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QUARK PHYSICS AT A PHI-MESON FACTORY*

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Abstract

Some physics objectives other than tests of CP and CPT of a phi factory are discussed. They include: (1) better measurements of the down-up quark mass difference using $\rho^\circ - \omega$ and $\pi^\circ - \eta$ mixing studies; (2) the detailed investigation of the validity of the OZI rule and of the quark structure of the ϕ meson via $e^+e^- \to \pi^+\pi^-$, $\pi^\circ\gamma$, and 3π measurements; (3) the extraction of important information on the structure of the 0^{++} meson which can be learned from measurements of radiative decays, in particular of $\phi \to \pi\pi\gamma$ and $\phi \to K\bar{K}\gamma$.

A phi factory is really a factory of tagged, monochromatic K_S and K_L mesons allowing precision measurements of various neutral K-decay modes. This enables one to make a precision measurement of the V_{us} element of the K-M matrix based on K°_{e3} decay and to perform critical tests of chiral perturbation theory, in particular through the accurate determination of the $K_{\pi 3}$, $K_{\mu 3}$, and $K \to \pi^\circ\gamma\gamma$ decay spectra. Also of interest are the $\pi\pi$ scattering lengths which are obtained from K_{e4} decays.

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A. Quark Physics

The Standard Model (SM) is proving to be an extraordinary success. Every experimental test performed is in accord with SM predictions. As a full fledged theory however, the SM has several conceptual problems. For instance:

1. the SM does not give the values of the masses of the constituent leptons and quarks, or even the order of magnitude;
2. the SM does not provide the three inter-family mixing angles, a priori all values are possible;
3. the SM reveals neither the origin nor the magnitude of the observed CP violation in K° decay.

Thus, every input parameter of the basic quarks of the SM must come from experiments. That is the reason why new particle accelerators such as a *Phi Factory* are needed. We discuss below some of the new data on quark physics that a ϕ factory can provide.

There is another serious shortcoming of the SM – it does not yield a practical model for quark confinement. Free quarks have not been seen in nature, presumably because quarks are permanently confined; therefore, the mass of quarks cannot be determined in a conventional manner. It is possible, using the Lagrangian of Quantum Chromodynamics, to define a theoretical mass-like quantity, the so-called current quark mass. It is known from model calculations [1] that the effects of confinement cancel one other substantially in the ratio of the *current* quark masses. Specifically, this is the case for the following ratio R of quark-mass differences

$$R \equiv (m_s - \hat{m})/(m_d - m_u),$$

with $\hat{m} = \frac{1}{2}(m_d + m_u)$. One may interpret R as the ratio of SU(3) to SU(2) breaking. In Chiral Symmetry the u, d, and s quark masses are zero. In this context, R is the ratio of the "relative" s-quark mass over the "relative" d-quark mass.

It has been stressed by Lane and Weinberg [2] that in any renormalizable theory of strong interactions based on quarks and flavorless gauge bosons, *the only sources of* *isospin* breaking are the d-u quark mass difference and electromagnetic interactions. A recent assessment [3] of experiments pertaining to tests of charge symmetry shows that indeed all known charge-symmetry breaking effects support this sweeping assertion. The results of ten evaluations of the mass-difference ratio R have been summarized in Table I. This table originates from Ref.[3], where the various entries are discussed in detail. The table is based on two measurements of meson-mass splittings in an s-quark and in a b-quark system, two cases of neutral meson mixing, several rates of charge-symmetry violating decays, and three baryon mass splittings. It is heartening that the values of R for the seven determinations that involve mesons is the same, even though they span several classes of measurements. The average value is $R_m = 36 \pm 4$. Together with the value f_m $(m_s - \hat{m}) = 111 \pm 10$ MeV, obtained from seven different meson-multiplet mass splittings [3], this yields $m_d - m_u = (3.1 \pm 0.4)/f_m$ MeV, where f_m is a theoretical coefficient, the mesonic quark-binding factor. The value of f_m may be evaluated using different models; it is in the neighborhood of 1.0, (see Refs. [1 and 3]). The average R value obtained from baryon measurements is $R_b = 45 \pm 3$. This value, together with f_b $(m_s - \hat{m})_b = 163 \pm 15$ MeV, obtained from seven baryon-multiplet mass splittings [3], yields $m_d - m_u = (3.6 \pm 0.4)/f_b$ MeV, where f_b is the baryonic quark-binding factor. This is in good agreement with the mass difference obtained from the analysis of the meson data implying that the mesonic and baryonic quark-binding factors are not very different.

The most precise determinations of R come from neutral meson mixings and from the comparison of rates of rare decays involving charge-symmetry breaking decay modes because in these cases the electromagnetic effects are the smallest. At an e^+e^- collider *with variable energy*, one can accurately measure the excitation function for $\sigma_t(e^+e^- \rightarrow \pi^+\pi^-)$ in the region of the ρ meson to measure $\rho - \omega$ interference. This is particularly suitable to obtain the down-up quark mass difference. Isospin pure neutral states mix because the masses of the up and the down quark are different. Consider the states

$$|\rho^\circ> = \frac{1}{2}\sqrt{2}\,|u\bar{u} - d\bar{d}>$$

and

$$|\omega> = \frac{1}{2}\sqrt{2}\,|u\bar{u} + d\bar{d}> .$$

The hamiltonian

$$H_m = m_d\bar{d}d + m_u\bar{u}u$$

yields

$$<\rho^\circ|H_m|\omega> = (m_d - m_u) \times \tilde{f},$$

where $\tilde{f}$ is a numerical factor that is evaluated with the aid of a model for quark confinement such as the bag model. Calculations [3] indicate that $\tilde{f}$ is close to unity. Shown in Fig. 1 by the dashed line is the production of two pions in e^+e^- collision, calculated without $\rho - \omega$ interference. The ω meson, produced electromagnetically, can be seen, albeit barely, as the little pimple on top of the broad ρ bump. The $\rho - \omega$ interference due to the d-u quark mass difference could be positive and that is indicated by the solid line; for a negative interference, the resulting pattern is given by the long dashed line in Fig. 1. The insert in the picture shows the experimental results [4], which imply that the $\rho - \omega$ interference in e^+e^- production is positive. The numerical value for the mixing is

$$<\rho^\circ|H_m|\omega> = -(2.7 \pm 0.4) \text{ MeV}.$$

The pure electromagnetic mixing is well known from photoproduction experiments

$$<\rho^\circ|H_{em}|\omega> = +(0.43 \pm 0.04) \text{ MeV}.$$

It would be useful to measure the $\pi^+\pi^-$ production at least with a tenfold increased statistics to reduce the error in the χ^2 analysis to the 3% level and thereby improve our evaluation of $m_d - m_u$.

There is another case of meson mixing which is of major importance, namely $\pi^\circ - \eta - \eta'$. This may be studied via the ratio of rare decay rates of the ϕ meson, specifically

$$\phi \to \pi^\circ\gamma, \qquad \text{BR } (1.31 \pm 0.13) \times 10^{-3},$$

$$\phi \to \eta\gamma, \qquad \text{BR } (1.28 \pm 0.06) \times 10^{-2},$$

$$\phi \to \eta'\gamma, \qquad \text{BR unknown, and} < 4 \times 10^{-4}.$$

While $\rho^\circ - \omega$ and $\pi^\circ - \eta$ meson mixings are driven by the difference in mass between the down and up quarks, the situation is quite different for $\omega - \phi$ mixing. That is due, all or in part, to the SU(3) singlet-octet mixing in the vector meson nonet which in turn is reflected in the quark content of the mesons. In the case of ideal octet-singlet mixing, the ϕ meson is a pure $s\bar{s}$ state,

$$|\tilde{\phi}\rangle = |s\bar{s}\rangle.$$

If there is some admixture of light quarks we can represent the physical ϕ as

$$\begin{aligned} |\phi\rangle =& \alpha_1|s\bar{s}\rangle + \alpha_2|u\bar{u} + d\bar{d}\rangle/\sqrt{2} + \alpha_3|u\bar{u} - d\bar{d}\rangle/\sqrt{2} \ = \\ & \alpha_1|\tilde{\phi}\rangle + \alpha_2|\tilde{\omega}\rangle + \alpha_3|\tilde{\rho}^\circ\rangle, \end{aligned}$$

where $\tilde{\omega}$ and $\tilde{\rho}^\circ$ indicate the pure SU(2) ω and ρ states. The dominant decay of the ω is to 3π. If the OZI rule holds the decay $\phi \to 3\pi$, which has a BR of (1.9±1.1)%, proceeds via the $\tilde{\omega}$ component. Complications for the experimental as well as the theoretical analysis are due to the decay $\phi \to \rho\pi$, which has a BR of 13%; our best estimate is that α_2 is less or equal than 0.15. The decay $\phi \to 2\pi$, which has a BR of $(8\pm5) \times 10^{-5}$, could proceed via $\tilde{\rho}$ admixture. In that case the data indicates that $\alpha_3 << \alpha_2$. A recent analysis, [5], which includes also the appropriate phase space considerations for the different ϕ decay modes, shows that the data is still inconclusive as to the numerical value of α_1 and α_2. Achasov et al., [5] conclude their article with a plea for new data: "...there is an urgent need for making new studies with high statistics on a *special* *machine* of the full set of reactions $e^+e^- \to \pi^+\pi^-\pi^\circ$, $\pi^\circ\gamma$, K_LK_S, $n\gamma$ and $\pi^+\pi^-$ in the energy region $\sqrt{s} = 700 - 1050$ MeV." A ϕ *factory* would play a pivotal role in determining the quark structure of the ϕ and thereby investigate the validity of the OZI rule. Is the violation that seems apparent in $\phi \to 3\pi$ and $\pi^\circ\gamma$ decay genuine or merely a manifestation of the light-quark content of the ϕ?

The phi factory is bound to yield a new, high precision value for the ratio

$$r = \Gamma(\phi \to K_LK_S)/\Gamma(\phi \to K^+K^-).$$

The current experimental value is $r = 0.69 \pm 0.03$. Charge symmetry implies that the corrected ratio, r_c, has the value 1.0 with $r_c = r \times f \times c \times \tilde{m}$, where f is the phase space factor (1.54), from which we obtain $r \times f = 1.06 \pm 0.04$; c is the Coulomb correction for the K^+K^- system, and $\tilde{m}$ is a correction for the down-up quark mass difference. One of the reasons for this interest in the accurate value for r is that it enables one to probe the Coulomb corrections in meson decays which depend critically on the "radius" of the resonance. Pilkuhn [6] recommends $c = 0.98$ if the "radius" is 0.75 fermi and $c = 1.05$ if the "radius" is zero. A different approach to the Coulomb correction has recently been recommended by Atwood and Marciano [7] in connection with the evaluation of the ratio

$$\Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^\circ B^\circ).$$

There is a special interest [8] in a measurement of the decay $\phi \to (a_\circ\gamma)$ and $(f_\circ\gamma)$ via measurements of the decay rates and spectra for $\phi \to \pi\pi\gamma, \phi \to \pi\eta\gamma$ and $\phi \to K^+K^-\gamma$. This will help illucidate the possible formation of 0^{++} mesonic states such as glueballs, KK molecules or $q^2\bar{q}^2$ states [8].

B. K-Decay Physics at a ϕ Factory

A phi factory is the best and only practical factory for *tagged* monochromatic K_S° and K_L° mesons. A few of the K_L° and none of the K_S° decay modes have been studied in detail while their physics harvest is very rich. The importance of a phi factory lies in the opportunity for a new generation of neutral K-meson decay measurements based on the availability of abundant, clean, tagged K-mesons. The examples discussed below are selected from a detailed survey presented in a recent report [9].

The main advantages for K decay studies which are expected to be offered by a ϕ factory are:

i) the extremely good background conditions;

ii) the possibility of tagging the kaon species one wants to study, for example, the decay mode $K^{\pm} \to \mu^{\pm}\nu$ may be used for tagging $K^{\mp}$, the decay mode $K_S \to \pi^+\pi^-$ to tag K_L, and $K_L \to \pi\mu\nu$ for K_S;

iii) the possibility of imposing powerful kinematical constraints from knowing the kaon energies, which will allow an almost background-free reconstruction of the decay vertex.

Combined with a high performance detector, with a large (4π) acceptance and uniform resolution which is essential for measuring the Dalitz plots, these qualifications should allow the performing of K-decay experiments with improved, or at least different systematics, compared to the conventional kaon beams.

A ϕ factory therefore provides very interesting opportunities for performing accurate measurements of K decays with good statistics. Extremely favorable, if not unique, is the possibility of observing decays of tagged, monochromatic K_L and of K_S-mesons, in particular to study decays with a photon in the final state. Especially important in this respect is the availability of a pure K_S beam with a well-defined energy, which is extremely difficult to obtain from a conventional fixed target source.

The available statistics are determined by the luminosity of the machine, which we expect to be in the range between 10^{32} and $10^{33} s^{-1} cm^{-2}$. Correspondingly, with an e^+e^- cross section at the ϕ peak of 4.4 10^{30} cm^2, with a luminosity of $5 \times 10^{32} s^{-1} cm^{-2}$, a detector acceptance of 3π sterad and a useful detector volume of 8 m^2, we expect the following rates for events tagged by condition ii) above per calendar year:

$$5 \times 10^9 \ K^{\pm}/\text{year},$$

$$1 \times 10^9 \ K_S/\text{year},$$

$$2 \times 10^9 \ K_L/\text{year}.$$

These numbers do not include the efficiencies of the detectors. With such statistics we can foresee significant progress in the following cases:

i) Accurate studies of K decays with branching ratios as small as $10^{-6} - 10^{-7}$, including detailed decay spectra.

ii) Improved limits on rare (but not ultrarare) K decay modes, with sensitivities down to 10^{-9}. This would be particularly important in the case of K_S, for which limits on the specific modes are either poor or non existent.

On the theoretical side, this program would allow a significant test of the current theoretical description of weak decays. This involves hadronic matrix elements of the effective electroweak transition Hamiltonian, which is expressed at the constituent level by Feynman diagrams involving quarks (and leptons). While this "short-distance" quark transition amplitude is calculated in perturbation theory in terms of standard model parameters such as quark masses and mixing angles, the hadronic matrix elements represent the effect of (nonperturbative) strong interaction physics. In addition, in several cases there are the so-called "long-distance" contributions, due to transitions proceeding directly through hadronic degrees of freedom, which are determined also by quark confinement dynamics. The classical example is $K_L \to \gamma\gamma$ through $K_L \to (\pi^\circ, \eta, \eta') \to \gamma\gamma$.

The current theoretical framework for describing kaon decays is based on the general notion of an approximate, spontaneously broken chiral $SU(3)_L \times SU(3)_R$ symmetry of QCD. In the limit of this symmetry, which occurs for zero light quark masses, the π,

K and η would be massless (i.e. Goldstone bosons of the symmetry). Since Goldstone bosons have interactions which vanish when mass and energy are zero, one can expand the transition amplitudes involving pions and kaons with finite mass and small momenta, such as those relevant to K decays. The coefficients of this expansion are strongly constrained by the symmetry, and this leads to a general description of low-energy pion and kaon interactions in terms of a few physical constants.

In practice such an expansion can be obtained by means of an effective interaction chiral Lagrangian, in terms of π, K and η fields instead of quark fields. This incorporates the properties of the strong interactions mentioned above, so as to reproduce in lowest order the classical results of soft-meson theory derived from current-algebra and PCAC. Such a Lagrangian is then used as a computational tool to quantitatively evaluate electroweak transition amplitudes. In particular, the expansion in the meson masses and momenta is determined by higher order Feynman diagrams in this effective chiral Lagrangian such as the chiral perturbation formulas of Gasser and Leutwyler, Ref. [10]. In this way one can predict a large variety of K decays, accounting for strong interaction effects in a rather general way, in terms of a reduced number of coupling constants which must be taken from experiment. Many important aspects are not known such as incorporating the vector mesons in the chiral Lagrangian description.

As an alternative way to exploit the general framework offered by chiral symmetry, it has been proposed to implement unitarity directly for the lowest order amplitude. This can lead to a description of K decays, which is both economical and accounts for important phenomenological properties of strong interactions. Truong [11] has considered the cases of $K \to 2\pi$ and $K \to 3\pi$ in this context.

At the present stage, numerous predictions of the formalism sketched above are not yet tested. A systematic study of K decays with good accuracy would allow a decisive test of the theoretical nonperturbative framework suggested by chiral symmetry, and thus would test the basic principles underlying QCD in addition to the electroweak forces of the standard model.

In what follows, we briefly discuss those kaon decays for which the ϕ factory can contribute in a significant way to the physics program outlined above.

Semileptonic decays

(a)K_{l3}. The rate of K_{e3} decay provides the most precise determination of the Kobayashi-Maskawa quark mixing matrix element V_{us}. There are two different decays:

$$K_{e3}^{+} \equiv K^{+} \to \pi^{0} e^{+} \nu, \qquad \Gamma(K_{e3}^{+}) = 3.89 \times 10^{-6}\ \mathrm{sec}^{-1},$$

$$K_{e3}^{0} \equiv K_{L} \to \pi^{-} e^{+} \nu, \qquad \Gamma(K_{e3}^{0}) = 3.72 \times 10^{-6}\ \mathrm{sec}^{-1}.$$

The reported error in $\Gamma(K_{e3}^{+})$ is $\pm 1\%$, whereas the error in $\Gamma(K_{e3}^{0})$ is difficult to assess since the quoted value comes from a constrained fit that is not internally consistent. The error is at least 3%. The K_{e3}^{+} and K_{e3}^{0} rate difference may be reconciled by a correction for the mass difference between the u and the d quarks given by Leutwyler and Roos [12]. This results in:

$$V_{us} = 0.2200 \pm 0.0013 \quad \text{from } K_{e3}^{+},$$

$$V_{us} = 0.2188 \pm 0.0020 \quad \text{from } K_{e3}^{0}.$$

This method is theoretically superior to the one that uses baryon decays.

V_{us} enters, together with V_{ud} and V_{ub}, in the fundamental test of the unitarity of the KM matrix with three generations. At present we have

$|V_{ud}| = 0.9742 \pm 0.0011$ (average of $0^{+} \to 0^{+}\beta$ decays),

$|V_{us}| = 0.2197 \pm 0.0019$ (average of $K_{\ell 3}$ and hyperon decays),

$$|V_{ub}| < 0.01,$$

and yields

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0023.$$

This is discussed in Ref. [13]. Since the determination of V_{ud} is expected to be improved, it is desirable to also improve the knowledge of V_{us}, by directly measuring $\Gamma(K^0_{e3})$ in a tagged K_L beam to a precision of e.g. 1%.

Another interesting aspect is the measurement of the form factors of $K_{\mu 3}$ decay. For example, of great importance in the context of chiral symmetry is the test of the Callan-Treiman relation, which enables one to predict the value of the slope of the scalar form factor to be $\lambda_o = +0.017 \pm 0.004$ including finite pion mass corrections [14]. The current values quoted by the Particle Data Tables are $\lambda_o = +\ 0.004\ \pm 0.007$ from K^+_{e3} and $\lambda_o = +\ 0.025\ \pm 0.006$ from K°_{e3}. Present data from $K^+_{\mu 3}$ show significant deviations from this relation and disagree in general from $K^\circ_{\mu 3}$. In addition, the data on K_L are not all compatible with each other; another generation of experiments is needed to improve this situation. Related to this issue is the measurement of the muon longitudinal polarization. There is appreciable disagreement among various experiments.

(b) K_{l4}. Similarly to the physics of the preceding case, are the $K \rightarrow \pi\pi e\nu_e$ and $K \rightarrow \pi\pi\mu\nu_\mu$ decays, which occur with a branching ratio $(2-6) \times 10^{-5}$. They are of great interest with regard to the chiral Lagrangian realization of QCD. Indeed a precise determination of the vector and axial-vector form factors would allow a decisive test of this theoretical approach [15,16]. Good $K_{\ell 4}$ data would lead to an improved determination of the low-energy $\pi - \pi$ phase shifts. This is the cleanest process to determine the $\pi\pi$ scattering length and provides a significant test of chiral symmetry. Only a limited number of events (a few tens) have been collected so far for the K_L mode, so there is a good possibility to fill this gap using the tagged K_L beams available at a ϕ factory.

Radiative leptonic and semileptonic decays

(a) $K_{\ell 2\gamma}$. The "structure dependent" photon emission amplitude for $K \rightarrow e\nu\gamma$ has a distinguished role in the context of the chiral Lagrangian description of K decays. Also, the knowledge of this amplitude is necessary to make the $O(\alpha)$ correction of the leptonic ratio

$$\frac{\Gamma(K \to e\nu_e)}{\Gamma(K \to \mu\nu_\mu)} = (2.42 \pm 0.11)\ 10^{-5},$$

where the $K_{\ell 2\gamma}$ amplitude represents the main theoretical uncertainty. As is well known, this ratio represents a stringent test of $\mu - e$ universality and of the V-A charged weak currents in the strangeness changing weak interaction. The structure-dependent amplitude of $K \to e\nu\gamma$ depends on a vector plus an axial-vector form factor, which can be measured from the upper range of the photon spectrum, where it can be distinguished from the bremsstrahlung. The present theoretical determinations of these form factors are rather poor [17]. The same is true for the process $K \to e\nu e^+ e^-$, which depends on a third form factor, which is also very badly determined, so that it is practically impossible to test the theoretical predictions. It is desirable to improve on these measurements, possibly at a ϕ factory, if it turns out that the dangerous K_{l3} background can be kept under control.

(b) $K_{\ell 3\gamma}$. The decays $K \to \pi e\nu\gamma$ are also very appealing theoretically, since the structure-dependent (non-bremsstrahlung) amplitude can be predicted unambiguously in the chiral symmetry framework. Essentially, this is done in terms of the same parameters as the preceding case, plus the ratio f_K/f_π [18]. A good measurement would be a challenging test of the theory.

Nonleptonic K decays with photons or lepton pairs in the final state

These decays involve the nonleptonic $\Delta S = 1$ Hamiltonian and have branching ratios below 10^{-4}. Historically, they have been considered in the context of the GIM suppression [19] of flavor-changing neutral current transitions by Gaillard and Lee [20]. Besides probing the standard model at the one-loop level, these transitions provide sensitive tests of the non perturbative approaches used in estimating the hadronic matrix elements of the electroweak hamiltonian. For this reason they have recently been reconsidered with much interest in the framework of the chiral Lagrangian formalism [21].

The decays belonging to this category, and their predicted branching ratios in chiral perturbation theory, are given in Table 2. Looking at this, we see that there are some cases in which the potential of the ϕ factory should allow significant progress. These are:

(a) $K_L \rightarrow \pi^0\gamma\gamma$. This decay is predicted unambiguosly in the chiral Lagrangian approach in terms of known parameters. In particular, the spectrum of the invariant mass of the photon pair is characteristic for this type theory [22]. From the knowledge of this process, one can estimate the CP-conserving two-photon exchange contribution to the decay $K_L \rightarrow \pi^0 e^+ e^-$ (which cannot be measured at a ϕ factory for reasons of luminosity); this allows the extraction of the CP-violating one-photon exchange contribution to this process. Therefore, it opens the interesting possibility of studying CP violation, once the transition $K_L \rightarrow \pi^0 e^+ e^-$ will be observed. The decay $K_L \rightarrow \pi^0\gamma\gamma$ has been recently observed; the branching ratio is given in Table 2 (actually that value refers to decays with invariant two-photon mass larger than 280 MeV). Although the experimental result is somewhat higher than the theoretical prediction from chiral lagrangians, it is encouraging that the two-photon distribution is in accord with that approach. Also, the value of the branching ratio does not seem to obscure the CP-violating amplitude in $K_L \rightarrow \pi^0 e^+ e^-$. Finally, we notice that no experimental limit exists on the analogous decay $K_S \rightarrow \pi^0\gamma\gamma$.

(b) $K^\pm \rightarrow \pi^\pm\gamma\gamma$. Although not competitive with standard $K^\pm$ beams from the point of view of statistics, the *phi* factory is perhaps useful for this kind of two-photon process because good photon detectors are likely available. These decays have the same theoretical interest as the preceding neutral kaon decays, namely the unambiguous determination in the chiral Lagrangian approach (in particular of the $\gamma\gamma$ spectrum), and the relevance to the inclusion of vector mesons, and of vector meson dominance.

(c) $K_L \rightarrow \gamma e^+ e^-$. Accurate experimental determinations of this decay (and also of $K_L \rightarrow \mu^+\mu^-$) seem feasible at a ϕ factory, in particular of the Dalitz plot, which has some interest for distinguishing among various theoretical predictions. Such an analysis has been recently started [23]. No limit on the process $K_S \to \gamma\, l^+l^-$ exists, which is an interesting decay for the analogous reasons. A few events of the e^+e^- mode could be observed at a ϕ factory.

(d) $K \to \pi\pi\gamma$. These decays are determined by a bremsstrahlung amplitude, which can be reliably estimated in terms of $K \to \pi\pi$, and by a "direct emission" amplitude. The latter allows a test of the validity of the $\Delta I = 1/2$ rule outside the framework of purely hadronic weak processes. Also, $K \to \pi\pi\gamma$ decays are sensitive to nonperturbative model estimates of hadronic matrix elements; in particular, they should allow the clarification of the role of vector mesons in chiral Lagrangians [10]. Therefore, these decays are of interest at a ϕ factory for experiments with good statistics

Conclusions

The kaon decays introduced in the preceding sections provide a significant window of important physics for a facility such as the ϕ factory. Of fundamental importance is the verification of the realizations of the electroweak Hamiltonian, in particular the one based on chiral symmetry of strong interactions. Due to the possibility of tagging and of imposing kinematical constraints, the ϕ factory is certainly a competitive facility for all K_S decays and the K_L decays with photons and/or lepton pairs in the final state. In the case of some selected decays of charged kaons, the experimental facilities may be favorable for an accurate study.

References

[1] J. Gasser and H. Leutwyler, Physics Reports **C87**, 77 (1982).

[2] K. Lane and S. Weinberg, Phys. Rev. Lett. **37**, 717 (1976).

[3] G.A. Miller, B.M.K. Nefkens, I. Slaus, Physics Reports (in press).

[4] L.M. Barkov et al., Nucl. Phys. **56B2**, 365 (1985).

[5] N.N. Achasov et al., INP preprint 89–115, Novosibirsk; also Phys. Lett. B **233**, 474 (1989).

[6] H. Pilkuhn, Nucl. Phys. **B82**, 365 (1974).

[7] D. Atwood and W.J. Marciano, Phys. Rev. D **41**, 1736 (1990).

[8] N.N. Achasov and V.N. Ivanchenko, Nucl. Phys. **B315**, 465 (1989).

[9] R. Battiston, D. Cocolicchio, G.L. Fogli, N. Paver, in *Status and Perspectives of K Decay Physics*, CERN–TH 5664/90 preprint.

[10] J. Gasser and H. Leutwyler, Nucl. Phys. **B250**, 465 (1985).

[11] T.N. Truong, Phys. Lett. **B207**, 495 (1988).

[12] H. Leutwyler and M. Roos, Z. Phys. C - Particle and Fields **25**, 91 (1984).

[13] W.J. Marciano and A. Sirlin, Brookhaven preprint **BNL–39**, 658 (1987).

[14] J. Gasser and H. Leutwyler, Nucl. Phys. **B250**, 517 (1985).

[15] E. Schabalin, Sov. J. Nucl. Phys. **49**, 365 (1989).

[16] N. Bijnens et al., Nucl. Phys. **B337**, 635 (1990).

[17] P.Depommier, in *Proceedings of the Workshop on Production and Decay of Light Mesons, Paris, 1988*, edited by P. Fleury, (World Scientific (Singapore) p. 135.

[18] B.R. Holstein, Phys. Rev. D **41**, 2829 (1990).

[19] S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D. **2**, 1285 (1970).

[20] M.K. Gaillard and B.W. Lee, Phys. Rev. D **10**, 897 (1974).

[21] G. Ecker, A. Pich, and E. de Rafael, Phys. Lett. **B237**, 481 (1990).

[22] G.D. Barr et al., Phys. Lett. **B242**, 523 (1990).

[23] G.D. Barr et al., Phys. Lett. **B240**, 283 (1990).

TABLE I

Values of the ratio $R \equiv (m_s - \hat{m})/(m_d - m_u)$ based on different CSB measurements from Ref. [2]

Source	R	Ref.	Source	R	Ref.
$K^+ - K^\circ$	43±4	A-1,2	$p - n$	51±10	A-1,2
$D^+ - D^\circ$	33±10	A-1	$\Sigma^+ - \Sigma^-$	43±4	A-1,2
$\rho - \omega$ mixing	39±5	A-1	$\Xi^\circ - \Xi^-$	42±6	A-1,2
$\psi' \to \psi\pi^\circ/\psi\eta$	30±4	A-1,3			
$\eta \to 3\pi^\circ/\pi^+\pi^-\pi^\circ$	38±9	A-4			
$\eta' \to \eta 2\pi^\circ/3\pi^\circ$	35±9	A-5,6			
$\eta \to 3\pi^\circ$	54^{+110}_{-24}	A-7			
	Average: $R_m = 36 \pm 4$			Average: $R_b = 45 \pm 3$	

R_m is the average of the meson based determination; the baryon dependent average is R_b.

Reference

[A-1] J. Gasser and H. Leutwyler, Physics Reports **C87**, 77 (1982).

[A-2] S. Weinberg in **A Festschrift** for I.I. Rabi (Trans. N. Y. Acad. of Sci.) **38**, 185 (1977).

[A-3] B.L. Ioffe and M.A. Shifman, Phys. Lett. **95B**, 99 (1980).

[A-4] LL. Ametller et al., Phys. Rev. D **30**, 674 (1984).

[A-5] D.J. Gross, S. B Treiman and F. Wilczek, Phys. Rev. D **19**, 2188 (1979).

[A-6] F. Binon et al., Sov. J. Nucl. Phys. **39**, 903 (1984).

[A-7] J.M. Cline, Phys. Rev. Lett. **63**, 1338 (1989).

Table 2. Rare decay modes of K_S, K_L and $K^{\pm}$. All entries are from Ref. [9].

Decay mode	Theory	Experiment
$K_S \to \gamma\gamma$	2×10^{-6}	$(2.4 \pm 1.2) \times 10^{-6}$
$K_S \to \gamma\, e^+e^-$	3.2×10^{-8}	
$K_S \to \gamma\mu^+\mu^-$	7.5×10^{-10}	
$K_L \to \gamma\gamma$	$[10^{-4}]$	$(4.9 \pm 0.4) \times 10^{-4}$
$K_L \to \gamma\, e^+e^-$	9.1×10^{-6}	$(1.7 \pm 0.9) \times 10^{-5}$
$K_L \to \gamma\mu^+\mu^-$	2.3×10^{-7}	$(2.8 \pm 2.8) \times 10^{-7}$
$K_L \to \pi^0\gamma\gamma$	6.8×10^{-7}	$(2.1 \pm 0.6) \times 10^{-6}$
$K^+ \to \pi^+\gamma\gamma$	5.8×10^{-7}	$< 1.0 \times 10^{-6}$
$K_S \to \pi^0\gamma\gamma$	3.3×10^{-8}	
$K^{\pm} \to \pi^{\pm}e^+e^-$	(input)	$(2.7 \pm 0.5) \times 10^{-7}$
$K^{\pm} \to \pi^{\pm}\mu^+\mu^-$	6.1×10^{-8}	$< 2.3 \times 10^{-7}$
$K_S \to \pi^0 e^+e^-$	$(5\text{–}50)\times 10^{-10}$	$< 4.5 \times 10^{-5}$
$K_S \to \pi^0\mu^+\mu^-$	$10^{-9} - 10^{-10}$	
$K_L \to \pi^+\pi^-\gamma\,\|_{IB}$	1.45×10^{-5}	$(1.52 \pm 0.16) \times 10^{-5}$
$K_L \to \pi^+\pi^-\gamma\,\|_{DE}$	$(7.0 - 1.19) \times 10^{-5}$	$(2.89 \pm 0.28) \times 10^{-5}$
$K_S \to \pi^+\pi^-\gamma\,\|_{IB}$	2.41×10^{-3}	$(1.85 \pm 0.10) \times 10^{-3}$
$K_S \to \pi^+\pi^-\gamma\,\|_{DE}$	2.02×10^{-7}	$< 6 \times 10^{-5}$
$K^+ \to \pi^+\pi^0\gamma\,\|_{IB}$	2.88×10^{-4}	$(2.55 \pm 0.16) \times 10^{-4}$
$K^+ \to \pi^+\pi^0\gamma\,\|_{DE}$	$(1.05 - 1.94) \times 10^{-5}$	2×10^{-5}

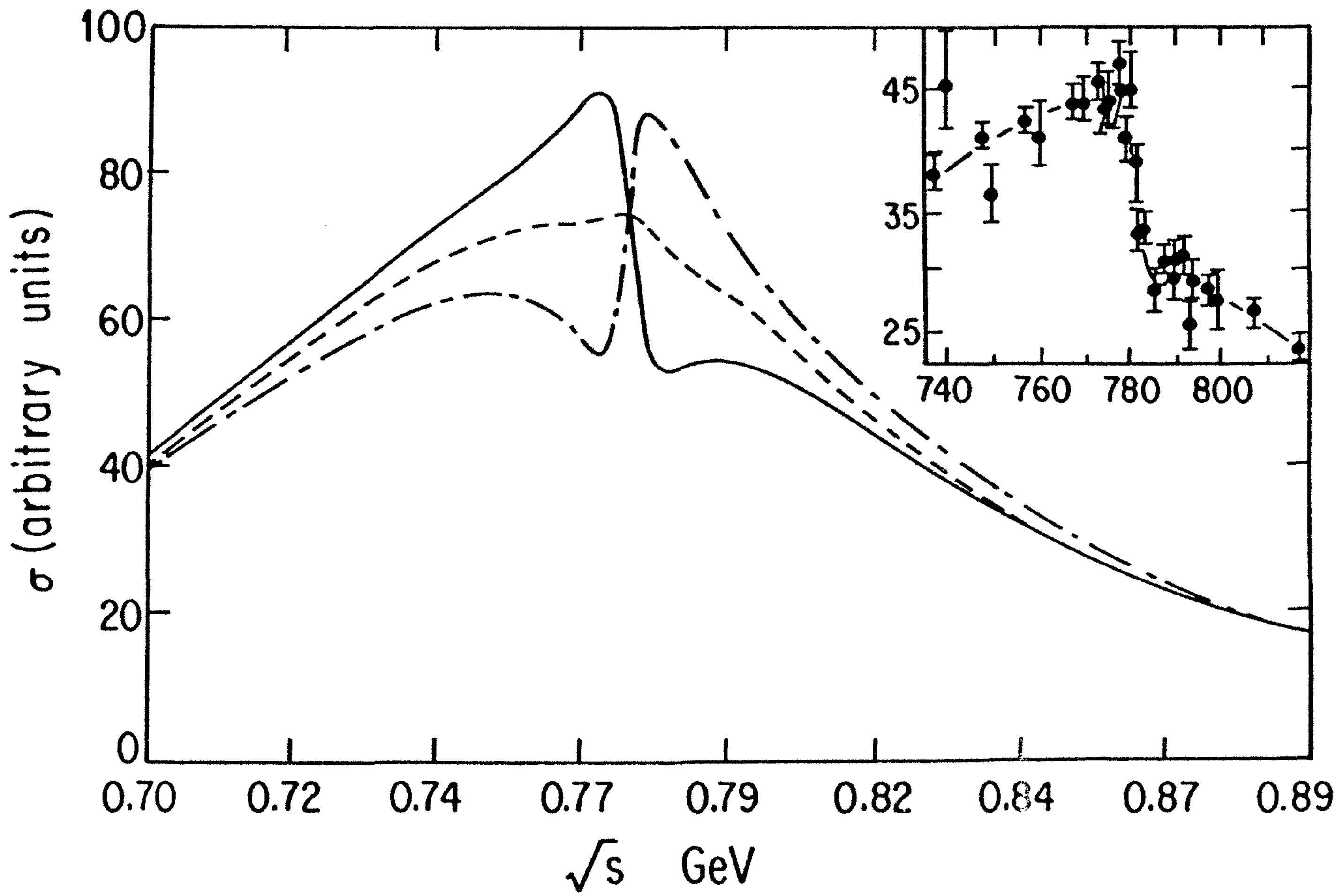

Fig. 1 $\rho - \omega$ mixing observed in the energy dependence of $\sigma(e^+e^- \to \pi^+\pi^-)$. The short dashed line shows the pure electromagnetic processes, $\sigma(e^+e^- \to \rho^\circ \to \pi^+\pi^-)$ and $\sigma(e^+e^- \to \omega \to \pi^+\pi^-)$ without $\rho - \omega$ mixing. The solid line shows the case of $\rho - \omega$ mixing with a positive matrix element, and the dot-dashed line for a negative matrix element.

Fig. 1