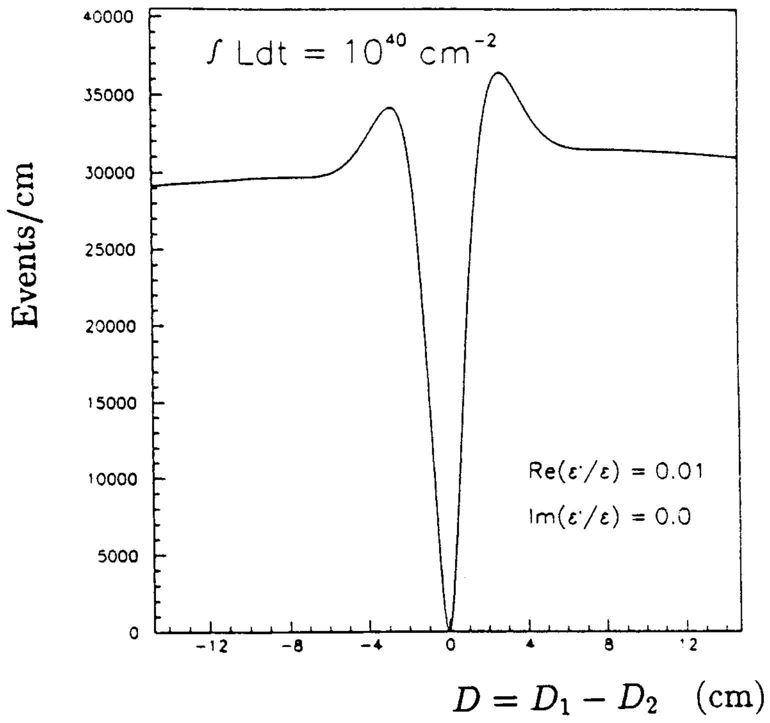

Fig. 5.2. $f_1 = \pi^+\pi^-$, $f_2 = \pi^0\pi^0 \Rightarrow \Re(\epsilon'/\epsilon)$, $\Im(\epsilon'/\epsilon)$.

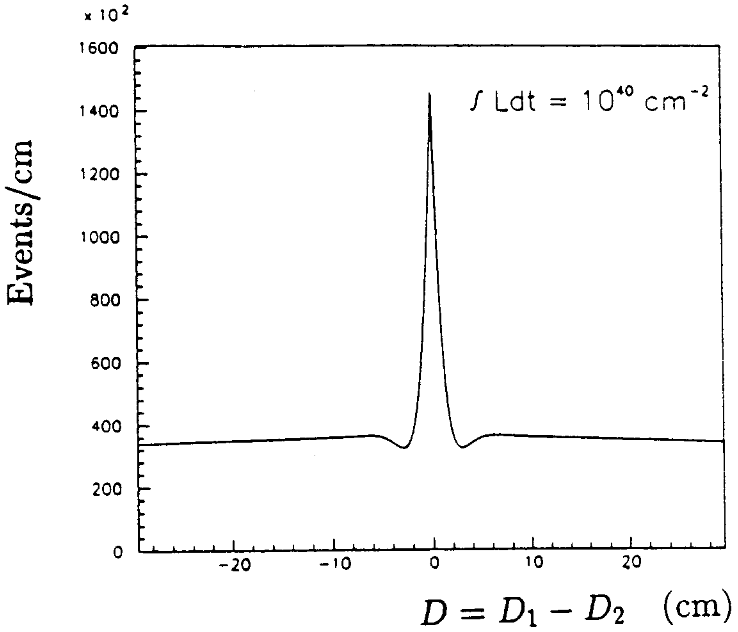

Fig. 5.3. $f_1 = \pi^-\ell^+\nu$, $f_2 = \pi^+\ell^-\nu \Rightarrow$ CPT, T.

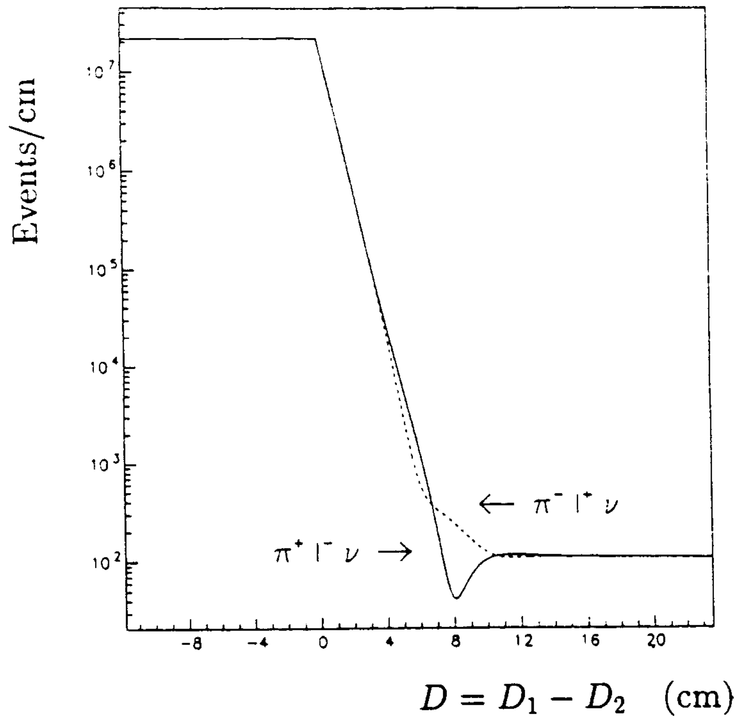

Fig. 5.4. $f_1=\pi^+\pi^-$ or $\pi^0\pi^0$, $f_2=\pi^-\ell^+\nu$ or $\pi^+\ell^-\nu \Rightarrow$ CPT, Δm, $|\eta_{\pi\pi}|$, $\phi_{\pi\pi}$.

4. By choosing $f_1 = \pi\pi$, and $f_2=$ all other decay channels of the other K, the "inclusive method," we improve statistics relative to choosing a single semileptonic channel, and thus obtain the best measurements of the magnitudes of η_{+-} and η_{00} as well as $\Re\epsilon_K + i\Im\delta_K$.
5. By choosing $f_1 = \pi^\pm\ell\nu$, and $f_2=$ all other decay channels of the partner K one can obtain the best measure of the $\langle K_S|K_L\rangle$ overlap, *i.e.*, determine both $\Re\epsilon_K$ and $\Im\delta_K$.
6. With K_S's, using K_L's for tagging, we can measure the asymmetry in the semileptonic decays of the K_S. The difference between this asymmetry, and that in the semileptonic decays of the K_L's, measures the real part of the CPT-violation parameter δ_K.
7. By measuring the difference in rates into two positive same sign leptons of the K pair from that into two negative same sign leptons we perform the so-called "Kabir" test,[20] which if $\Delta S = \Delta Q$ is assumed, allows us to probe the K^0- $\overline{K}^0$ mass difference to 1×10^{-18}.[8]
8. Alternate Ways of Measuring $\Re(\epsilon'/\epsilon)$. We can also use the classical method of the double ratio

$$\mathcal{R}^{\pm}/\mathcal{R}^{0}=\frac{K_L\to\pi^+\pi^-}{K_S\to\pi^+\pi^-}\Big/\frac{K_L\to\pi^0\pi^0}{K_S\to\pi^0\pi^0}=1+6\times\Re(\epsilon'/\epsilon),$$

using tagging to select pure K_S and K_L beams as implied in eq. (4.1). Other ways of measuring $\Re(\epsilon'/\epsilon)$ from selected final states are:[26]

$$\frac{N(\pi^+\pi^-\pi^+\pi^-)}{N(\pi^0\pi^0\pi^0\pi^0)}\times\Big(\frac{BR(K_S\to\pi^0\pi^0)}{BR(K_S\to\pi^+\pi^-)}\Big)^2=1+6\times\Re(\epsilon'/\epsilon)$$

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

While all the methods listed are not statistically independent, they provide very useful checks because of the very different dependence on all systematic effects. Fig. 5.5 shows a typical interference pattern and the very small effect of the experimental resolution in the measurement of $\Delta t\times\Gamma_S$ in KLOE. Figure 5.6 shows the statistical accuracy reachable for $\Re(\epsilon'/\epsilon)$ with the time asymmetry method and for the double ratio method vs. detector dimension. For the case of $\Im(\epsilon'/\epsilon)$, the relevant parameter is the spatial resolution for the measurement of the decay paths. In KLOE we are capable of a resolution in Δt of $\sim\Gamma_S/2$, or 3 mm in space, at small distances from the interaction point. This implies that we can measure $\Re(\epsilon'/\epsilon)$ to $\sim10^{-4}$ and $\Im(\epsilon'/\epsilon)$ to $\sim10^{-3}$, approximately a factor 10 better than present experiments. It is important to stress that the measurements of $\Re(\epsilon'/\epsilon)$ and $\Im(\epsilon'/\epsilon)$ by KLOE at DAΦNE will not so much compete with as complement the next generation of fixed target experiments (though we do expect to reach comparable accuracies), because of our use of a totally different approach. We have almost orthogonal systematics problems. This will lend additional credibility if both groups obtain similar results, and allow mutual checks if we do not.

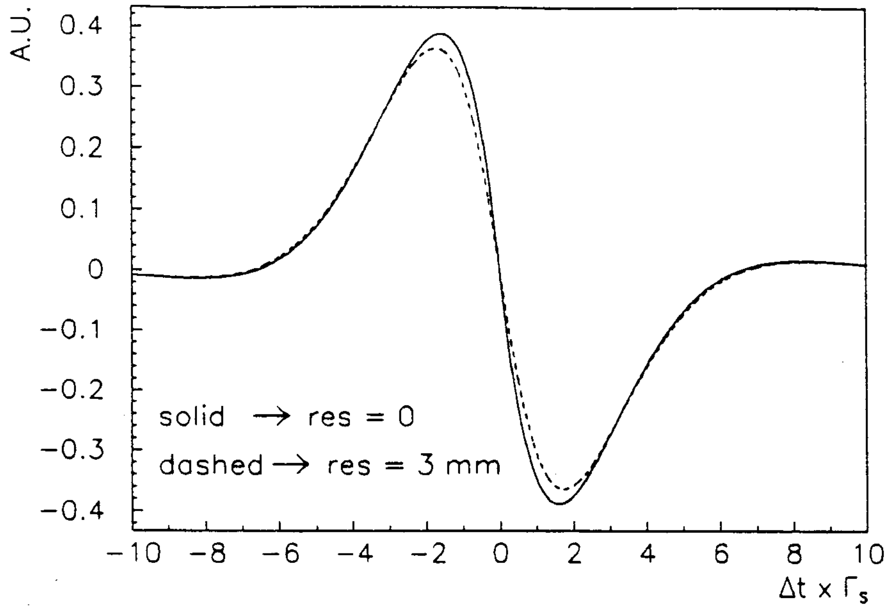

Fig. 5.5. Interference pattern without (solid line) and with finite resolution (dashed line).

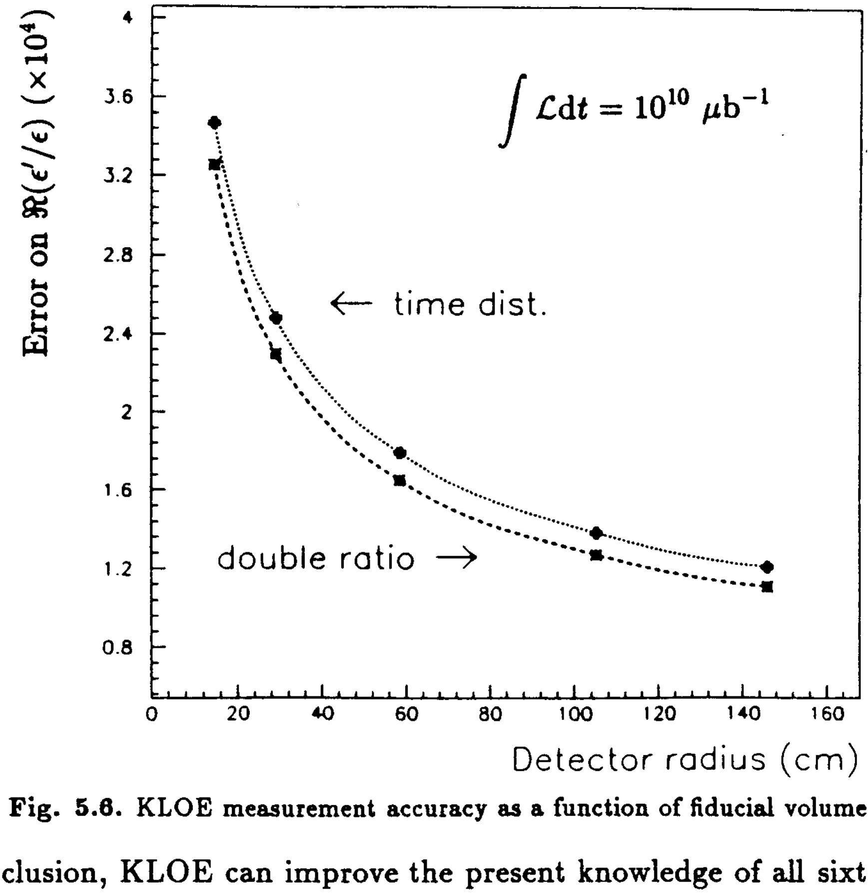

Fig. 5.6. KLOE measurement accuracy as a function of fiducial volume radius.

In conclusion, KLOE can improve the present knowledge of all sixteen observables in the K_S,K_L system by up to one or two orders of magnitudes, and, by measuring the real part of δ_K, allow us to separate all the individual CPT violating parameters.[8] If the $\Delta S = \Delta Q$ rule is relaxed, so that 4 new parameters are added to describe the neutral kaon system, only one other experimental input (involving tagging strangeness without use of semileptonic decays of K's) is needed to completely disentangle all eight CP and CPT violating parameters.[15]

6. Other Searches for CP Violation.

6.1 K_S DECAYS

1. So far the only CP violation has been observed in the K_L system. Observation of $K_S \to 3\pi^0$ would constitute a new proof of CP violation. At present the upper limit on the BR is 3.7×10^{-5}. The amplitude ratio η_{000} can be written as

$$\frac{\langle\pi^0\pi^0\pi^0|\,K_S\,\rangle}{\langle\pi^0\pi^0\pi^0|\,K_L\,\rangle} = \eta_{000} = \epsilon + \epsilon'_{000} \qquad (6.1)$$

where ϵ'_{000} is the "direct" CP violating contribution. For $\epsilon'_{000}=0$, one obtains

$$BR(K_S \to 3\pi^0) = 2\times10^{-9} \qquad (6.2)$$

which is just observable, corresponding to $\sim$30 events in one year. While ϵ'/ϵ is naturally suppressed by the $\Delta I = 1/2$ rule, this is not the case for ϵ'_{000}/ϵ. However the expected suppression for ϵ'/ϵ is only $\sim$1/20 and it appears therefore unlikely that $\epsilon'_{000}/\epsilon > 2\times10^{-2}$, giving small hope for the observation of direct CP violation in $K_S \to 3\pi^0$.

2. Similarly, because we can tag the K_S's by using K_L's, we can observe the difference in rates between $(K_S\to\pi^\pm\ell^\mp\nu)$, which is expected to be $\sim16\times10^{-4}$ in one year's run at DAΦNE, using known lifetimes and the KLOE geometry. KLOE can measure it to 4×10^{-4}. Again this would only be a measurement of ϵ and not of ϵ'. Still, the observation for the first time of CP violation in two new channels would be of considerable interest.

6.2 $K^\pm$ DECAYS

1. Evidence for direct CP violation can be also be obtained from the decays of charged kaons which are copiously produced at DAΦNE. CPT invariance requires that the total rates for $K^\pm \to 3\pi$ be identical while CP requires equality of the partial rates for $K^\pm \to \pi^\pm\pi^+\pi^-$ ($\tau^\pm$) and for $K^\pm \to \pi^\pm\pi^0\pi^0$ ($\tau'^\pm$). We define the fractional decay rate differences for τ and τ' modes as:

$$A = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}\,, \quad A' = \frac{\Gamma'^+ - \Gamma'^-}{\Gamma'^+ + \Gamma'^-}\,. \tag{6.3}$$

The present experimental information is[2] $A = (0.7 \pm 1.2) \times 10^{-3}$ and $A' = (0 \pm 6) \times 10^{-3}$, while theoretical estimates are $\mathcal{O}(10^{-8})$.[27] Measurements of rate differences of the order of $10^{-4} - 10^{-5}$ require very tight control of systematics effect. The possibility of tagging at DAΦNE, permits in fact an exact cancellation of efficiencies in this type of measurements and sensitivities of few$\times 10^{-5}$ can be achieved.

2. There is the possibility of observing differences in the Dalitz plot distributions for K^+ and K^- decays in both the τ and τ' modes. In particular the Dalitz plot population has a slope in the ódd pion energy distribution, usually characterized by a parameter g, which from CP invariance must satisfy $g(\tau^+) = g(\tau^-)$ and $g(\tau'^+) = g(\tau'^-)$. Present experimental limits on the asymmetry[2] $A = (g^+ - g^-)/(g^+ + g^-)$ range from few$\times 10^{-2}$ to few$\times 10^{-3}$, while KLOE could reach sensitivities of $\sim 10^{-4}$.[28] Predictions, which include chiral perturbation to order p^4 and electroweak penguins, vary from $\leq 4.5 \times 10^{-5}$[29] to $\leq (10^{-6})$.[27]

3. $K^\pm$ radiative decays: differences in rates in the radiative two pion decays of $K^\pm$, $K^\pm \to \pi^\pm \pi^0 \gamma$, are also proof of direct CP violation. The present experimental limit[2] for $\Delta\Gamma/2\Gamma$ is $<5 \times 10^{-2}$ and the theoretical prediction is $\leq 10^{-3} \times \sin\delta$, where δ is the CKM phase angle.[30] The KLOE sensitivity is $\sim 1.4 \times 10^{-3}$. While most of the tests described in this chapter are unlikely to reveal an effect, the large improvement on experimental limits possible with KLOE makes these studies very interesting and a *must vis a vis* the theoretical predictions.

7. Rare K Decays.

DAΦNE, because of eq. (4.1), is unique. By tagging one can effectively have a beam of K_S, with no background, with up to 10^{10} kaons per year. The availability of pure K_S beams will dramatically improve knowledge of K_S branching ratios (most are not measured yet) for searches $K_S \to \pi^0 \nu\bar{\nu}$, $e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^0 e^+ e^-$, $\pi^0 \mu^+ \mu^-$ etc., down to the 10^{-8} or better range, from statistics. Background effects have not yet been examined in detail at present, however, KLOE compares favorably with some BNL set-ups. A searchfor $K_S \to \pi^0\gamma\gamma$ might yield a few detected events. Tens to hundreds of decays $K^\pm \to \pi^\pm\gamma\gamma$ or $K^\pm \to \pi^\pm\mu^+\mu^-$, can also be detected. Existing limits on $K^\pm \to \pi^0\mu^\pm\nu\gamma$, $\pi^\pm\pi^\pm\mu^\mp\nu$, $\pi^\pm\gamma\gamma\gamma$ and $l^\pm\nu\nu\nu$, may be substantially improved.

8. K–Mesons and the Chiral Lagrangian

High energy experiments have given quite convincing proofs that the strong interactions are correctly described by an exact gauge theory, QCD, based on the *color* SU(3) gauge group. At low energies, in the non-perturbative QCD regime, it is not possible at present to obtain quantitative predictions about hadron dynamics from the exact lagrangian. The most promising attempts at present, numerical lattice simulations, are still at a rather crude level.

A possible approach to low energy problems is based on the approximate QCD invariance under the chiral transformations $\mathrm{SU(3)_L} \otimes \mathrm{SU(3)_R}$.[31] At lowest order, $\mathcal{O}(m^2)$ or $\mathcal{O}(p^2)$, the amplitudes are determined in terms of f_π and the quark masses. Many predictions can be obtained, such as the Weinberg relation for $\pi - \pi$ scattering lengths and the Callan–Treiman (CT) relation.

8.1 SEMILEPTONIC DECAYS

In the last decade, several authors[32] have extended chiral perturbation (CHPT) studies, in semileptonic K decays, to the next order terms in the chiral expansion ($\mathcal{O}(m^4)$, $\mathcal{O}(p^4)$, $\mathcal{O}(m^2p^2)$). This extension introduces new parameters which must be determined experimentally. Many new amplitudes can then be predicted. In this respect, several relevant measurements can be performed at DAΦNE:[33]

1. $K_{\ell 3}$: At lowest order the CT relation predicts the slope of the scalar form factor. There is at present disagreement between K^+ data and K_L results and different experiments are mutually incompatible.[2] The world averages are λ_0=0.004±0.007, for K^+ and 0.025±0.006 for K_L, both in disagreement with the CT prediction, 0.017±0.004. KLOE can measure λ_0 for K_L to an accuracy of 1.4×10^{-5}. The quoted accuracy includes the effects of the measuring resolution and of cuts and ambiguities in $\pi\mu$ assignments.[34] Similar accuracy are obtained for $K^\pm$ and for λ_+.

2. $K_{\ell 4}$: There is only one measurement of the relevant form factors. KLOE can improve vastly on this topic. These decays also provide another opportunity for the determination of the $\pi\pi$ phase shifts.

3. $K_{\ell 2,\gamma}$, $K_{\ell 2,e^+e^-}$, $K_{\ell 3,\gamma}$: Apart from the radiative term, the amplitudes depend on the K charge radius and three other parameters about which conditions are obtained from pion physics. Additional constraints and checks would follow from the processes listed.

8.2 Non-Leptonic *K* decays

Parallel efforts involving extending CHPT calculations to higher orders, as applied to non-leptonic decays of K's, have been proliferating.[35] Also, of extreme interest to DAΦNE are the radiative non-leptonic K decays.[36] The rate for $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ and the $\gamma\gamma$ distributions are uniquely predicted by the chiral lagrangian approach. Dalitz type decays of K mesons and two photon production of pions are also of great interest. Both can be studied with KLOE.

8.3 Photon-Photon Physics

Photon-photon scattering, resulting in a pair of pions, can be described in several ways.[37] From the CHPT point of view, $\gamma\gamma \rightarrow \pi^+\pi^-$ is described by a function $\bar{\alpha}^*_{\pi^0}(s)$, the generalized π^0 polarizability, where $\sqrt{s} = W$ is the c. m. energy.[38] At threshold ($\sqrt{s} \leq 0.5$ GeV), the Crystal Ball (CB) results are consistently higher than chiral perturbation predictions. This discrepancy is reduced, within chiral perturbation, by including 2-loop effects, which give a sizeable contribution to the cross-section in this region. The status of the data on $\gamma\gamma$ physics is reviewed in ref. 39 and comparison with the predictions of chiral symmetry indicate that more precise measurements are needed. The process $\gamma\gamma \rightarrow \pi^0\pi^0$ can be studied at DAΦNE,[40] where an integrated e^+e^- luminosity of $\sim 5 \times 10^{39}$ cm^{-2} can provide measurements of $\bar{\alpha}^*_{\pi^0}(s)$ to a few % accuracy,[41] corresponding to $\sim 10^4$ observed events, almost an order of magnitude improvement over the CB results.[39]

For the process $\gamma\gamma \rightarrow \pi^+\pi^-$ the cross-section is dominated by the Born term, making it harder to measure chiral perturbation corrections.[41] Additional information can however be obtained from the angular distribution. With the quoted integrated luminosity, the same accuracy as in the $\pi^0\pi^0$ case could be achieved.

9. e^+e^- Annihilations into Hadrons from Threshold to 1.5 GeV

Precise measurements of $\sigma(e^+e^- \rightarrow \text{hadrons})$ up to energies of $\sim$1.5 GeV are necessary for the calculation of the muon anomaly a_μ.[42] The hadronic contributions to a_μ due to vacuum polarization and light by light scattering result in the largest uncertainty in a_μ. The estimate, based on poorly known cross sections for hadronic e^+e^- annihilation from the 2π threshold up to $\sim$ 1 GeV, gives:[42] $a_\mu^{hadr} = 702(19) \times 10^{-10}$ making it impossible to observe the weak interaction contribution which, to one loop, is[43] $a_\mu^{weak} = 19.5\,(0.1) \times 10^{-10}$.

The required accuracy for the measurements[44] of $\sigma(e^+e^- \rightarrow \text{hadrons})$ is $\sim 0.5\%$, readily accessible to KLOE. Recently, however, doubts have been raised on the validity of the approach used to evaluate the light by light scattering contributions due to quark or hadron loops,[33,45] which contribute 20×10^{-10} to a_μ.

We recall that an accurate determination of the K form factor at the ϕ mass will allow measurements of the interference of the ϕ meson with the ρ, ω mesons and possibly with higher $s\bar{s}$ excitations. Finally spectroscopic studies up to 1.5 GeV are still of interest, for example, the search for the mysterious 1.1 GeV resonance.[46]

10. Radiative ϕ Decays

10.1 $\phi \rightarrow \eta'\gamma$

Precise measurements of the $\eta - \eta'$ mixing has important bearings on quark models and QCD, in particular on the question of whether there are gluonic components in the η and η' wave functions.[47] In this regard, measurements of the radiative ϕ decays to η and to η', which are feasible with great sensitivity with KLOE, can lead to a really decisive test, when combined with the information coming from other sources such as e.g. the analogous J/Ψ decays and the two-photon decays of η and η'. To complete the determination of the η' parameters we need measurements of the rare transition $\phi \rightarrow \eta'\gamma$. There is some room for a non-vanishing gluonic component in the η'. To give an idea of the expected order of magnitude of the branching ratio, for no gluonium in the η' and a mixing angle of 20° we expect $\mathrm{BR}(\phi \rightarrow \eta'\gamma) \sim 1.2 \times 10^{-4}$. A Monte Carlo study[48] shows that KLOE can reach, during the commissioning year of DAΦNE, BR's of $\sim 10^{-6}$. This is another interesting piece of physics for KLOE in the context of quark models and QCD.

10.2 $\phi \rightarrow f_0\gamma$

At the end of 1995, DAΦNE will begin delivering of the order of 500 ϕ -mesons/sec. This provides a unique opportunity to study the $f_0(975)$ in ϕ radiative decays, even for branching ratios which in some estimates could be as low as 1×10^{-6}. This unique, lightest scalar meson state is poorly described by current models,[49] and more information is essential. By Monte Carlo studies we show that the branching ratio above can easily be measured in the neutral decay channel $f_0 \rightarrow \pi^0\pi^0$.[48] In decays to $\pi^+\pi^-$, there are backgrounds from continuum processes.[50] Interference between one of these processes and the f_0 amplitude leads to very interesting and complex patterns.[51] A complete study of the photon spectrum from $e^+e^-\to\pi^+\pi^-\gamma$ at the ϕ peak, after suppression of continuum contributions by suitable kinematics and angular cuts, can determine the sign of the $\phi f_0\gamma$ coupling even for the smallest branching ratio, thus providing a totally new piece of information for the investigation of the nature of the f_0.[52]

11. Rare η and π^0 Decays

Since the η meson is isoscalar and non-strange, its decay modes provide information complementary to those of the π^0, which is isovector, and of the Kmeson which is strange. At the present time, the non-leading decay modes of the η are badly known. With a branching ratio of 1.28% for $\phi\to\eta\gamma$, one expects the production of 6×10^8 η's in the length of time necessary to achieve an accuracy of 10^{-4} in the measurement of $\Re(\epsilon'/\epsilon)$. This will allow measurements of the BR of many rare decay modes of the η with about two orders of magnitude higher statistics than in previous experiments. Through the decays $\phi\to\rho\pi$ and $\phi\to\pi^+\pi^-\pi^0$, ten times more π^0's than η's will be produced at DAΦNE.[53]

1. Electromagnetic Decay Modes These decays give the transition form factor $F(q_1^2,q_2^2)$ for $q_2^2=0$ and $q_1^2\neq0$. The best measured decay is $\eta\to\mu^+\mu^-$, ($BR=5.1\pm0.8\times10^{-6}$ at Saclay). The accuracy of all electromagnetic decays, including Dalitz and double Dalitz, could be considerably improved with the K-LOE detector.

2. C and CP Tests The decays $\eta\to\ell^+\ell^-\pi^0$ test C and CP conservation in electromagnetic processes down to the level of $10^{-8}-10^{-9}$ where one can expect a contribution from two-photon exchange.[54] This is the level reachable at DAΦNE. Current experimental limits are two or three orders of magnitude higher. The current upper limit on the C-violating process $\eta\to3\gamma$ ($BR<5\times10^{-4}$) will be considerably improved.

3. Lepton Number Violation A preliminary upper limit of 10^{-4} has been set on the BR of the lepton number violating process $\eta\to\mu^+e^-$, at Saclay. Up to four orders of magnitude in precision will be gained at DAΦNE.

12. The Strange Sea in the Nucleon

A study of KN interactions listed below, at low energies, will shed light on the strange sea quark content in the nucleon.[55] Strange sea quark pairs seem to contribute to the static properties of the nucleon, to its mass, spin and magnetic moment. At present the low energy KN data base is extremely poor or even not existing. At DAΦNE the complex $K^{\pm}N$ scattering amplitudes at kinetic energies below $T_K = 14$ MeV can be studied for the first time by measuring elastic $K^{\pm}$p scattering (including Coulomb-nuclear interference to determine the real part of the scattering amplitude), charge exchange $K^-p \to \bar{K}^0 n$, regeneration $K_L \to K_S$ (containing information on $K^{\pm}n$ scattering), elastic $K^{\pm}d$ scattering (also containing information on $K^{\pm}$n scattering).

13. Hypernuclei Physics

Hypernuclei allows one to obtain, in an indirect way, information on hyperon-nucleon interaction in the low momentum region.[56] They can be produced at DAΦNE by stopping the tagged monochromatic K^- beam in a 100mg/cm^2 target through the reaction $K^-\text{p} \to \Lambda\pi^0$ or $\to \Sigma^{\pm}\pi^{\mp}$, $\to \Sigma^0\pi^0$. Interesting questions such as whether the $\Delta I = 1/2$ rule is broken in Λ hypernuclei, or whether Σ hypernuclei are produced at all, can be answered at DAΦNE.[57] A special purpose detector FINUDA is being proposed specifically for these studies.[57]

14. Conclusion

From the previous sections it is clear that, while the original motivation for building DAΦNE was the study of the origin of CP violation, it soon developed that a vast rich variety of physics can be investigated here. The present paper does not by any means exhaust all that is possible, and more theory papers suggesting other problems which can be investigated are coming in continually. An example is the suggestion of testing the non-local character of quantum theory in systems of two neutral kaons at a ϕ factory.[58]

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