A. Zallo:

THE FRASCATI Φ-FACTORY DAΦNE

Presented at the
NAN 91 Workshop on p¯p collisions
Moscow, July 1991
THE FRASCATI $\Phi$-FACTORY

$DA\Phi NE$

A. Zallo

Laboratori Nazionali di Frascati dell'I.N.F.N.
P.O. Box 13, I-00044 Frascati, Italy
NAN-91 Workshop on $pp$ collisions,
Moscow, July 1991

Abstract

The physics items that can be studied at the Frascati $\Phi$ factory $DA\Phi NE$ are reviewed. The design of $DA\Phi NE$ has the potential to increase by an order of magnitude the sensitivity in detecting CP violating processes. Detailed studies of Kaon mesons physics and tests of Chiral perturbation theory can be done. Kaon-nucleus interactions at very low energies, hypernuclei formation with stopped Kaons can also be studied at $DA\Phi NE$, showing the possibility to accomplish also a large nuclear program.

1 Introduction

The $DA\Phi NE$ $\Phi$ factory is a $e^+e^-$ collider, with a target luminosity $\mathcal{L} = 1 \times 8 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at the $\phi(1020)$ production threshold [1].

The construction of this collider has started in January 1991; it is expected to be ready for the experimental activity at the end of 1995. The $\phi$ production cross section peaks at $\approx 4.0 \mu$b. A one year data taking ($10^7$s) at a luminosity $\mathcal{L} = 1 \times 10^{33}$ cm$^{-2}$s$^{-1}$ provides $\approx 2 \times 10^{10}$ charged Kaon pairs, $\approx 5 \times 10^8 \eta$ and $\approx 5 \times 10^7 \pi^0$ [2],[3].

Final states with $K^0\bar{K}^0$ are produced with a cross section of $\approx 1.2 \mu$b from the $\phi$ decay, whose $C = -1$ assignment forces the $|K_S K_L>$ state only to be selected. The $\phi$ is produced at rest in the laboratory and therefore $K$'s are monochromatic with a momentum $P_{K^0} = 110 Mev$.

In contrast to high energy $e^+e^-$ collisions the number of decay modes is low, the multiplicity of particles in the final state is small and also the particle species are limited.
The main drawback of a $\Phi$ factory is connected to the low energies of the particles produced. For example, the photons coming from $K_{S,L} \rightarrow \pi^0\pi^0$ have energies as low as 15 Mev and this puts special requests on the energy resolution and efficiency of the electromagnetic calorimeter. Besides the big difference in the decay length of $K_S$ (0.6 cm) and $K_L$ (342 cm) is a big constraint in the design of detectors able to measure the decay point of $K_S$ with a reasonable efficiency for $K_L$.

With this considerations in mind the physics potential of a $\Phi$ factory has been recognized by many people and several proposals to build $\Phi$ factories have been considered[1],[2],[4],[5]. The main item is the study of CP violating phenomena. A measurement of the $Re(e^\chi R)$ ratio with a total error $\Delta(Re(e^\chi R)) \simeq 10^{-4}$ in 1-2 years running at $DA\Phi NE$'s luminosity seems to be possible.

At present, $Re(e^\chi R)$ has been measured by only two fixed target experiments [6],[7], with results in disagreement at the 2$\sigma$ level. Several experimental procedures have been proposed to measure $Re(e^\chi R)$ via the integrated decay rates of $K_{S,L}$ in two and three pion final states, the most demanding request being an accurate measurement of photon energies and $K_L$ decay lengths in the $K_L \rightarrow 2\pi^0,3\pi^0$ channel [8].

CP violation does not exhaust the physics capabilities of a $\phi$ factory. Detailed studies of K mesons physics can be accomplished. Rare Kaon decays[3] with a $BR \simeq 10^{-6}$ are accessible to a $\phi$ factory, such as radiative decays $K \rightarrow \gamma\gamma, \pi\pi\gamma$, etc. Radiative $\phi$ decays are of big importance to clarify the problematic associated to $\eta - \eta'$ mixing, as well as to study scalar states such as $f_0(975)$, whose excessively small width has caused a bulk of hypotheses [9] ( $K\bar{K}$ molecule, $qq\bar{q}\bar{q}$ states, gluon plasma). The $K_S K_L$ system offers also an ideal playground for the study of paradoxes concerning the foundations of Quantum Mechanics [10].

2 The $DA\Phi NE$ machine

The $DA\Phi NE$ project consists in the construction of a two rings colliding beam $\Phi$ Factory and a 510 Mev $e^+e^-$ injector [1],[11].

The project has been approved and funded; the engineering design has started in January 1991; construction and commissioning is scheduled for the end of 1995. A general layout of the complex, inside the existing buildings, is shown in Fig.[1].

The luminosity goals are $\mathcal{L} = 10^{32}$ cm$^{-2}$s$^{-1}$ for the end of 1995 and a factor 10 higher for the end of 1996.

The design philosophy to achieve this goal has started from the experimental fact that the highest luminosity reached up to now at the $\phi$ energy, with flat beams and two interactions per turn, is $\mathcal{L} = 4.3 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$ obtained at VEPP-2M in Novosibirsk. Taking into account that

$$\mathcal{L} = h\mathcal{L}_0$$

($\mathcal{L}_0$ is the single bunch luminosity and $h$ the number of bunches), the conservative approach has been chosen to construct a machine with many bunches since the increase of $\mathcal{L}_0$ requires the assumption of luminosities never achieved until now.

The choice of a low $\mathcal{L}_0$ should help in keeping the beam luminosity lifetime to a reasonable value (20 hrs). This solution forces to construct two separate rings in which electrons and positrons circulate in opposite directions and collide at a horizontal half angle $\theta_x = 10$ mrad.

The $DA\Phi NE$ design parameters are shown in Tab.1. Remembering that

$$\mathcal{L}_0 = \frac{h f_0 \xi^2 \varepsilon (1 + \kappa)}{\beta_y}$$
($f_0$ is the revolution frequency, $\beta_y$ is the value of the vertical $\beta$ function at the interaction point, $\xi$ the linear tune shift parameter, $\epsilon$ the emittance and $\kappa$ the coupling coefficient), we see that the $DA\Phi NE$ parameters are very similar to the VEPP-2M ones with the exception

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_0 (cm^{-2} sec^{-1})$</td>
<td>4.510^{30}</td>
</tr>
<tr>
<td>$\xi$</td>
<td>.04</td>
</tr>
<tr>
<td>$\epsilon^{\max} (m - rad)$</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>.01</td>
</tr>
<tr>
<td>$\beta_y(IP)(m)$</td>
<td>.045</td>
</tr>
<tr>
<td>$\beta_z(IP)(m)$</td>
<td>4.5</td>
</tr>
<tr>
<td>$N^{\max}(particles/bunch)$</td>
<td>8.910^{10}</td>
</tr>
<tr>
<td>$h^{\max}(N_{\text{er of bunches}})$</td>
<td>120</td>
</tr>
<tr>
<td>$f_0 (MHZ)$</td>
<td>3.17</td>
</tr>
<tr>
<td>$\sigma_z(IP)(mm)$</td>
<td>2.11</td>
</tr>
<tr>
<td>$\sigma_y(IP)(mm)$</td>
<td>0.021</td>
</tr>
<tr>
<td>$\sigma_z(IP)(m)$</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 1: $DA\Phi NE$ design parameters at 510 Mev.

Figure 2: Beam half-separation in the low-$\beta$ region; the heavy dots mark the parasitic crossing points.

of $f_0$, $\epsilon$ and the number of crossing. The beam-beam parameter $\xi$ that enters quadratically in the luminosity formula has a value that is normally achieved in the $e^+ e^-$ colliders. The value chosen for the emittance is very high and this implies a large physical and dynamical aperture of the lattice of the machine. Also the collision frequency has been pushed upward in order to gain luminosity. The very low $\beta_y$ implies a small bunch length ($\sigma_z < \beta_y/1.5$); considering also the large values of $h$ and $f_0$ this means that very high peak and absolute currents will circulate in the machine.

In conclusion the design of the machine, for what concerns the optimization of the luminosity, is quite conservative if we consider the single bunch luminosity; but is very demanding if we consider the necessity to maintain very high currents circulating in the rings. This requests a careful study of the multibunch instabilities that can be excited in the radio frequency (RF) cavities.

The low-$\beta$ insertion (Fig. [2] from [11]) is composed of a quadrupole triplet followed by a
long drift and a special designed split field magnet. In order not to reduce too much the solid angle covered by the experimental apparatus, the low-β insertion is confined within a cone of half-aperture angle 8.5° over a length of ±5 m. This constrains the outer diameter of the first quadrupole to 12.9 cm, requiring a good design of this element.

3 CP violation measurements at DAΦNE

A new measurement of Re(θ') is the most important result to be achieved at a Φ factory. These parameters measure the amplitude of the K_S, K_L system to two pions final states:

$$\frac{<\pi^+\pi^- | K_L>}{<\pi^+\pi^- | K_S>} = \eta_{+-} = \epsilon + \epsilon'$$

$$\frac{<\pi^0\pi^0 | K_L>}{<\pi^0\pi^0 | K_S>} = \eta_{00} = \epsilon - \epsilon'$$

The experimental observation of $\epsilon' \neq 0$ would be proof that CP is violated directly in the decay amplitudes. Two fixed target experiments NA31[6] and E731[7] have presented in the last years contrasting results for the measurement of this quantity. They measure the ratio

$$\frac{R^±}{R^0} = \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} \simeq 1 + 6 Re(\frac{\epsilon'}{\epsilon})$$

The last results [12] obtained with the analysis of the full sample of data

$$Re(\frac{\epsilon'}{\epsilon}) = (2.30 \pm 0.70)10^{-3} \ (NA31)$$

$$Re(\frac{\epsilon'}{\epsilon}) = (0.60 \pm 0.69)10^{-3} \ (E731)$$

are still inconsistent; the confidence level of their compatibility is less than 10%. In particular the NA31 results don't agree at 99% c.l. with the superweak model; E731 is consistent with this model.

A prudent interpretation of these results is that they impose an upper bound on Re(θ') of the order of $10^{-3}$; the difference between the two results is a measurement of the true level of the statistic and systematic uncertainty $\Delta(Re(\frac{\epsilon'}{\epsilon})) \simeq 10^{-3}$. Remembering that the present theoretical predictions for the direct CP violation, at the presently preferred range of the top mass ($100 < M_t < 180 Gev$), indicates $Re(\frac{\epsilon'}{\epsilon}) = \simeq 10^{-3}[13]$, measurements with statistical and systematic errors $\Delta(Re(\frac{\epsilon'}{\epsilon})) \simeq 10^{-4}$ are required to pin down this question.

NA31 has proposed an upgrade of the experiment that should produce about $10^6 K_L \rightarrow \pi^0\pi^0$ for 1995[14]; this number is consistent with a statistical error $\Delta(Re(\frac{\epsilon'}{\epsilon})) \simeq 10^{-4}$.

In 1996 DAΦNE should get a similar measurement with roughly the same statistical error but with better and in any case different systematic errors. In the following we will analyze the potentiality of DAΦNE to improve by an order of magnitude these searches and the physical constraints on the detector design.

3.1 Statistical accuracy in a measurement of Re(θ')

The rates for the process

$$e^+e^- \rightarrow \phi \rightarrow K_LK_S \rightarrow \pi^+\pi^-\pi^0\pi^0$$
are calculated in the exemplifying case of a ($\xi$) vanishing phase, as required if CPT invariance holds; the interference term between $K_S$ and $K_L$ amplitudes may be neglected as far as higher order terms in $\frac{\xi}{\tau_L} = 1.72 \cdot 10^{-3}$ are negligible. In this approximation the time integrated rates $N_i$ are:

$$
N(K_S \to \pi^+\pi^-) N(K_L \to \pi^0\pi^0) \approx \frac{\varepsilon^2}{2} (1 - 4\frac{\varepsilon'}{\varepsilon})
$$

$$
N(K_S \to \pi^0\pi^0) N(K_L \to \pi^+\pi^-) \approx \frac{\varepsilon^2}{2} (1 + 2\frac{\varepsilon'}{\varepsilon})
$$

$$
N(K_S \to \pi^+\pi^-) N(K_L \to \pi^+\pi^-) \approx \varepsilon^2 (1 + 2\frac{\varepsilon'}{\varepsilon})
$$

$$
N(K_S \to \pi^0\pi^0) N(K_L \to \pi^0\pi^0) \approx \frac{\varepsilon^2}{4} (1 - 4\frac{\varepsilon'}{\varepsilon})
$$

Any of these rates is suitable to evaluate ($\xi$), the latter may be too difficult to handle from an experimental point of view. Contributions proportional to ($\xi$) have different signs in different rates and overall coherence reduces statistical and systematical errors.

A weighted mean has a statistical error

$$
\sigma_N(\frac{\varepsilon'}{\varepsilon}) = \frac{1}{6\sqrt{N_1}}
$$

where $N_1 = N(K_S \to \pi^+\pi^-) N(K_L \to \pi^0\pi^0)$. Therefore to achieve $\sigma(\xi) \simeq 2 \cdot 10^{-4}$, with an ideal fully efficient apparatus, in 100 typical running days, a mean luminosity $\bar{L} = 0.8 \cdot 10^{32} cm^{-2} sec^{-1}$ is required.

The asymmetry

$$
A = \frac{N_2 - N_1}{N_2 + N_1} \simeq 3\frac{\varepsilon'}{\varepsilon}
$$

is also a suitable quantity to evaluate ($\xi$); only CP violating events are selected and systematical errors would be reduced.

The corresponding statistical error is

$$
\sigma_A(\frac{\varepsilon'}{\varepsilon}) = \frac{1}{3\sqrt{2\sqrt{N_1}}}
$$

Therefore to achieve $\sigma(\xi) \simeq 2 \cdot 10^{-4}$ in 100 days from the asymmetry measurement, a mean luminosity $\bar{L} = 1.5 \cdot 10^{32} cm^{-2} sec^{-1}$ is required.

A simulation has been done for a spherical fiducial volume with a radius $R = 1.5 m$, taking into account a finite resolution $\sigma = \pm 3 mm$ in the vertex reconstruction. No background has been simulated. The $t_1, t_2$ distribution has been fitted[10] with the expected distribution. To achieve $\sigma(\xi) = 2 \cdot 10^{-4}$ in 100 running days the required mean luminosity is $\bar{L} = 2.5 \cdot 10^{32} cm^{-2} sec^{-1}$.

### 3.2 The systematics in the measurement of $Re(\xi)$

We will analyze the systematic of the measurement of $Re(\xi)$ with the double ratio method. The double ratio $R^{\text{obs}}$, directly constructed from observed number of events,
\[ R_{\text{obs}} = \frac{\frac{N_{\pi^+\pi^-}(K_L \rightarrow \pi^+\pi^-)}{N_{\pi^0\pi^0}(K_S \rightarrow \pi^+\pi^-)}}{\frac{N_{\pi^0\pi^0}(K_L \rightarrow \pi^+\pi^-)}{N_{\pi^0\pi^0}(K_S \rightarrow \pi^+\pi^-)}} \]

can be factorized as

\[ R_{\text{obs}} = R \times R_{\gamma} \times R_{\eta} \]

(\( R_{\gamma} \) and \( R_{\eta} \) are the double ratio of the decay rates and the product of the geometrical acceptance, detection and reconstruction efficiency for each individual decay mode, integrated on the fiducial volume of the detector).

The limit on the achievable accuracy is put by the measurement of \( K_L \rightarrow \pi^0\pi^0 \) that requires a powerful electromagnetic calorimeter. Because of the tagging of the other \( K_{S,L} \) the knowledge of the four photon shower's apices is sufficient to determine the decay vertex and so the path length. The accuracy on the path length is of the order of the accuracy with which the apices are known. So in first approximation photon energy measurements are necessary to confirm the correct pairing of the \( \gamma \) to the parent \( \pi^0 \) but don’t determine the accuracy in the measurement of the path length and so on \( R_{\gamma} \).

The determination of the geometric acceptance is connected to the rate loss due to the finite resolution with which the \( K_{S,L} \) decay point is measured. The vertex resolution function of the \( \pi^0 \) detection can be obtained from a comparison of the vertex position determined from the \( K^\pm \) and \( \pi^\pm \) intersection to that obtained for the \( \pi^0 \rightarrow 2\gamma \). The uncertainty in the difference in the vertices for the two modes is the error in the determination of the peak position of the vertex resolution function \( \sigma_{\text{vert}} \). This error is related to the radius of the fiducial volume \( R_{\text{fid}} \)

\[ \frac{\Delta R_{\gamma}}{R_{\gamma}} = \frac{\sigma_{\text{fid}}}{R_{\text{fid}}} = \frac{\sigma_{\text{ext}}}{R_{\text{fid}}} \sqrt{N(K_L \rightarrow \pi^0\pi^0)} R_{\text{fid}} \approx 1 \times 10^{-4} \]

(To simplify we have considered only the measurement of the decay \( K_L \rightarrow \pi^0\pi^0 \)). Assuming \( \sigma_{\text{vert}} \approx 1 \, \text{cm} \) and \( R_{\text{fid}} \approx 1.5 \, \text{m} \) we obtain \( \frac{\sigma_{\text{fid}}}{R_{\text{fid}}} = \approx 4 \times 10^{-5} \).

The determination of the vertex of the events can also be obtained from the measurement of the photon's time arrival to the calorimeter, because \( K_{S,L} \) are produced with very low velocities \( \beta = \approx 0.216 \). Assuming a time accuracy \( \sigma_{\text{tof}} \approx 300 \, \text{ps} \) we get

\[ \sigma_{\text{vert}} \approx \sigma_{\text{tof}} \times \beta_L \times \frac{1}{\sqrt{N}} + L \times \Delta \beta_L \approx 1.2 \, \text{cm} \]

So also this second method satisfies the precisions required for the measurement of \( R_{\gamma} \).

The detection efficiencies are given by \( \phi \rightarrow K^+K^- \) where one of the charged Kaons decays via \( \pi^\pm\pi^0 \). This process provides a tagged sample of \( \pi^\pm \) and \( \pi^0 \) that have almost exactly identical kinematics as those from \( K_{S,L} \rightarrow \pi^+\pi^- \) and \( \pi^0\pi^0 \). The expected tagged event rate is \( \approx 10^4 \), big enough to test the detector performances along the total fiducial volume with the desired precision.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Background</th>
<th>Relative B.R.</th>
<th>Rejection Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_L \rightarrow \pi^0\pi^0 )</td>
<td>( K_L \rightarrow \pi^0\pi^0\pi^0 )</td>
<td>1:241</td>
<td>1.2 \times 10^{-2}</td>
</tr>
<tr>
<td>( K_L \rightarrow \pi^+\pi^- )</td>
<td>( K_L \rightarrow \pi\mu\nu )</td>
<td>1:135</td>
<td>1.6 \times 10^{-5}</td>
</tr>
<tr>
<td>( K_L \rightarrow \pi^+\pi^- )</td>
<td>( K_L \rightarrow \pi\nu )</td>
<td>1:189</td>
<td>1.1 \times 10^{-5}</td>
</tr>
<tr>
<td>( K_L \rightarrow \pi^+\pi^- )</td>
<td>( K_L \rightarrow \pi^+\pi^0 )</td>
<td>1:61</td>
<td>3.0 \times 10^{-5}</td>
</tr>
</tbody>
</table>

Table 2: Rejection ratios for relevant \( K_L \) decays.
The error on $R^{obs}$ is connected to the background events $N_{\text{Backgr}}$ that are mis-identified as $K_{S,L}$ decays in two pions. The rejection factor $\kappa$ necessary to get the required precisions is

$$\kappa \leq \frac{Br(K_L \to \pi\pi)}{Br(\text{Backgr})} \frac{1}{3\lambda\sqrt{N_{\pi\pi} + N_{\text{Backgr}}}}$$

A list of possible background decays with the relative branching and rejection ratios required is given in Tab.2[15]; it has been assumed that $N_{\text{Backgr}}$ can be estimated with a precision $\lambda \simeq 15\%$.

Another source of background is the process

$$\phi \to \gamma + f_0(975) \to \gamma K_SK_S$$

This background does not affect the measurement of $Re(\frac{\epsilon'}{\epsilon})$ because can be removed with simple cuts on the decay path length. It can affect the measurement of $Im(\frac{\epsilon'}{\epsilon})$ because $K_SK_S$ pairs decay with an intensity peaked at $\Delta(t) = 0$ if $Br(\phi \to f_0(975)\gamma)$ is as large as $5 \times 10^{-5}$[16]; recent estimates give for this branching ratio the values between $0.35 \times 10^{-7}$ and $2 \times 10^{-6}$[17].

The effect of regeneration in $D\phi NE$ is due to $K_L \to K_S$ because all $K_S$ decay in vacuum; the observed value is

$$Re^{obs}(\frac{\epsilon'}{\epsilon}) \simeq Re(\frac{\epsilon'}{\epsilon})(1 - 300\alpha)$$

where $\alpha$ is the regeneration probability of $K_L \to K_S$. No precise estimations exist on $\alpha$ because the total cross section $K-p$ is unknown at the $D\phi NE$ energy. Different estimations on the value of the cross section put the range of the error on $Re(\frac{\epsilon'}{\epsilon})$ from 40% to 7%[18]. This effect is however measurable in few days of running adding for instance some material around the beam pipe.

### 3.3 General requirements for a $\phi$ factory apparatus

The detector for the measurement of $\frac{\epsilon'}{\epsilon}$ should cover as much solid angle as possible in order to optimize the statistical rates and minimize the error in the background subtraction; in any case due the 8.5° degree region covered by the quadrupoles it cannot be bigger than $\simeq 0.98\%$.

The tracking should be a Helium based drift chamber to minimize the multiple scattering contribution to momentum and vertex resolution and reduce the $K_L$ regeneration effects as much as possible[19]. A large detection efficiency for $K_L$ of $\simeq 25\%$ turns into a decay volume of $\simeq 1.5m$ and so the chamber radius should be $\simeq 2m$. Assuming a spatial resolution of $200\mu$, a momentum resolution of 1% requests a magnetic field of $\simeq 0.1T$. The inner radius of the chamber should be of $\simeq 8$ cm in order to get a negligible contribution from $K_S$ regeneration. The expected vertex resolution for $\pi^+ + \pi^-$ decay will be around 1 mm([15]).

The requests for the electromagnetic calorimeter are a good spatial resolution of the order of a few mm, good timing performances and a reasonable energy resolution. A fine grain lead-scintillating fiber sampling calorimeter can measure the apex of the $\gamma$ with a $\sigma$ of a few mm; energy resolutions of $\simeq \frac{8}{\sqrt{E(\text{GeV})}}$, time resolutions of $\simeq \frac{400ps}{\sqrt{E(\text{GeV})}}$ have been obtained with the present technology[20],[21]. A complete Monte Carlo simulation of the reconstruction of $K_SK_L$ decays to $\pi^+ + \pi^- + \pi^0\pi^0$ has been done[22]. The simulation has considered the radiative correction of the initial state, the energy spread of the machine, the energy, time and spatial resolution of the detector described. The results show a $\sigma_{\text{vert}} \simeq 8$ mm and a $\sigma \simeq 16MeV$ for the reconstruction of the $K_S, K_L$ mass.
3.4 CP violation in 3π decay

The observation of the decay $K_S \rightarrow 3\pi$ is also in the capabilities of an experiment at a powerful $\Phi$ factory. In particular $K_S \rightarrow 3\pi^0$ and isotropic $K_S \rightarrow \pi^+\pi^-\pi^0$ are CP violating decays. The decay $K_S \rightarrow \pi^+\pi^-\pi^0$ is allowed, but strongly reduced, if orbital angular momenta are involved. The CP violating amplitude is

$$B_{CPviol}(K_S \rightarrow 3\pi) \sim B(K_L \rightarrow 2\pi) \cdot B(K_L \rightarrow 3\pi) \cdot \left(\frac{\tau_S}{\tau_L}\right)^2 \sim 3 \cdot 10^{-9}$$

if CP violation is mainly due to the mass mixing. The CP allowed decay

$$B_{CPcons}(K_S \rightarrow \pi^+\pi^-\pi^0) \sim (2 \pm 1) \cdot 10^{-7}$$

has never been detected. In the $\pi^+\pi^-\pi^0$ final state the two amplitudes may interfere, increasing the possibility to detect CP violation in this $K_S$ decay. The $\pi^+\pi^-\pi^0$ Dalitz plot must be uniform for the CP violating decay. On the contrary the CP allowed decay must have a strong radial dependence: the simplest distribution [23], taking into account the spherical harmonics involved, is like $[(T_1 - T_2)(T_2 - T_3)(T_3 - T_1)]^2$. CP violation manifests itself as an interference with alternate signs in the six sectors of the Dalitz plot. A factor 2 is gained in sensitivity by looking at the interference in the $\pi^+\pi^-\pi^0$ final state, with respect to the $3\pi^0$ final state, taking into account the different branching ratios [24].

CP violation in the decay $K_L \rightarrow \pi^+\pi^-\pi^0$, with non zero orbital angular momenta, might be detected as well. The relative width is related to the above mentioned widths, if CP violation is mainly due to the mass mixing. Namely:

$$B_{CPviol}(K_L \rightarrow \pi^+\pi^-\pi^0) \simeq B_{CPviol}(K_S \rightarrow \pi^+\pi^-\pi^0) \frac{\tau_L}{\tau_S} \simeq 0.6 \cdot 10^{-9}.$$ 

This amplitude must interfere with the large, CP allowed, $K_L$ decay amplitude.

4 Non CP Violation Physics at DAΦNE

Many physics items different from CP violation measurements have been presented at the 1991 workshop for $DAΦNE$ at Frascati. I will summarize only a few of them; for a complete summary see [25]. These physics items refer to

1.) Open questions on K decay structure functions

<table>
<thead>
<tr>
<th>Theory</th>
<th>$\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiral perturbation theory</td>
<td>$1.7 \pm 0.4$</td>
</tr>
<tr>
<td>Current algebra (Callan-Treiman)</td>
<td>$\simeq 2$</td>
</tr>
<tr>
<td>Dalitz plot ('74)</td>
<td>$2.0 \pm 0.5$</td>
</tr>
<tr>
<td>Muon polarization ('76)</td>
<td>$4.4 \pm 0.8$</td>
</tr>
<tr>
<td>Dalitz plot ('80)</td>
<td>$4.6 \pm 0.5$</td>
</tr>
</tbody>
</table>

Table 3: $\lambda_0$ for $K_L \rightarrow \pi\mu\nu$

2.) $\gamma\gamma$ at low $\pi\pi$ mass.
3.) Scalar mesons.
4.) Nuclear physics at $DAΦNE$. 
4.1 Open questions on K decay structure functions

The branching ratio of $K_L \rightarrow \pi\mu\nu$ is very large (27%) but the radius of the scalar form factor $\lambda_0$ is to be considered partly unknown and the experimental results contradictory [26]. Values for $\lambda_0$ both theoretical and experimental are given in 3. The disagreement with theoretical predictions has been observed either looking at the Dalitz plot distribution[27] or at the muon polarization[28]. A detector to pin down these discrepancies should be able to measure the muon polarization; to do this measurement the previously described electromagnetic calorimeter should have a very good tracking capability.

The improvement factor expected from $DA\Phi NE$ will be 40[3]. Similar effects exist for $K_{\mu3}$ decays; in this case the improvement factor is 1000[3].

4.2 $\gamma\gamma$ Physics at low $M_{\pi\pi}$

The present data on $\gamma\gamma \rightarrow \pi\pi$ at low $M_{\pi\pi}$ are few, with large errors and contradictory. The total cross sections for

$$\gamma\gamma \rightarrow \pi^+\pi^-$$

from Pluto[29], DM1[30], DM2[31] disagree by a factor two the the Mark-II[32] data and expectations from $\pi\pi$ phase shifts. The Mark-II data are in better agreement with Chiral perturbation theory (ChPT). Data on $\gamma\gamma \rightarrow \pi^0\pi^0$ published by the Crystal Ball[33] collaboration are also in contradiction with ChPT and this is quite surprising considering that the absence of the Born term for this process should allow better theoretical calculations; on the other hand ChPT at three level does not predict correctly the $\pi\pi$ phase shifts at low energies[34].

Another information that can be extracted from $\gamma\gamma$ interactions at low masses is the pion polarizability[35]. The electric $\alpha$ and magnetic $\beta$ polarizabilities measure the amount of electric and magnetic dipole induced by an external electromagnetic field. Data on the electric polarizabilities can be extracted also from $\pi\pi$ photoproduction interactions in the Coulomb field of the nucleus, by radiative scattering of pions in the Coulomb field [36] or in radiative pion photoproduction[37]. Also the available measurements of the pion electric polarizability $\alpha$ are contradictory as can be seen in Tab.4.

From these considerations it seems very important to do $\gamma\gamma$ measurements at $DA\Phi NE$; considering that [38] for a given $e^+e^-$ luminosity the untagged $\gamma\gamma$ luminosity is about 20% of

<table>
<thead>
<tr>
<th>Process</th>
<th>$\alpha \times 10^5(Fm^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (ChPT)</td>
<td>$2.7 \pm 0.1$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow \pi^+\pi^-$[29]</td>
<td>$19.1 \pm 4.80$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow \pi^+\pi^-$[30]</td>
<td>$17.2 \pm 4.60$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow \pi^+\pi^-$[31]</td>
<td>$26.3 \pm 7.40$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow \pi^+\pi^-$[32]</td>
<td>$2.2 \pm 1.60$</td>
</tr>
<tr>
<td>$\pi Z \rightarrow \pi Z\gamma$[36]</td>
<td>$6.80 \pm 1.40$</td>
</tr>
<tr>
<td>$\gamma Z \rightarrow \pi Z$[37]</td>
<td>$20.0 \pm 12.0$</td>
</tr>
</tbody>
</table>

Table 4: Pion electrical polarizability $\alpha$

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \pi^0\pi^0$</td>
<td>$0.7 \times 10^4$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \pi^+\pi^-$</td>
<td>$0.9 \times 10^6$</td>
</tr>
</tbody>
</table>

Table 5: Events/year ($e^+e^- \rightarrow e^+e^-\pi\pi$)
the $\gamma\gamma$ luminosities at PEP/PETRA we see that also with a moderate luminosity $DA\Phi NE$ can do much better than Crystal Ball. The events/year for

$$e^+e^- \rightarrow e^+e^-\pi\pi$$

at $\mathcal{L} = 2.5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ are given in Tab.5[39].

Finally $DA\Phi NE$ gives the unique opportunity to perform double tagging at zero degrees; this is very important [38] because it could be possible to measure azimuthal correlations and so to separate helicity amplitudes.

### 4.3 Scalar mesons

The main search in hadron spectroscopy is for states beyond $q\bar{q}$; scalar mesons exist just below the $\phi$ mass [40], the $a_0(980\text{MeV})$ and $f_0(970\text{MeV})$ that decay into $\pi^0\eta, \pi\pi, KK$; the $f_0$ has the vacuum quantum numbers; their widths are 35 and 57 Mev. The nature of these particles is controversial. Many questions arise: why $M_{f_0} \approx M_{a_0}$; why their widths are so small.

There is now a considerable body of evidence that these particles are not simple $q\bar{q}$ $3P_0$ mesons and the hypothesis has been considered that they are $KK$ molecules [9], roughly analogous to the deuteron. The close values of masses and widths strongly suggests an ideally mixed pair of mesons, like $\rho$ and $\omega$, hence the $2\pi$ decay width should be much larger than observed. On the contrary, in the $KK$ molecule interpretation masses, widths and decay modes are naturally explained.

The radiative $\phi$ decay into these resonances is a discriminant measurement between these different models. A width

$$\Gamma(\phi \rightarrow f_0\gamma) \simeq 10^{-3}\text{MeV}$$

is expected [17] if the $f_0$ is also a $s\bar{s}$ state, yet a much smaller width is expected if a molecular state must be produced in the radiative decay.

We remember that $\phi \rightarrow K^0\bar{K}^0\gamma$ has been considered [17] as a possible source of background in the measurements of $(\xi)$. It can be eliminated on the basis of the relative decay times distributions; but in any case the detector proposed for $(\xi)$ should be able to measure it, unless very small.

### 4.4 Nuclear Physics at $DA\Phi NE$

Many authors at the Frascati 1991 workshop [41] on $DA\Phi NE$ have emphasized the possibility to use this machine as a unique, monochromatic, background free, source of very low energy Kaons; as the Kaons are produced in pairs it is possible to tag one and look at the interaction of the other with the matter. In 1995 $DA\Phi NE$ will be the unique source of $K^\pm$ at very low energy in Europe with a moderate intensity $(4 \times 10^3\text{s}^{-1})$, emitted over $4\pi$ at a luminosity $\mathcal{L} = 1 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$.

At the $\phi$ mass the Kaon momentum is 110 Mev/c and there are very few data for momenta lower than 300 Mev/c concerning elastic and total Kaon-Nucleon interactions. To understand the reasons of this lack of data, we remember[41] that the survival probabilities for Kaons after a given distance from the production point go down quickly at the increase of the distance; radiation safety reasons at proton machines fix this distance to $10 \div 15$ m; to have a reasonable intensity in experiments where lower energies are needed, a moderator is put in front of the experimental apparatus in order to decrease the momentum of the particles. The moderator introduces a large uncertainty in the momenta of the produced particles. For experiments with stopped $K^-$, thick targets (of the order of 1 g/cm$^2$) are used.
in order to have an acceptable stopping rate; this introduces a big error on the momentum of the emitted charged particles due to the uncertainty of the interaction point. On the contrary the 15 Mev Kaons produced at DAZNE stop in 100 mg/cm² and the error introduced in the determination of the interaction point matches the present day magnetic spectrometers.

T. Bressani[41] has sketched an apparatus that fully exploits the quality of this beam and is optimized for studies of Λ and Σ hypernuclei production with K⁺ at rest. The production of hypernuclei is signalled by the detection of monochromatic pions emitted in the decay[42].

The interest of the study of hypernuclei is based on the s quark content of these nuclei that provide informations not normally accessible in usual nuclear reactions. Particular interest should offer the possibility to produce deeply bound π⁻ states, predicted but never observed[43], from Λ decay in heavy nuclei, like ²⁰⁸Pb. Hypernuclei weak decays are also interesting because the presence of outgoing nucleons modifies by the Pauli principle, the rates; therefore the detection of these decays is a mean to study weak interactions in a peculiar environment.

Another relevant open question concerns the Kaon-Nucleon scattering lengths; the real part is positive according to the scattering data and negative according to the X-ray emission from Kaonic atoms[44]; to clarify this point low energy Kaon-nucleon data are needed.

Concerning the K⁺ nucleus interactions the present data on K⁺ nucleus total cross sections show evidences for a puzzling anti-shadowing effect that increases at lower Kaon momenta[45]. In fact plotting as a function of the Kaon momenta the ratio

\[ R = \frac{\sigma(K^{+12C})}{\delta \sigma(K^{+d})} \]

of the cross section for K⁺ scattering on ¹²C and deuterium, we get R bigger than one. The swelling of nucleons in K⁺ interactions is very surprising because due to the antiquark content, the K⁺ mesons don’t couple strongly to the nucleon; below 1 Gev/c the typical K⁺N cross section is an order of magnitude smaller than π⁻N and K⁻N cross sections. This translates in the fact that unlike other hadrons the K⁺ interactions with nuclei can be considered, to first order, as a single scattering with the nucleons; K⁺ are a sort of heavy electron; but this picture seems to be wrong and needs further study from both theoretical and experimental sides.

5 Quantum Mechanics paradox on a macroscopic scale

The φ decay into a neutral Kaon pair is a very suitable process to test Quantum Mechanics (QM) on a large scale. Many authors have emphasized paradoxes related to this process[46], which are a good illustration of the celebrated Einstein, Podolsky, Rosen arguments [47].

Actually paradoxes arise because the φ and the neutral Kaons are both superposition of states. Namely the φ is

\[ |φ> = \frac{1}{\sqrt{2}} [ |K^0(p)> - |K^0(-p)> ] \]

to achieve a C = -1 eigenstate. The strongly interacting neutral Kaons are superposition of the short-living and long-living mass eigenstates

\[ |K_S> = a|K^0> + b|\bar{K}_0> \]
\[ |K_L> = c|K^0> + d|\bar{K}_0> . \]
If CPT is conserved: \(a = c, b = -d\). If CP is also conserved: \(a = c = b = -d = \frac{1}{\sqrt{2}}\). Therefore, if neutral Kaons decay without interacting, it is also

\[
|\phi> = \frac{1}{\sqrt{2}}[|K_S(p)> |K_L(-p)>, |K_L(p)> |K_S(-p)>]
\]

and only events \(K_S(p), K_L(-p)\) will be detected.

Let us consider the following paradox as an example. If a thin regenerator is introduced on one side coherent regeneration takes place and a fraction of the events, decaying downstream the regenerator, will be either \(K_S(p)K_S(-p)\) or \(K_L(p)K_L(-p)\).

Yet coherent regeneration cannot arise for a spherical regenerator. Things are as if a neutral Kaon, crossing a regenerator, knows what is occurring simultaneously to the other neutral Kaon, no matter how far one Kaon is from the other. This paradox is predicted by QM because the \(\phi\) decomposition is invariant under the simultaneous transformations

\[
|K^0(\pm p)> = |K^0(\pm p)> + \alpha |\bar{K}^0(\pm p)>
\]

\[
|\bar{K}^0(\pm p)> = |\bar{K}^0(\pm p)> + \beta |K^0(\pm p)>
\]

where \(\alpha\) and \(\beta\) are the coherent regeneration amplitudes.

The doughnut of the storage ring is an appropriate regenerator to verify this prediction. For example [25] let us assume that 1 cm of Cu regenerator is brought close to the interaction region; some thousands of collinear \(K_S K_S\) events will be detected in few days, due to the \(K_S\) coherent regeneration in the Cu slab. However, if two regenerators are put symmetrical on both sides collinear \(K_S K_S\) events will never be detected (Fig. [3]). So Quantum Mechanics is such that if a Kaon interacts with matter on one side, the other Kaon immediately interacts or not, exactly in the same way on the opposite side, no matter how far it is.

By the way, this argument supports the suitability of a \(\Phi\) factory to study CP violation in neutral Kaon decay. In fact, this effect reduces in practice \(K_S\) regeneration in the apparatus, which may simulate a CP violating decay.

\[
\begin{align*}
K_S & \quad \rightarrow \quad \cdot \quad \rightarrow \quad K_L \\
K_S & \quad \rightarrow \quad \cdot \quad \rightarrow \quad K_L \quad \rightarrow \quad K_S \\
K_S & \quad \rightarrow \quad \cdot \quad \rightarrow \quad K_L \\
K_S & \quad \rightarrow \quad \cdot \quad \rightarrow \quad K_L
\end{align*}
\]

Figure 3: Illustrating the regenerators E.P.R. paradox.
6 Conclusions

Physics at DAΦNE will start at the end of 1995 with as main program the measurement of $\xi^\prime$.

In 1995 experiments at CERN and Fermilab will have new results with an increase in statistic and precision but the DAΦNE measurement will be in any case complementary. If $Re(\xi^\prime)$ will be not too small, DAΦNE has the unique chance to see CP violation also in 3 $\pi$ decays. If one considers the importance to test the presence of CP violation in weak decays per se, not only to test the Standard Model, it seems worthwhile to fulfill a program that should be able to give a definitive answer.

The other physics items that can be exploited at DAΦNE as tests of chiral dynamics, $\gamma\gamma$ production near threshold, nuclear physics put very stringent constraints on fundamental physical quantities; many of these measurements can be done only at DAΦNE.

Finally it should be considered that the possibility to achieve luminosities of $\approx 10^{33}$ will mean in any case a big improvement in the quality of low energy data produced at $e^+e^-$ machines.

7 Acknowledgements

I warmly thank the organizing committee for the good success of the NAN-91 workshop.

It is also a pleasure to thank Dr. R. Baldini-Ferroli for encouragement during the preparation of this article.

References

[1] Proposal for a $\Phi$ factory, LNF 90/031(R).
[5] F. Agamir et. al., The UCLA Particle beam physics (PBP) and $\phi$ factory conceptual design, CAA-0053-UCLA-2/90.


[16] V. Patera, *Measurement of $Re(\xi)$ and $\Delta \phi$ parameters at a $\Phi$ factory by means of the $K_L, K_S \rightarrow \pi^+ \pi^- \pi^0 \pi^0$ decay time difference*, Proceedings of the Frascati Workshop for Detectors and Physics at *DAΦNE*, Frascati (Italy), April 9-12, 499 (1991).


[22] C. Bloise, *Decay length reconstruction: $K_{S,L} \rightarrow \pi^0\pi^0$*, Proceedings of the Frascati Workshop for Detectors and Physics at *DAΦNE*, Frascati (Italy), April 9-12, 495 (1991).


[28] A.R. Clark et al., Determination of the $K_L \rightarrow \pi\mu\nu$ muon neutrino form factor by muon polarization measurements, Phys. Rev. D15, 553 (1977).


[31] Z. Ajaltouni et al., Photon Photon collisions, Contr. to VII Inter. workshop on $\gamma\gamma$ collisions, Paris, April 1986.


[33] H. Marsiske et al., A measurement of $\pi^0\pi^0$ production for two photon collision, Phys. Rev. D41, 3324 (1990).

[34] M.R. Pennington, Two photons into two pions out, Proceedings of the Frascati Workshop for Detectors and Physics at DAΦNE, Frascati (Italy), April 9-12, 361 (1991).


[38] A. Courau, $\gamma\gamma \rightarrow \pi\pi$ near the threshold at DAΦNE, Proceedings of the Frascati Workshop for Detectors and Physics at DAΦNE, Frascati (Italy), April 9-12, 373 (1991).


