CP VIOLATION IN THE K SYSTEM AND RARE DECAYS

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A quick review of CP violation and rare decays in the kaon system is presented. Both recent results and future projects in this active field are discussed.

1 What have we been learning from kaons lately?

The kaon system has been central in the shaping of the Standard Model. Its success is partly due to the fact of being the simplest one (*e.g.* in terms of limited number of important decay modes, relatively large lifetimes and lifetime differences) exhibiting all the subtleties required to support the observability of all kinds of CP violation. After such a long and successful career, the question arises of whether kaons can still provide important information on some fundamental issues in physics. We will see that this is indeed the case.

1.1 Direct CP violation

Among the most interesting HEP results of recent years, the final confirmation of the existence of direct CP violation in the weak decay of neutral kaons has an important place. The final result from NA48 [1] and the result from KTeV [2] on half of the collected statistics :

$$Re(\epsilon'/\epsilon) = (14.7 \pm 2.2) \cdot 10^{-4} \quad \text{(NA48 final)} \tag{1}$$
$$Re(\epsilon'/\epsilon) = (20.7 \pm 2.8) \cdot 10^{-4} \quad \text{(KTeV 1997 data)} \tag{2}$$

finally prove beyond any doubt that the ϵ' parameter describing direct CP violation is different from zero, confirming the indication of NA31 [3] (see fig. 1 and [5] for small corrections). These results are the conclusion of a long-standing endeavor, involving rather refined and varied experimental approaches on the two sides of the Atlantic [4]. This situation is still expected to improve

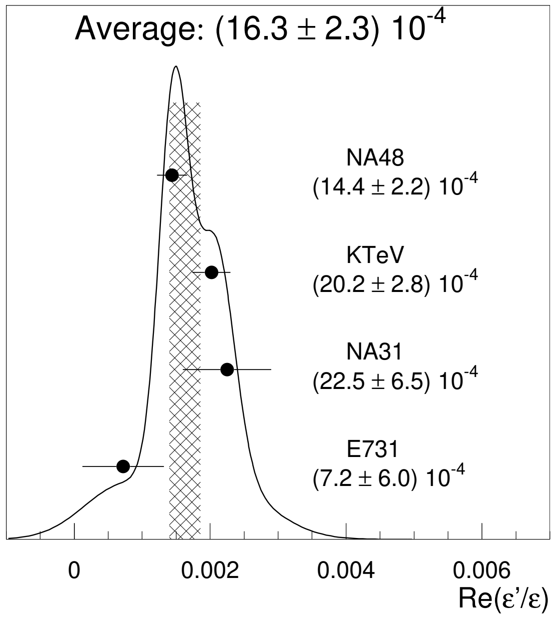

Figure 1: Ideogram of recent $\Re(\epsilon'/\epsilon)$ results. The error for the average was inflated according to the PDG procedure to take into account the unsatisfactory agreement of the data points. The significance is above 7 σ.

with additional KTeV data, and hopefully when a measurement from KLOE at the DAΦNE ϕ-factory will become available. Its significance is not spoiled by the fact that, despite huge efforts, important theoretical difficulties at the moment still hinder the precise computation of the SM prediction for this parameter: the existence of direct CP violation confirmed qualitatively the CKM paradigm by disproving alternative *Ansätze*, leading CP violation out of the corner of $K^0\bar{K}^0$ mixing, as confirmed just a few years later by the B-factories. Intense theoretical activity (mainly lattice QCD) is expected to continue, with the goal of bringing this 15% measurement to be a quantitative test of the Standard Model.

1.2 K_L decays

As a byproduct of the high K_L flux in direct CP violation experiments, several other interesting results were achieved. Precise measurements of the semileptonic charge asymmetry on samples of some 10^8 events were performed [8]:

$$\delta_L(e) = (3.32 \pm 0.07) \cdot 10^{-3} \tag{3}$$

leading to a more precise determination of the ϵ parameter, important to test lattice QCD computations. Several rare decays of K_L were also measured with high precision by these experiments, and are of high value to test and constrain Chiral Perturbation theory.

A new manifestation of indirect CP violation was measured as a large ($\approx$ 14%) asymmetry between the decay planes in the rare decay $K_L \to \pi^+\pi^-e^+e^-$. The measured asymmetry [9 10] nicely agrees with theoretical expectations, while no effect is detected [10] in the same decay for K_S, as expected.

1.3 K_S decays

Some progress toward the measurement of indirect CP violation in K_S decays was made: searches for $K_S \to \pi^0\pi^0\pi^0$ decays were performed both in NA48, looking for the $K_S - K_L$ interference close to the target, and by KLOE, exploiting its pure K_S beam. The KLOE preliminary result [11] (based on 450 pb^{-1} of integrated luminosity) is

$$BR(K_S \to \pi^0\pi^0\pi^0) < 2.1 \cdot 10^{-7} \quad (90\%\,\mathrm{CL}) \tag{4}$$

This result, while still 2 orders of magnitude above the SM prediction, improves the test for indirect CPT violation. Another result from KLOE is the first preliminary measurement of the K_S semileptonic charge asymmetry [11]:

$$\delta_S(e) = (-2 \pm 9 \pm 6) \cdot 10^{-3} \tag{5}$$

whose precision is however still far from what is needed for a CPT test by comparison to $\delta_L(e)$. Other recent results in rare K_S decays will be discussed in the following.

1.4 Lepton flavour violation and T violation

The intense activity in past years on searches for lepton flavour violation in rare kaon decays led to rather stringent limits [6]. Further progress is hindered not only by fluxes but also by backgrounds; moreover, such investigations seem no longer very competitive with experiments in the muon sector, except for specific models. No new dedicated experiments are planned, although more results are still expected as a byproduct of future high-flux enterprises.

Time-reversal violation was measured for the first time by CPLEAR [7], and its magnitude is consistent with the measured indirect CP violation, when CPT is imposed. A window of opportunity still exists for the search of T-odd correlations such as the transverse muon polarization in $K^+ \to \pi^0\mu^+\nu$ or $K^+ \to \mu + \nu\gamma$ decays, for which the Standard Model effect induced by final-state interactions is very small. The most recent experiment is KEK E246, using stopped kaons, which measured

$$P_T(\mu) = (-1.7 \pm 2.3 \pm 1.1) \cdot 10^{-3} \tag{6}$$

2 Ongoing experiments

2.1 CP violation

A search for direct CP violation in the decays of charged kaons is being carried on by the NA48/2 experiment, which took data in 2003 and 2004 aiming at a precision comparison of the Dalitz plot distributions for $K^\pm$ decays to 3 π. With a sample in excess of $2{\cdot}10^9$ $K^\pm \to \pi^\pm\pi^+\pi^-$ decays, and a good cancellation of systematic effects due to the use of an unique simultaneous $K^\pm$ beam coupled with frequent reversal of the beam and detector magnetic fields, a measurement of the asymmetry in the linear slope parameters at the level of $2 \cdot 10^{-4}$ can be achieved. Previous experiments reached precisions of a few 10^{-3}, and while the Standard Model effect is estimated to be 1 order of magnitude below the experimental sensitivity, enhancements are possible in new physics models. The OKA experiment at Protvino, in preparation, should also address the same issue with (alternating) RF-separated beams.

2.2 The Cabibbo angle

The interest in a precise measurement of V_{us}, the Cabibbo angle, was raised recently by an apparent violation of CKM matrix unitarity at the 2.2 σ level. Errors due to V_{ud} and V_{us} being similar, this called for a better measurement of V_{us}: the best precision is obtained by the BR of semileptonic K decays. Several new results were obtained recently: both E865 at Brookhaven and NA48/2 at CERN measured K^+ decays, KTeV at FNAL, NA48 and KLOE measured K_L decays, and KLOE also measured K_S decays. While these measurements are often intertwined

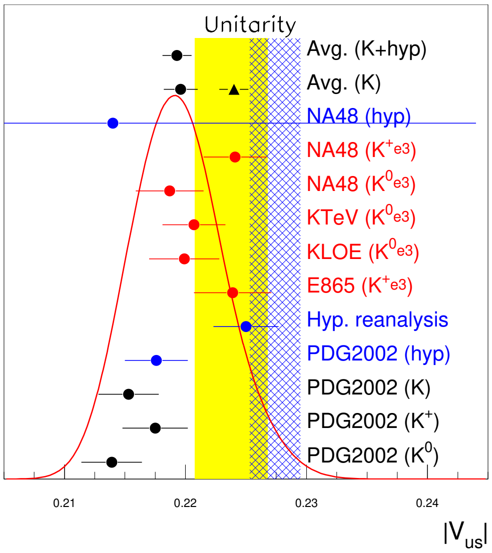

Figure 2: Ideogram of recent results on $|V_{us}|$. The most recent theoretical normalization factors are used to translate the measured semileptonic kaon branching ratios to the magnitude of the mixing angle; the two unitarity vertical bands correspond to different theoretical approaches.

due to the use of common input, the effect has been somewhat reduced, both due to new data and improvements in the theory (see fig. 2). More detailed analysis on both fronts is required to obtain a precise statement.

2.3 $\pi\pi$ interactions

Among the parameters of QCD which are predicted to best accuracy (2%) is the scattering length a_0^0 for two-pions with $L = I = 0$. Such parameter can be extracted from the form factors of $K^\pm \to \pi^+\pi^-e^\pm\nu$ (K_{e4}) decays. A 6% measurement was obtained by the BNL E865 experiment with $4 \cdot 10^5$ decays; NA48/2 plans to obtain a better result with more than 10^6 events. A different approach is also being pursued in NA48/2: the effect of $\pi^+\pi^-$ scattering can also be seen in a distortion of the phase space distribution of $K^\pm \to \pi^\pm\pi^0\pi^0$ when it proceeds through an intermediate $\pi^\pm\pi^+\pi^-$ state [12]. This new technique appears promising and capable of reaching a high level of precision. Still, for once, experiments are not yet a match for the excellent theoretical precision on this parameter.

3 A unique window on flavour physics

The present experimental information on the unitarity triangle, which aims at over-constraining the CKM picture of flavour physics to test it, only comes from double flavour-changing processes (mixing, mass differences and mixing-induced CP asymmetries). $\Delta F = 1$ processes, with a different sensitivity to new physics, are promising tools to give qualitatively new input, provided that the theoretical uncertainties linked to non-perturbative QCD effects which usually plague hadron physics can be kept under control. This turns out to be true for a set of flavour-changing neutral current K decays in which the tree Standard Model contribution is heavily suppressed by several effects: $K \to \pi\ell\overline{\ell}$ (ℓ being a lepton).

The focus of kaon physics is now turning to such class of ultra-rare decays which share several important theoretical advantages: their semi-leptonic nature allows the matrix element to be obtained directly from $K_{\ell 3}$ data, and short-distance (perturbative) physics dominates, therefore

Table 1: Standard Model predictions and experimental information on $K \to \pi\ell\bar{\ell}$ decays.

Mode	BR (theory vs. experiments)	Notes
$K_L \to \pi^0 e^+ e^-$	theory (SM): $(3.7 \pm 1.0) \cdot 10^{-11}$ [or $(1.7 \pm 0.6) \cdot 10^{-11}$ - disfav.] exp: $< 2.8 \cdot 10^{-10}$ FNAL KTeV	CPC + $\mathrm{CPV_{ind}}$ + $\mathrm{CPV_{dir}}$ [$\mathrm{CPV_{dir}} = 30 - 50\%$], $e^+e^-\gamma\gamma$ bkg. δBR $\sim 10\%$
$K_L \to \pi^0 \mu^+ \mu^-$	theory (SM): $(1.5 \pm 0.3) \cdot 10^{-11}$ [or $(1.0 \pm 0.2) \cdot 10^{-11}$ - disfav.] exp: $< 3.8 \cdot 10^{-10}$ FNAL KTeV	CPC + $\mathrm{CPV_{ind}}$ + $\mathrm{CPV_{dir}}$ [$\mathrm{CPV_{dir}} = 10 - 30\%$], δBR $\sim 10\%$
$K^+ \to \pi^+ \nu\overline{\nu}$	theory (SM): $(8.0 \pm 1.0) \cdot 10^{-11}$ exp: $(1.47^{+1.30}_{-0.89}) \cdot 10^{-10}$ 3 events (bkg 0.45) BNL E787+E949	not CP eigenstate, δBR $\sim 7\%$
$K_L \to \pi^0 \nu\overline{\nu}$	theory (SM): $(3.0 \pm 0.6) \cdot 10^{-11}$ exp: $< 5.9 \cdot 10^{-7}$ FNAL KTeV	pure $\mathrm{CPV_{dir}}$ δBR $\sim 2\%$

allowing to make precise predictions. In the case $\ell = \nu$, long-distance contributions are absent and moreover, in the K_L case the only significant contribution comes from *top* quarks in the loop, therefore allowing remarkably small theoretical uncertainties (see table 1).

The BR of the K_L decay modes (their short-distance part) directly measure the height of the unitarity triangle, while the K^+ decay allows the measurement of one of its sides. The measurement of these rare decays represent a unique handle to over-constraining the CKM triangle, complementary and in some cases superior to that of B decays; the simultaneous measurement of both decays with ν in the final state allows to determine the apex of the triangle just from the K sector, and the comparison to an independent determination from the B sector (when Δm_s will be known) would be a powerful test.

Clearly, these rare decays pose unprecedented experimental problems for their detection: the two neutrino modes have 2/3 invisible final states and non-closed kinematics, a rather serious problem for decays in which the signal/background ratio can be of order 10^{-8}.

3.1 $K_L \to \pi^0 \ell^+ \ell^-$

The K_L modes with charged leptons would appear to be more tractable, but they are plagued with irreducible QED backgrounds $K_L \to \gamma\gamma\ell^+\ell^-$. These modes also exhibit a more complicated phenomenology, with CP-conserving long-range contributions and CP-violating contributions due to K_S mixing besides the well-tractable short-distance part. In recent years this point has been clarified by some ancillary experimental measurements: both NA48 and KTeV measured $BR(K_L \to \pi^0\gamma\gamma)$, giving limits on the CP-conserving component, which turns out to be small and negligible for $K_L \to \pi^0 e^+ e^-$. NA48/1 recently measured both $K_S \to \pi^0 \ell^+ \ell^-$ decays:

$$BR(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8) \cdot 10^{-9} \tag{7}$$

$$BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9} \tag{8}$$

therefore determining the mixing contribution to the K_L decays to be the dominant one.

The picture is now clearer, and if the interference of the two CP-violating components is constructive (theoretically favoured) a measurement of the $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ branching ratios, would allow extraction of short-distance parameters [13].

3.2 $K^+ \to \pi^+ \nu\overline{\nu}$

This decay is not CP violating, and the theoretical precision on the SM BR is around 7%, with prospects of being improved below 4%.

The decay has been measured at BNL using stopped kaon decays. E787 detected 2 events, and its successor E949 1 more event, before being stopped after only 20% of the approved running time. The measured branching ratio is

$$BR(K^+ \to \pi^+ \nu \overline{\nu}) = (1.47^{+1.30}_{-0.89}) \cdot 10^{-10} \tag{9}$$

Measurements focused on the phase space region corresponding to pion momenta between the two monochromatic peaks due to $K^+ \to \pi^+ \pi^0$ and $K^+ \to \mu^+ \nu$ background; a second region below the $\pi^+ \pi^0$ peak was also investigated, but being populated by three-body decays it has a larger background, resulting in an upper limit.

3.3 $K_L \to \pi^0 \nu \overline{\nu}$

This CP-violating decay is predicted to the astonishing prediction of 2% for its SM contribution. The current upper limit is set by KTeV using the statistically limited Dalitz decay of the π^0:

$$BR(K_L \to \pi^0 \nu \overline{\nu}) < 5.9 \cdot 10^{-7} \tag{10}$$

which, besides being 4 orders of magnitude above the SM expectation, is also above the model-independent bound set by the companion K^+ decay.

4 Future programs

Two experiments are proposed with the goal of collecting several tens of $K^+ \to \pi^+ \nu \overline{\nu}$ decays using the decay in flight. This technique presents some advantages when compared to that of decays at rest, mainly due to the minimization of particle scattering and the easier detection properties at higher energies. The CKM project at FNAL was expected to use a new 22 GeV RF-separated beam and a detector with redundant tracking and velocity measurement (based on RICH), for both the K^+ and the π^+. After being stopped due to cost reasons, the collaboration is re-designing the experiment with a higher-energy unseparated beam, along the lines of another proposed experiment, under study by the NA48 collaboration at CERN. The latter is based on a new 75 GeV unseparated hadron beam, also with redundant measurements of charged particles based on spectrometers and silicon/gas tracking. While the use of higher-energy allows relaxing somewhat the requirements on the hermetic veto detectors, the main challenge is the kaon tracking in a very intense beam ($\sim$ 1 GHz for the CERN experiment). Both experiments are preparing proposals and aim to take data in 2009.

A new experiment using the stopped kaon technique with some improvements was also proposed for the new Japanese hadron facility J-PARC, to take data in 2008.

Two experiments are also proposed to search for $K_L \to \pi^0 \nu \overline{\nu}$. Experiment E391a at KEK is based on the use of a pencil beam and a double veto decay chamber with large acceptance: it took data in 2004 and is expected to continue in 2005. While not having the potential to reach the SM level, it is expected to achieve a single-event sensitivity around $O(10^{-10})$, as a pilot project for a more ambitious experiment at J-PARC, aiming at collecting more than 100 SM events after 2008. The KOPIO experiment at BNL will use instead a micro-bunched neutral beam allowing a K_L time-of-flight measurement, and a pre-radiator to get information on photon directions to suppress the main $\pi^0 \pi^0$ background. The experiment is expected to start in 2010, and aims at collecting 40 SM events with $S/B \sim 2$.

Other letters of intent for K experiments were submitted for J-PARC, among which an improved search for T-odd muon polarization in K^+ semileptonic decay, which should improve by an order of magnitude over the existing result.

5 Conclusions

Just by considering the ongoing and planned activities with kaons in all major HEP laboratories around the world, one can easily realize the high potential which such system still carries for probing the current paradigm of flavour physics. It may well be that Nature still has something to tell us through kaons.

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