

Physics opportunities at DAΦNE, the Frascati ϕ -factory

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ABSTRACT

The physics potential of a ϕ -factory is reviewed: minimum luminosity requirements for an e^+e^- collider are evaluated. The parameters of the Frascati based project, DAΦNE, are discussed with a preliminary construction schedule for the machine.

1. Introduction

One of the most interesting topics in the study of fundamental interactions is discrete symmetry in the basic Hamiltonian. Out of the discrete symmetries C , P and T , both P , C and the product CP have been experimentally shown to be violated in electroweak interactions. Maximal parity violation is one of the building blocks of the $V - A$ weak interaction theory, and K_L^0 decays have given proof that CP is (non-maximally) violated.^[1]

This last phenomenon can be naturally incorporated in a theory like the Standard Model in which three quark generations mix through three mixing angles and a complex phase, although our present experimental knowledge does not exclude other possible explanations of it. CP violation ultimately bears on the scalar sector of the Lagrangian.

A higher step in invariance for discrete symmetries is CPT : this symmetry is one of the basic principles of the Quantum Field Theory and should hold at least throughout an energy scale of the order of the Planck mass, where gravitational effects may start to become evident. Tests of CPT invariance would provide us, if a hint of non-conservation should be discovered, with the evidence for completely new physics.

As mentioned before the only experimental proof of CP violation comes from K_L^0 decays; the standard model predicts two different sources of CP violation, one related to the non-orthogonality of the K^0 mass eigenstates, which in turn stems out of the asymmetry of the second order transition $K^0 \leftrightarrow \bar{K}^0$, the other, usually called direct CP violation, in the decay amplitude itself that is schematized with the so called *Penguin diagrams*. CP violation phenomena should be experimentally detectable in many B and K decays: the detailed study of how this symmetry is broken would yield a considerable insight to extremely high mass scales.

This *physics potential* of the study of CP violation phenomena has been recognized by many groups and several proposals to build ϕ -factory have been presented.^[2-6]

A factory is an accelerator capable of producing a particular species of particles in a very well controlled kinematic situation and a low background environment, so that a detailed study of that particular species can be performed: e^+e^- colliders, are often chosen as tool for factories, thanks to the extreme cleanliness of the production mechanism. The main concern, in this case, is the machine luminosity, since production cross sections are lower than the hadronic case.

2. Physics at a ϕ -factory

Kaons have always provided interesting clues for new physics, from parity non conservation,^[7] to Cabibbo mixing,^[8] to CP violation,^[1] to the prediction of absence of FCNC through the GIM^[9] mechanism: their quarks composition is such that they make an excellent laboratory for studying weak interactions. Strong interactions, which take place between the products of the weak decays, can be studied as well; such interactions occur at a mass scale that, even if completely outside the range of perturbative QCD, can be actually evaluated by chiral perturbation theory (Ch. P. T.) allowing stringent tests of the latter.^[10]

A ϕ -factory, which produces the ϕ meson at rest through e^+e^- annihilation, is in fact an ideal K factory. About 80% of the ϕ width is accounted for by two-body K decays; furthermore the two daughter kaons are, given the spatial properties of the ϕ wave-function, created in a fully antisymmetric state, and this opens up very interesting experimental possibilities. Because of the two body decay mechanism with which kaons are produced, most measurements can be performed with the tagging technique so that branching ratios, for instance, will be measured in a completely unbiased way.

Before going into a more detailed description of the physics program at a ϕ -factory it is useful to state a *minimum goal* for the ensemble of the machine and detector. The benchmark I will choose is the measurement of ϵ'/ϵ in the K^0 system. There are different ways to measure ϵ'/ϵ at a ϕ -factory: for the time being I will keep with the *standard method* used in hadronic machines, namely the double ratio method. Such an observable is:

$$\mathcal{R}^\pm/\mathcal{R}^0 = \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} \sim 1 + 6 \times \epsilon'/\epsilon \quad (2.1)$$

Given the present measurements of ϵ'/ϵ ,^[11,12] I would name as *minimum goal* for a ϕ -factory reaching a statistical accuracy on that quantity of 3×10^{-4} in one *physics year* ($\approx 10^7$ s) running time. Systematics at a ϕ -factory can be better controlled than in experiments with K_L^0 beams. We foresee for this type of error an upper limit of 1.5×10^{-4} .

The above requirements on the ϵ'/ϵ statistical error translate into a number of reconstructed K_L^0 decays $\approx 500,000$ (for the rarest mode), which in turn means a

product of peak luminosity times detection efficiency of:

$$\mathcal{L} \times \epsilon = 3 \times 10^{31} \text{cm}^{-2} \text{s}^{-1} \quad (2.2)$$

In the ϕ decay at rest the $\beta\gamma$ for the K_L^0 (K_S^0) is ~ 0.25 so that the decay length is 342 cm (0.6 cm.): it is difficult to design an apparatus that has a K_L^0 detection efficiency bigger than 30%. This consideration alone sets the lower limit on the collider luminosity at $1 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$. On the other hand reasonable extrapolations of the parameters of operating machines set the upper limit on the achievable peak luminosity at $1 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$.

We will assume, in the following, that the collider will yield a peak luminosity of $5 \times 10^{32} \text{cm}^{-2} \text{sec}^{-1}$; this assumption on the expected luminosity will be substantiated in the section concerning the Frascati design of the machine.

With the assumed luminosity the physics opportunities can be summarized as follows:

1. Substantial improvement in the CP and CPT violation measurements in the K^0 system.
2. Possibility of observing CP violation in the charged K system.
3. Precise measurements of *not so rare* K decays with particular emphases on K_S^0 . (Branching ratios $\sim 10^{-6}$)
4. Improvements on upper limits on rare decays (Branching ratios $\geq 10^{-9}$). Such improvements will be extremely important again for the K_S^0 .
5. High precision measurements of Kaons' known branching ratios .
6. Measurements of ϕ rare decays.
7. Study of hadronic spectroscopy in the mass region around 1 GeV, with particular emphases to the scalar states accessible through the radiative ϕ decay.
8. Precise measurement of the η - η' mixing.

2.1. CP AND CPT VIOLATION

Besides the standard way of measuring ϵ'/ϵ , which was discussed above, the correlated production of $K_L^0 K_S^0$ in the ϕ decay allows the determination of the real part of ϵ'/ϵ through the measurement of the asymmetry in the decay path lengths ($\Delta l \gg \beta\gamma\tau_{short}$).

Such an asymmetry, if measured in the interference region, would yield the phase difference, $\Delta\phi$, between η_{+-} and η_{00} . A $\Delta\phi$ different from zero would be an

indication of CPT violation in the decay amplitude. It is worth noticing, however, that, if the $\Delta I = \frac{1}{2}$ rule holds also for the CPT non conserving amplitudes, then CPT violation could occur even if the phase difference between η_{+-} and η_{00} were zero. Typical sensitivities in this measurement are of the order of 1 degree with the luminosities mentioned above.

Given its unique possibility of tagging, a ϕ -factory offers the opportunity of measuring directly the impurity parameter ϵ for the K_S^0 and this in turn allows a test of T invariance. The only other test of T invariance obtained up to now, concerns the neutron dipole moment: the present sensitivities are $\sim 10^{-25}$ e - cm, while both the standard and the superweak models predict values four or five orders of magnitude lower. At a ϕ -factory, using the semileptonic decay of the neutral kaons, it will be possible to perform the Kabir test.^[13] The charge asymmetry in the same sign lepton yield:

$$A_T = \frac{N_{ll} - N_{\bar{l}\bar{l}}}{N_{ll} + N_{\bar{l}\bar{l}}} = 2\text{Re}(\epsilon_l + \epsilon_s) \quad (2.3)$$

will be measured to $\sim 1 \times 10^{-3}$ allowing a 6σ test of the balance between T and CP violations. Analogous information can be gathered from the direct measurement of the impurity parameter for the K_S^0 . Here the measurement has a slightly lower statistical significance, as the analyzing power is smaller: the error on ϵ_s can be written as:

$$\delta\epsilon_s = \frac{\delta A_l^s}{2} \approx \frac{4.3 \times 10^{-4}}{2\sqrt{\epsilon_{tag}}} \quad (2.4)$$

where:

$$A_l^s = \frac{N(K_S^0 \rightarrow l^+) - N(K_S^0 \rightarrow l^-)}{N(K_S^0 \rightarrow l^+) + N(K_S^0 \rightarrow l^-)} \quad (2.5)$$

and ϵ_{tag} is the tagging efficiency for the K_S^0 .

A ϕ -factory would also offer opportunities for hunting direct CP violation phenomena in the charged kaons sector.

Unfortunately the two body decay of the K^\pm into $\pi^\pm\pi^0$ is ruled out : the expected asymmetry level for this decay is of the order of 10^{-6} well beyond experimental reach.^[14]

In the three body decays there have been many recent calculations that seem to suggest that both the $\pi^0\pi^0\pi^\pm$ channel and the $\pi^\pm\pi^\mp\pi^\mp$ channel could show CP

violation effects, especially in the Dalitz plot slope.^[15] With the quoted luminosity, 3σ effects would be detectable. An other channel in which CP effects might be seen is $K^+ \rightarrow \pi^+ \pi^0 \gamma$: in spite of a minuscule branching ratio ($\sim 10^{-4}$) a sizeable asymmetry is expected (~ 0.001). This translates into a 2σ effect with 9×10^9 produced kaons.

As a last example I will mention the asymmetry in the partial widths of the K^\pm leptonic decays: actual limits could be improved by a couple of orders of magnitude.

2.2. RARE K DECAYS

As mentioned in the introduction, a ϕ -factory cannot compete with hadronic kaon factories in searching for very rare decays of these mesons: it will, however, be possible to search for many *not so rare* ($Br \sim 10^{-6}$) decays of both K_L^0 and K_S^0 and measure them accurately. With the assumed luminosity, upper limits on less frequent decays could be improved to a statistical sensitivity of the order of 10^{-9} .

Here are few examples of interesting decays:

1. K_S^0 decays into three pions: the $K_S^0 \rightarrow \pi^0 \pi^0 \pi^0$ decay, with an expected branching ratio of $\sim 2 \times 10^{-9}$ is a clear case of CP violation; a ϕ -factory would allow to detect few events. The decay $K_S^0 \rightarrow \pi^+ \pi^- \pi^0$ contains both CP conserving and CP violating parts, owing to higher angular momenta involved in the decay. Expected branching ratios are of the order of few unities $\times 10^{-7}$ ^[16] while the mass matrix CP violating part would be of the order of 8×10^{-10} .
2. K^0 radiative decays ($K_L^0, K_S^0 \rightarrow \gamma\gamma, \gamma l^+ l^-$): expected branching ratios range between 10^{-4} and 10^{-9} . This type of decay proceeds through a one-loop FCNC transition at the quark level; long distances contributions however are important too. Such contributions will be different for K_L^0 and K_S^0 ; in the K_L^0 case, for instance, diagrams with a single pole will contribute, while in the K_S^0 case meson loops are the mechanism responsible for the transition.
3. $K \rightarrow \pi\gamma\gamma$: these decays are calculable in chiral perturbation theory so they provide a good test of this theory with *e.g.* the $\gamma\gamma$ invariant mass spectrum, which is unambiguously predicted. It is worth noticing that the branching ratio $K_L^0 \rightarrow \pi^0 \gamma\gamma$ is necessary to disentangle the two contributions, the CP violating $K_L^0 \rightarrow \pi^0 e^+ e^-$ that proceeds through one virtual γ , and the CP conserving amplitude that proceeds through two virtual photons.

4. $K \rightarrow \pi\pi\gamma$: in the K^0 case would yield information on the $\Delta I = \frac{1}{2}$ rule outside the $K \rightarrow \pi\pi$ decay. Important information could also be obtained concerning direct CP violation. This transition has two components: the so called inner bremsstrahlung and the direct emission. While the former can be reliably evaluated, the latter has long distance contributions which cannot be evaluated with the same reliability. Experimental data will surely help to clarify the situation.

K semileptonic decays. The study of semileptonic decays (K_{l3}) will allow crucial tests of chiral perturbation theory through the measurement of the form factors; in addition basic relations like the Callan-Treiman one that relates the average charge radius to masses and decay constants, can be tested to a high degree of accuracy. At the moment of this writing the agreement of the data with the Callan-Treiman relation is at the level of a couple of σ . The study of the K_{l4} decay will yield extremely important information on $\pi\pi$ scattering, besides the various form factors associated with the decay. It is worth noticing that the world database for the decay $K_L^0 \rightarrow \pi\pi l\nu$ contains 16 events.

2.3. HADRONIC SPECTROSCOPY

Many open problems concerning low energy hadron spectroscopy are at the moment on the floor: a ϕ -factory could give ample contributions to their understanding. Again I will mention few topics:

1. ϕ radiative decays: branching ratios for the decay $\phi \rightarrow \eta\gamma, \pi^0\gamma$ have been measured; the decay $\phi \rightarrow \eta'\gamma$ (for which only an upper limit exists) would shed some light on the glue content of the η and η' mesons.
The radiative decays of the ϕ will give access to 0^{++} mesons; in particular the $f_0(975)$ and the $a_0(980)$ will be produced in quite a clean environment. Different compositions foreseen for these mesons would result in dramatically different branching ratios for the radiative transition.
2. The SU_2 breaking, resulting from the mass difference between u and d quarks can be studied through the $\rho - \omega$ mixing; the role of the Okubo-Zweig-Iizuka (OZI) rule in the non strange decay of the ϕ could be studied; the big difference in branching ratio between the $\phi \rightarrow \pi^+\pi^-\pi^0$ and $\phi \rightarrow \rho\pi$ could be understood together with the role of the OZI rule for these transitions.

3. Semileptonic decays of the ϕ ; this class of decays would allow cross checking of transition like $e^+e^- \rightarrow \phi P$ with P being a pseudoscalar meson.
4. Rare decays of the ϕ meson: C violating decays *e.g.* $\phi \rightarrow \rho\gamma, \omega\gamma, \eta\pi^0$ could be searched for. The $\phi \rightarrow \pi\pi$ decay (doubly suppressed) should be studied in detail too.

Other measurements concerning low energy hadron spectroscopy will be performed thanks to the enormous database that will be collected on ϕ decays; rare decays of η, η', π^0 will also be within experimental reach.

3. The machine

I will give here a brief review of the design criteria that have been used for DAΦNE together with the underlying philosophy that has dictated the various choices.* The design of the machine has been optimized with the following constraints:

- 1 The final goal for peak luminosity is $1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$, at the ϕ mass.
- 2 A luminosity of at least $2\text{-}3 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ should be reached within, or shortly after, the first year of operation.
- 3 The machine must have a very high degree of tunability and should be based as much as possible on conventional techniques; the luminosity improvements should be achieved with minimal disruption to the experimental program.
- 4 The ultimate experimental goal is to collect $\sim 10,000 \text{ pb}^{-1}$ in one *physics year* (10^7s), so average luminosity has to be close to the peak value.

3.1. DESIGN CRITERIA

To define the interplay of the various factors that concur in the luminosity, let us review the luminosity formula for an e^+e^- collider :

$$\mathcal{L} = f \times \frac{\xi^2 \times \epsilon \times (1 + \kappa_\beta)}{\beta_y} \times \sqrt{\frac{\kappa_\beta}{\kappa}} \quad (3.1)$$

* Much of the discussion reported in the following is based on the DAΦNE proposal^[2] and ref 3

where f is the collision frequency, ξ is the beam-beam parameter, β the betatron function, κ_β the ratio of the vertical to horizontal betatron function at the interaction point (I.P.) and κ the coupling parameter.

High luminosity will necessarily imply high emittance, high repetition rate, high beam-beam tune-shift and low β_y . These parameters will however have different weights in the general performances of the machine. Let us analyze how the variations of each of them affects the machine characteristics and the experimental apparatus.

Working at a very low β_y requires a small bunch length ($\sigma_z \leq \frac{\beta_y}{1.5}$) in order to take full advantage of the small beam spot; this in turn will imply that very high peak currents will circulate in the machine and that particles losses due to Touschek effect ($\tau_T \sim \sigma_z$) will play an important role in the beam lifetime. The design of the interaction region will require focussing elements very close to the interaction point which will reduce the solid angle coverage of an experimental apparatus.

Collision frequency is a parameter that has to be pushed upward in order to gain luminosity: very high collision frequency will imply the usage of two different rings; in addition the crab crossing option would have to be implemented if an angle crossing is the design choice. In this case horizontal crossing rather than vertical would be preferred as the former would be less critical and less demanding on the crabbing cavities.

Emittance should be as high as possible, but cannot be increased at a zero cost: in order to keep the lifetime of the beams long, that is to say at least 5 - 10 times longer than injection times, increasing the emittance would imply a bigger physical (and dynamical) aperture, increasing construction costs and requiring an extra-careful alignment of the ring itself.

The beam-beam parameter is probably the most important factor that appears in the luminosity formula: the \mathcal{L} depends quadratically on it and this should be exploited to obtain a big gain. It is also true, however, that there is no accepted theory with which ξ limits can be evaluated. A conservative design will then be based on realistic (and achieved) values of ξ leaving possible improvements on this parameter to the experimentation.

These basic ideas can be summarized in the following table in which most of the relevant parameters for DAΦNE are reported.

Parameter	Value	unities
Beam energy	510	MeV
Circumference	99.00	m.
Bending radius(main dipoles)	1.464	m.
Bending radius(wigglers)	0.90	m.
Crossing angle	20.0	mr.
Energy loss/turn	13.75	KeV/turn
Rel. Energy spread	4.33×10^{-4}	
Collision frequency	70 – 350	MHz
# of bunches	23 – 115	
# of particle/bunch	8.9×10^{10}	
ξ_y	0.04	
ξ_x	0.04	
β_y	4.5	cm.
β_x	4.5	m.
Natural emittance (vert.)	1.83×10^{-11}	m. rad.
Natural emittance (horiz.)	$1. \times 10^{-6}$	m. rad.
Beam dim. @ I.P.(vert.)	21.	μ .
Beam dim. @ I.P.(horiz.)	2.11	mm.
Bunch length	3.0	cm.
Total current	1.02 – 5.1	A.
Sync. Rad. power/beam	13.5 – 67.5	KW.
Luminosity	$1 - 5 \times 10^{32}$	$\text{cm}^{-2} \text{s}^{-1}$

It is worth noticing that even at $\mathcal{L} \sim 1 \times 10^{33} \text{cm}^{-2} \text{sec}^{-1}$ the expected beam lifetime is of the order of a couple of hours, ensuring that average and peak luminosity will not differ by more than 20-25 %, if the injection time is ≤ 10 minutes.

3.2. DAΦNE PRELIMINARY SCHEDULE

Finally I would like to give a preliminary schedule on the machine completion: the physics program outlined in the first chapter is interesting enough to require an all out effort to get the machine ready to operate as soon as possible. At the Frascati National Laboratory we practically have on hand all the buildings to house the collider complex, since the old Frascati storage ring *Adone* will be decommissioned and dismantled within the next two years. The schedule for the machine can be then summarized as follows:

Completion of the detailed engineering design	end 1991
Completion of bids-packages to outside contractors	end 1991.
Decommissioning and dismantling of Adone	beginning 1993
Installation of the new components	1993-1994
Beam commissioning	Beginning 1995

The first beam-beam collisions are expected during the summer of 1995.

4. Conclusions

The physics opportunities offered by an e^+e^- based ϕ -factory are extremely interesting: they range from tests of the basic invariance principles to very detailed checks of Q.C.D. at the non-perturbative level. The experimental program that can be carried out at such a facility seems extremely attractive, if the luminosity of the collider is at least in the few $\times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ range. The technology to reach such values for the luminosity seems to be on hand, and the Frascati National Laboratories have committed themselves to design and build such a facility on the time scale of five years: very exiting times lay ahead of us.

ACKNOWLEDGEMENTS

It is a pleasure to thank the Organizing Committee for a very interesting, smoothly organized and fruitful Conference.

It is also an honor for me to offer my best wishes to Prof. Giorgio Salvini, one of the founding fathers of modern particles physics in Italy, who has become this year Professor Emeritus at the Università "La Sapienza" in Rome.

REFERENCES

1. J.Cristenson, J.Cronin, V. Fitch, R. Turlay Phys. Rev. Lett.**13** 138 (1964).
2. "Proposal for a ϕ -factory " Nota Interna Laboratori Nazionali di Frascati **LNF-90/031**
3. S. Bartalucci *et al.* Dafne technical note **G-2** Nov. 1990
4. G.M.Tumakin "Proposal for B and ϕ factories in Novosibirsk" Proceedings of the 1989 AEEE Particle Accelerators Conference , March 20-23 1989 , pag.441
5. M. Fukawa *et al.*KEK Report **90-12** Aug. 1990
6. F. Aghamir *et al.* "The UCLA particle beam physics (PBP) and ϕ -factory conceptual design " **CAA-0053-UCLA-2/90**
7. T.D.Lee and C.N.Yang , Phys. Rev. **50**, 263 (1956)
8. N. Cabibbo Phys. Rev. Lett. **10**, 531 (1963);
N. Cabibbo Phys. Rev. Lett. **12**, 62 (1964)
9. S.L. Glashow, J. Iliopoulos, L.Maiani Phys. Rev. **D2**, 1285 (1970)
10. R. Barbieri *et al.* "Relazione del gruppo di studio sulla ϕ -factory", Nota Interna Laboratori Nazionali di Frascati **LNF-90/041** May 1990
11. H.Buckhardt *et al.*, Phys.Lett. **B206**, 118 (1988).
12. J.R. Patterson *et al.*, Phys. Rev. Lett. **64**, 399 (1990).
13. P.K.Kabir, Phys. Rev. **D2**, 540 (1970).
14. C. Dibbs R. Peccei, Contribution to the UCLA workshop on "Testing *CPT* and studying *CPT* violation at a ϕ -factory" Los Angeles, March 1989
15. A. A. Bel'kov *et al.*, Phys. Lett. **B204**, 425 (1989) and references quoted therein
16. S. Fajfer, J.M. Gerard , Z. Phys. C **42**, 425 (1989);
Hai-Yang Cheng, Phys. Lett. **B238** 399 (1990).