Kaon physics and discrete symmetries: status and perspectives

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Abstract. A brief review of recent discrete symmetry tests with kaons is presented, and prospects for future studies are discussed.

1. From genesis to revelation

Kaons have been a remarkably effective tool to provide insight for the shaping of the Standard Model (SM) as we know it. They played the key role in the discovery that basic discrete symmetries are often broken in Nature. After leading to the fall of parity, kaons showed the existence of CP violation, thus causing the start of a large set of experimental and theoretical studies, which eventually shed a flebile light on the deep connection between discrete symmetries and flavour [1] [2].

Sixty-six years after the first published observation of a K meson in cosmic rays, one might wonder whether investigations on kaons have exhausted the information that such relatively simple but rich system can provide: it turns out that this is not yet the case, as will be discussed in the following.

2. Close to the edge

Most of the recent experimental results obtained from kaon decays stem from the pluri-decennial research endeavours which aimed at clarifying the existence of direct CP violation.

In 1980, when Jim Cronin and Val Fitch received the Nobel prize for the discovery of CP violation, achieved in 1963 [3], the situation on the most subtle violation of a discrete symmetry in Nature was still described in these words: “At present our experimental understanding of CP violation can be summarized by the statement of a single number” [4]. The above sentence referred to the long-standing lack of conclusive understanding about the existence of more straightforward CP-violation effects in kaons, such as a partial decay width difference between CP-conjugate particles.

Even more strikingly, still at the end of the ’90s no other measurement of CP violation had been detected elsewhere, and the ad-hoc ansatz of a rather peculiar super-weak interaction [5] being responsible for CP violation required increasing uncomfortable attention.
KTeV at FNAL and NA48 at CERN were third-generation experiments aiming at the measurement of the $c'/c$ parameter, representing direct CP violation in the decay amplitudes. Both experiments took data at the end of the '90s, using high-energy proton beams to produce long- and short-lived neutral kaons on a fixed target. The ingenuity involved in these experiments is well worth appreciating, but goes beyond the scope of this paper (the interested reader can find some details in [6]). Let us just recall that around 1999 the existence of direct CP violation was finally confirmed [7] [8].

The importance of such measurement is foremost a qualitative one, as it provided the first confirmation of the CKM paradigm incorporating CP violation in the Standard Model; soon after the B-factories indeed showed CP violation to be an ubiquitous effect in neutral flavoured mesons [9].

The final results on direct CP violation from the entire (1997-1999) KTeV data set have just been recently released [10]: these refer to 6 (10) million $K_L(K_S)$ decays into $\pi^0\pi^0$ and 25 (43) million $K_L(K_S)$ decays into $\pi^+\pi^-$. Improvements with respect to the previous KTeV result include a reduction of the systematic error linked to the reconstruction of the $\pi^0\pi^0$ mode, mainly through improved Monte Carlo simulations.

Together with the final NA48 result [11] this now gives the current world average:

$$\Re(c'/c) = (16.4 \pm 1.9) \cdot 10^{-4}$$

(see [12] and [13]) which proves the existence of direct CP violation at about 9 standard deviations, with reasonable statistical consistency ($\chi^2$/dof = 5.2/3), see figure 1.

![Figure 1. Recent experimental determinations of $\Re(c'/c)$.

Nature has not been too kind on this issue, hiding very well direct CP violation effects in the most accessible meson system in which it appears. Expressed in a different way, the measured
value of $\epsilon'/\epsilon$ describes a difference in neutral kaon partial decay widths which is indeed quite tiny:

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(K^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(K^0 \to \pi^+\pi^-)} = (5.18 \pm 0.61) \cdot 10^{-6}$$

(2)

The above figure can be better compared to typical “large” measured asymmetries in the $B$ meson system, which can reach into the ten percent range, appearing however for decay modes with branching ratios of order $10^{-5}$.

The rather good experimental precision obtained calls for the possible inclusion of this measurement as a quantitative constraint on the consistency of the SM flavour structure, in the so-called unitarity triangle. Unfortunately this is not yet possible, due to the dire theoretical difficulties in computing the SM value of $\epsilon'/\epsilon$ which, besides the usual uncertainties related to low-energy hadronic physics, is also plagued by large accidental cancellations. Lattice QCD holds the promise to resolve this issue, and progress in the theoretical estimation of $\epsilon'/\epsilon$ has been somewhat slow but constant in time (see e.g. [14])

3. More

The legacy of the KTeV and NA48 experiments is much larger than the above main result shows, as several other key measurements were obtained from the careful analysis of the huge data samples collected.

The “classic” indirect CP violation parameter $\epsilon$ must be mentioned first: its real part has been traditionally measured through semi-leptonic decay asymmetries of $K_L$, which are now obtained from samples of $O(10^8)$ decays per experiment, resulting in

$$\delta^{(e)}_L = \frac{\Gamma(K_L \to \pi^-e^+\nu) - \Gamma(K_L \to \pi^+e^-\overline{\nu})}{\Gamma(K_L \to \pi^-e^+\nu) + \Gamma(K_L \to \pi^+e^-\overline{\nu})} = (3.322 \pm 0.055) \cdot 10^{-3}$$

(3)

The KLOE experiment at the DAΦNE kaon factory was also designed for a direct CP violation measurement with a very different technique, and although it could not compete directly in such arena, it turned out to be a very important source of kaon physics measurements. With 2.5 billion correlated $K_SK_L$ pairs collected in 2000-2006, KLOE performed several precision Branching Ratio measurements, with the unique advantage of absolute flux normalization. As a significant example, KLOE performed the first measurement of the semi-leptonic decay asymmetry of $K_S$[15]:

$$\delta^{(e)}_S = (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \cdot 10^{-3}$$

(4)

While this asymmetry is still compatible with zero due to the limited statistics related to the small BR $\approx 7 \cdot 10^{-4}$, it should be remarked that the equality of $\delta_S$ and $\delta_L$ is a test CPT symmetry in meson mixing, which could become significant if more data were available.

The straightforward way of extracting the $\epsilon$ parameter is by direct measurement of the BR of the CP-violating decay $K_L \to \pi\pi$. Recent measurements by KTeV [16], KLOE [17] and NA48 [18] resulted in a significant shift in most of the $K_L$ branching ratios with respect to previously known values (figure 2). The main reasons for such “BR revolution” are be found in the improved treatment of radiative correction effects, and the proper accounting of systematic error correlations.

The value of $\epsilon$ is now known with a remarkable 0.5% precision, and while this puts a constraint on the unitarity triangle (see fig. 3), its quantitative strength as a SM test is still limited

1 "We expect a 20% result on $\epsilon'/\epsilon$ in 3 years", a lattice theoretician, whose name will go undisclosed, publicly stated in 2009.
by theory, as the uncertainties in the parameterization of hadronic effects in the computation of $K^0 - \bar{K}^0$ mixing dominate the error in the extraction of the CKM parameters from the experimental quantity.

Figure 3. Recent determination of the apex $(\bar{\rho}, \bar{\eta})$ of the unitarity triangle (by the UTFIT collaboration[19]), on which the $\epsilon_K (\equiv \epsilon)$ band is visible.

Again, steady progress in lattice QCD is improving the situation, and now next-to next-to-leading order computations are becoming available, leading to theoretical errors approaching
the 10% level (see e.g. [14]). A breakdown of the theoretical error [20] suggests that further progress is now becoming increasingly difficult, since about one third of the error is parametric, mostly due to the knowledge of the $|V_{cb}|$ CKM parameter, but many comparable sources of non-parametric theoretical uncertainty compete to build up the rest.

4. Empty spaces

Searches for CP violation in other hadronic kaon decay modes are sensitive to direct CP-violating effects, which could in principle get sizable contributions from New Physics (NP).

$3\pi$ decays of $K_S$ are the counterpart of the traditional $K_L \to 2\pi$ modes, with a large penalty due to the much larger total decay width of the $K_S$. They have not yet been detected, not even at the expected level driven by indirect CP violation ($BR \sim 10^{-9}$).

Experiments at hadronic machines look for such decays through $K_S - K_L$ interference searches: NA48/1 put a limit of $BR(K_S \to 3\pi^0) < 2.3 \cdot 10^{-7}$ (at 90% CL) with $O(10^8)$ kaon decays [21]. KLOE also searched for this decay, reaching a limit of $BR(K_S \to 3\pi^0) < 1.2 \cdot 10^{-7}$ with 2 signal candidate [22] (see fig. 4).

![Figure 4](image_url)

Figure 4. KLOE signal boxes for $K_S \to 3\pi^0$ on simulated (left) and real data (right); the simulated data corresponds to twice the integrated luminosity (and about 2.7 times the efficiency) of the real data.

For a long time CP violation was only detected in decays of flavoured neutral mesons, where it can exhibit a rather complex phenomenology, depending on the process (mixing, decay, or both) in which the relevant complex phases appear. Charged mesons, in contrast, can only exhibit direct CP violation in the decay, and any difference in decay properties between a positively and a negatively charged meson is the most straightforward manifestation of CP symmetry violation.

The simplest decays of $K^\pm$ which can support large CP violation are the three-pion modes; the presence of two unsuppressed isospin amplitudes in such decays allows in principle a significantly larger interference (and thus CP violation) than in the $K^0 \to 2\pi$ modes of $\epsilon'$ fame.

A high-statistics investigation of such decays was performed by the NA48/2 experiment, focusing on the difference in the linear Dalitz plot slopes $g$ to avoid normalization issues; the pretty large BRs (1-5%) allowed to work with background-free samples of several $10^9$ decays, which were collected in 2003-04. Control of systematics was the key issue in pushing the measurement to cover the allowed range of asymmetries down to the $10^{-4}$ level, below which the SM contribution might be expected to appear (with significant theoretical uncertainties). Using simultaneous collinear $K^+$ and $K^-$ beams, and exploiting maximal cancellations of systematics,
NA48/2 closed the window for possible asymmetries significantly larger than the SM [23], as predicted by some SUSY models (see fig. 5):

\[ A_g = \frac{g^+ - g^-}{g^+ + g^-} = (-1.5 \pm 2.1) \cdot 10^{-4} \quad (K^+ \to \pi^+\pi^+\pi^-) \tag{5} \]

\[ A_g = \frac{g^+ - g^-}{g^+ + g^-} = (1.8 \pm 1.8) \cdot 10^{-4} \quad (K^- \to \pi^+\pi^0\pi^0) \tag{6} \]

\[ A_g = \frac{g^+ - g^-}{g^+ + g^-} = (1.8 \pm 1.8) \cdot 10^{-4} \quad (K^- \to \pi^+\pi^0\pi^0) \tag{6} \]

Figure 5. Experimental results on CP violation in the comparison of linear Dalitz plot slopes in \( K^\pm \to \pi^\pm\pi\pi \) decays.

Radiative decay modes such as \( K^\pm \to \pi^\pm\pi^0\gamma \) also offer a chance to investigate CP violation without having to deal with flux normalization issues, through the comparison of the radiative photon spectrum. With 220 thousand events detected, NA48/2 observed for the first time the \( \sim 3\% \) interference term between Bremsstrahlung and Direct Emission amplitudes (where CP violation might show up), detecting no evidence for any asymmetry [24] [25].

Radiative decays of neutral mesons, such as \( K_L \to \pi^+\pi^-\gamma \) were also investigated in the past, without detecting any sign of CP violation. From such decays, the time-honored technique of exploiting internal \( e^+e^- \) conversion to get information on photon helicity led to the measurement of a large CP asymmetry in the angle between the di-pion and di-electron planes in the rare \( K_L \to \pi^+\pi^-e^+e^- \) decay [26]:

\[ A_\phi = (13.8 \pm 2.2)\% \tag{7} \]

This result is very well consistent with the prediction, related to the usual \( K_L \to \pi^+\pi^- \) CP violation, mostly of indirect origin. No asymmetry is measured in the companion decay \( K_S \to \pi^+\pi^- \), as expected [26].

5. Any colour you like

CPT symmetry, despite being a cornerstone of all known theories\(^2\), is nevertheless very actively tested experimentally, in many different systems.

Numerically, the most striking CPT test in particle physics is given by the measured mass difference between \( K^0 \) and \( \bar{K}^0 \), obtained from a combined analysis of all kaon decay modes using unitarity, in the form of the Bell-Steinberger relation.

\(^2\) Except possibly for string theory (but which possible phenomenon is not encompassed by string theory, by the way?).
Using the recent KTeV data on $K \rightarrow 2\pi$ decays, combined with input from NA48, KLOE and CPLEAR, one obtains \cite{10}

$$|m(K^0) - m(\bar{K}^0)| < 4.0 \cdot 10^{-19} \text{GeV}/c^2$$

at 95% CL, as a limit for validity of CPT symmetry in the meson mixing process, assuming CPT symmetry in the decays (see fig. 6).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure6}
\caption{Determination of the mass and decay width differences between $K^0$ and $\bar{K}^0$.}
\end{figure}

This latter assumption is consistent with the KTeV measurement of $\Im(\epsilon'/\epsilon)$ (proportional to the phase difference of the two $K \rightarrow \pi\pi$ decays) being close to zero (see fig. 7).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure7}
\caption{KTeV results on the real and imaginary parts of $\epsilon'/\epsilon$, and comparison with the expectation in case of CPT symmetry using final-state interaction phase measurements.}
\end{figure}

The only direct measurement of time reversal violation (without any assumption on CPT but still equivalent to CP) is the Kabir asymmetry measured by CPLEAR \cite{27}, between the probabilities of $K^0 \leftrightarrow \bar{K}^0$ transitions:

$$\frac{P(\bar{K}^0 \rightarrow K^0) - P(K^0 \rightarrow \bar{K}^0)}{P(\bar{K}^0 \rightarrow K^0) + P(K^0 \rightarrow \bar{K}^0)} = (6.6 \pm 1.3) \cdot 10^{-3}$$

(9)
While we only discussed tests of discrete symmetries, it should be pointed out that many other interesting results were obtained as byproducts of the above investigations, such as the much improved determination of the Cabibbo mixing angle (or $|V_{us}|$), to 0.23% precision, from improved measurements of $K \to \pi \ell \nu$ ($K_{\ell 3}$) decays; this resulted in a stringent test of unitarity in the first row of the CKM matrix [28].

As a second example, much improved measurements of the BR for the helicity suppressed leptonic decay $K^\pm \to e^\pm \nu$ ($K_{e2}$) recently allowed to perform stringent tests for deviations from the $V - A$ structure of weak interactions and the presence of lepton-flavour violating effects [29] in NP, which could significantly affect the ratio of BRs between $K_{e2}$ and $K_{\mu 2}$.

6. High hopes

In the near future an upgrade of the KLOE experiment [30] should pursue with much higher statistics the kind of interferometry studies which were already started, allowing more stringent tests of CPT, Lorentz symmetry, and testing the validity of quantum mechanics itself (see [31]).

Other experiments are in preparation to improve the existing tests of discrete symmetries with kaons. One is the elegant TREK experiment [32], aiming at a ten-fold improvement in the measurement of the muon polarization $P^T$ transverse to the decay plane in the $K^+ \to \pi^0 \mu^+ \nu$ decay. A non-zero value for such quantity at a level above $10^{-4}$ would be an indication of time-reversal violation in New Physics, still allowed by the current limit ($P^T < 5 \cdot 10^{-3}$) set by the KEK E246 experiment [33].

The next frontier in extracting physics from kaons lies in brave searches for ultra-rare decay modes: it has been long known that a few kaon decay modes are unique probes for New Physics in the flavour sector [34], due to the extraordinary precision achievable in the theoretical prediction of their BR (at the few percent level). Some features of these modes are summarized in table 1; the hard-GIM suppression in the SM which allows large NP contributions, and the extraction of the hadronic part of the amplitude from the very well measured $K_{\ell 3}$ decay, are the two key points to understand the relevance of these processes.

| Mode | BR(SM) | BR(exp) |
|------|--------|---------|
| $K_L \to \pi^0 e^+ e^-$ | $10^{-11} (3 \cdot 10^{-12} \text{ CPV}_{\text{dir}})$ | $< 2.8 \cdot 10^{-10}$ |
| $K_L \to \pi^0 \mu^+ \mu^-$ | $10^{-11} (1 \cdot 10^{-12} \text{ CPV}_{\text{dir}})$ | $< 3.8 \cdot 10^{-10}$ |
| $K^+ \to \pi^+ \nu \sigma$ | $(8.5 \pm 0.7) \cdot 10^{-11}$ | $1.47^{+0.30}_{-0.89} \cdot 10^{-10}$ |
| $K_L \to \pi^0 \nu \sigma$ | $(2.6 \pm 0.4) \cdot 10^{-11}$ | $< 2.6 \cdot 10^{-8}$ |

Table 1. Ultra-rare kaon decay modes, listing the experimental information and theoretical prediction on their BRs ($\text{CPV}_{\text{dir}}$ denotes the short-distance, direct-CP violating part of the BR).

The four decay modes in table 1 probe different classes of NP; the modes with neutrinos in the final state are the cleanest from a theoretical point of view, and represent the new “holy grail” of physics with kaons and one of the most powerful probes of NP at large.

The $K^+$ mode was detected by the dedicated BNL experiments E787 and E949, with a total of seven candidate events [35], while only limits exist for the $K_L$ mode [36], whose (directly) CP-violating nature contributes to reducing further the intrinsic theoretical uncertainties in the BR prediction.

Out of many proposals which were put forward for the search of these decays, at least two projects are steadily ongoing.
NA62 at CERN [37] aims to measure $O(100)$ $K^+ \to \pi^+ \nu \bar{\nu}$ events in two years of data-taking, starting in 2013, exploiting a new experimental approach based on high-energy (75 GeV/c) $K^+$ decay in flight (figure 8).

![Figure 8. Layout of the NA62 experiment at CERN for the measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay.](image)

KOTO at J-PARC [38] is the successor of the pilot project E391a [36] at KEK, aiming at a first detection of the $K_L \to \pi^0 \nu \bar{\nu}$ decay starting in 2011, with a future upgrade path to collect tens of events using a dedicated beam line. It is based on the use of a hermetic detector and a pencil-like neutral beam (figure 9).

![Figure 9. Layout of the KOTO experiment at J-PARC for the measurement of the $K_L \to \pi^0 \nu \bar{\nu}$ decay.](image)

Fermilab plans for physics at the intensity frontier, exploiting a future very intense proton accelerator (so-called “Project X”) [39], do include ultra-rare kaon decay measurements as a central research topic. 3 MW of beam power at 3 GeV from such a machine could deliver (around 2020) enough kaons to get several hundreds decays in both the $K^+$ and $K_L$ ultra-rare modes, and experiments are envisaged for both such measurements. Such a machine would also offer the possibility of performing a ultimate $K^0 \to 2\pi$ phase measurement, bringing the $K^0 - \bar{K}^0$ mass difference CPT test to a level of sensitivity corresponding to the Planck scale.
The KLOD R&D program for a $K_L$ measurement at Protvino should also be mentioned, as well as the OKA project, in the same laboratory, using a separated charged kaon beam.

7. Los endos

The whole issue of discrete symmetries violation in fundamental particles was born with kaons, and this system - being the simplest one which exhibits the full set of weak-interaction effects linked to flavour - is still at the forefront of research on the topic which gives the title to this conference. The low mass, on the hadronic scale, is what gives kaons distinct advantages over other meson systems, both in terms of large lifetime and lifetime difference of the physical states (which allow a most varied set of experiments), of tiny mass difference (resulting in unparalleled probing power on virtual effects) and limited number of dominant decay modes (a significant experimental simplification). The theoretical limitations of dealing with lower-energy systems, on the other hand, are not such to cancel the above-mentioned advantages.

The smallest BRs ever measured were obtained from careful kaon experiments, and experimenters have now taken up the challenge of stepping up from tens to hundreds of kW of beam power.

All such considerations lead the author to believe that kaons will still be playing an important role on the stage of future investigations of Nature’s broken symmetries.

It is a pleasure to thank A. Di Domenico and the Organizing Committee of Discrete 2010 for the kind invitation, and for providing such a pleasant experience at the conference.

References

[1] N. Cabibbo, Phys. Rev. Lett. 10 (1963) 531.
[2] M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.
[3] J.H. Christenson et al., Phys. Rev. Lett. 13 (1964) 138.
[4] J.W. Cronin, Rev. Mod. Phys. 53 (1981) 37.
[5] L. Wolfenstein, Phys. Rev. Lett. 13 (1964) 562.
[6] M.S. Sozzi, Discrete symmetries and CP violation, Oxford University Press (2008).
[7] A. Alavi-Harati et al (KTeV collaboration), Phys. Rev. D 67 012005.
[8] A. Lai et al NA48 collaboration, Eur. Phys. Jour. C 22 (2001) 231.
[9] B. Aubert et al (BaBar collaboration), Phys. Rev. Lett. 87 (2001) 091801; K. Abe et al (Belle collaboration), Phys. Rev. Lett. 87 (2001) 091802.
[10] E. Abouzaid et al (KTeV collaboration), preprint arXiv 1011.0127, submitted to Phys. Rev. D (November 2010).
[11] J.R. Batley et al (NA48 collaboration), Phys. Lett. B 544 (2002) 97.
[12] K. Nakamura et al. (Particle Data Group), J. Phys. G 37 (2010) 075021.
[13] M. Sozzi, Eur. Phys. Jour. C 36 (2004) 37.
[14] http://www.infn.it/Lattice2010.
[15] F. Ambrosino et al (KLOE collaboration), Phys. Lett. B 636 (2006) 173.
[16] T. Alexopoulos et al (KTeV collaboration), Phys. Rev. D 70 (2004) 092006.
[17] F. Ambrosino et al (KLOE collaboration), Phys. Lett. B 638 (2006) 149.
[18] A. Lai et al (NA48 collaboration), Phys. Lett. B 645 (2007) 26.
[19] UTfit collaboration, http://www.utfit.org.
[20] J. Brod, these proceedings.
[21] A. Lai et al (NA48/1 collaboration), Phys. Lett. B 610 (2005) 165.
[22] F. Ambrosino et al (KLOE collaboration), Phys. Lett. B 619 (2005) 61.
[23] J.R. Batley et al (NA48/2 collaboration), Eur. Phys. J. C 52 (2007) 875.
[24] J.R. Batley et al (NA48/2 collaboration), Eur. Phys. J. C 68 (2010) 75.
[25] G. Anzivino, these proceedings.
[26] J. Adams et al (KTeV collaboration), Physical Review Letters 80 (1998) 4123; A. Lai et al (NA48 collaboration), Eur. Phys. Jour. C 30 (2003) 33.
[27] A. Angelopoulos et al (CLEAR collaboration), Phys. Lett. B 444 (1998) 43.
[28] M. Antonelli et al., Eur. J. Phys. C 69 (2010) 399.
[29] F. Ambrosino et al (KLOE collaboration), Eur. Phys. J. C 64 (2009) 627; ibid. 65 (2010) 703. C. Lazzeroni et al (NA62 collaboration), arXiv:1008.1219, submitted to Phys. Lett. B (2011).
[30] G. Amelino-Camelia et al (KLOE-2 collaboration), arXiv:1003.3868 (2010).
[31] B. Hiesmayr, A. De Santis, these proceedings.
[32] J-PARC proposal P-06, at http://j-parc.jp/NuclPart/Proposal_e.html.
[33] M. Abe et al (KEK E246 collaboration), Phys. Rev. Lett. 93 (2004) 131601.
[34] A.J. Buras et al., Rev. Mod. Phys. 80 (2008) 965; E. Stamou, these proceedings.
[35] S. Adler et al (BNL E949 collaboration), Phys. Rev. D 77 (2008) 052003.
[36] J.K. Ahn et al (KEK E391a collaboration), Phys. Rev. D 81 (2010) 072004.
[37] NA62 Technical Design, CERN NA62-10-07, CERN, Geneva, December 2010.
[38] J-PARC proposal P-14, at http://j-parc.jp/NuclPart/Proposal_e.html.
[39] Project-X web pages at projectx.fnal.gov.