

## REVIEW AND OUTLOOK ON KAON PHYSICS\*

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The status of kaon physics and its prospects are reviewed. A new round of experiment is taking data with the potential of making a significant step in sensitivity on many fronts by the end of the decade.

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**1. Introduction**

After more than seventy years from their discovery [1], kaons are still an important tool to address fundamental questions in particle physics. The compelling questions that we wish to answer using kaons include:

- Are there any other sources of CP violation in addition to the complex phase of the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix?
- To which extent is the lepton universality respected?
- Are there more than three generations of fundamental fermions?
- How far can we push the high-energy frontier looking at rare processes, is there new physics accessible from the study of loop-mediated meson decays?
- Can we test other fundamental symmetries such as CPT? To which extent?

The common denominator of the above questions is that they all require a solid theoretical foundation where clear questions can be formulated without too much ambiguity. In this respect, kaons are particularly interesting

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because the Standard Model (SM) expectations are precise and not affected by large hadronic uncertainties. It is to be noted that experiments in this area of particle physics tend to be innovative and not simply the incremental improvement of the previous generation. Conversely though, the field is mature and a significant effort is needed to challenge our understanding. In conclusion, even if we have entered the Higgs Boson era, a strong kaon physics programme seems perfectly justified.

A new round of kaon experiments is taking data, KLOE-II at the Frascati  $\Phi$  factory, KOTO at J-PARC and NA62 at CERN, together with OKA at Protvino and LHCb at the LHC promise to make steady progress in order to address the compelling questions listed above.

## 2. Direct CP violation

An important experimental endeavor took place two decades ago to measure direct CP violation in the kaon system. The quantity of interest is

$$\text{Re } \epsilon'/\epsilon = \frac{1}{6} \left\{ 1 - \left| \frac{\eta_{00}}{\eta_{\pm}} \right|^2 \right\},$$

where

$$\eta_{00} = \frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_S \rightarrow \pi^0 \pi^0)}$$

and

$$\eta_{\pm} = \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)}.$$

A non-zero value of  $\text{Re } \epsilon'/\epsilon$  signals the direct CP violation, that is CP violation present in the decay of the neutral kaon and not limited to the mixing of the meson. To perform this important test about the origin of CP violation, experiments were made on both sides of the Atlantic [2, 3]. The experimental situation was settled at the beginning of this century, when it was demonstrated that  $\text{Re } \epsilon'/\epsilon$  is different from zero beyond doubt [4]:  $16.6 \pm 2.3 \times 10^{-4}$ . While the measurements firmly establish direct CP violation and rule out *superweak* models [5], a precise theoretical prediction within the SM remains difficult to obtain because of cancellations between electroweak (EW) and QCD *penguin* operators.

A useful SM formula to display the difficulty of the theoretical calculation is the following [6]:

$$\frac{\epsilon'}{\epsilon} = 10^{-4} \left[ \frac{\text{Im } \lambda_t}{1.4 \cdot 10^{-4}} \right] \left[ a \left( 1 - \hat{\Omega}_{\text{eff}} \right) \left( -4.1 + 24.7 B_6^{(1/2)} \right) + 1.2 - 10.4 B_8^{(3/2)} \right],$$

where  $\text{Im } \lambda_t = \text{Im } V_{td}V_{ts}^* = |V_{ub}||V_{cb}|\sin\gamma$ , isospin breaking corrections are parameterized by  $a = 1.017$  and  $\hat{\Omega}_{\text{eff}} = (14.8 \pm 8.0) \times 10^{-2}$ , and  $B_6^{(1/2)}$  and  $B_8^{(3/2)}$  are the parameters describing the QCD and EW penguins which tend to cancel each other. It is obvious from the formula that the relative importance of the QCD and EW penguins can affect the SM prediction by an order of magnitude. According to dual QCD [6], the following inequality holds:  $B_6^{(1/2)} \leq B_8^{(3/2)} < 1$ . The first lattice calculation [7] gives  $\text{Re } \epsilon'/\epsilon = 1.4 \pm 6.9 \times 10^{-4}$  in agreement with the large- $N$  methods and sizably below the experimental number by 2.1 standard deviations. The effect of pion rescattering on enhancing the QCD penguin and hence the SM prediction for  $\text{Re } \epsilon'/\epsilon$  is still debated [8]. The situation is well-summarized with a picture (Fig. 1) and Table I, where a comparison between experiment and some theoretical results are compared. Hopefully, lattice QCD will be able to clarify the SM prediction soon.



Fig. 1. A. Buras and A. Pich debate the value of the SM prediction for  $\epsilon'/\epsilon$  in MITP Mainz, during a session of the NA62 Physics Handbook workshop in January 2016. We are eagerly waiting from lattice QCD a final answer.

TABLE I

Comparison of the experimental and theoretical situation for direct CP violation in the  $K \rightarrow \pi\pi$  system.

| $\text{Re } \epsilon'/\epsilon$ | $(\times 10^{-4})$ |
|---------------------------------|--------------------|
| Experiments                     | $16.6 \pm 2.3$     |
| Buras <i>et al.</i> [9]         | $1.9 \pm 4.5$      |
| KNT [10]                        | $1.1 \pm 5.1$      |
| Pich <i>et al.</i> [8]          | $15.0 \pm 7.0$     |
| BEF [11]                        | $22.0 \pm 8.0$     |
| Lattice QCD [7]                 | $1.4 \pm 6.9$      |

### 3. $K_S \rightarrow \pi^0 \pi^0 \pi^0$

In the SM of quark mixing, the CP violation due to neutral kaon mixing effects is expected to be the same in  $K_L$  and  $K_S$  once the different lifetimes and quantum numbers of the final states are taken into account. A nice, clean test can be performed measuring the decay  $K_S \rightarrow \pi^0 \pi^0 \pi^0$  which is purely CP violating. Progress is expected from the KLOE II Collaboration at the Frascati  $\Phi$  factory. The prediction in the SM is

$$\text{BR}(K_S \rightarrow \pi^0 \pi^0 \pi^0) = |\epsilon|^2 \times \frac{\tau_S}{\tau_L} \text{BR}(K_S \rightarrow \pi^0 \pi^0 \pi^0) \approx 3 \times 10^{-9},$$

where  $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$  is the mixing parameter.

Currently, the best limit is provided by the KLOE Collaboration [12]:  $\text{BR}(K_S \rightarrow \pi^0 \pi^0 \pi^0) \leq 2.6 \times 10^{-8}$  at 90% C.L. A deviation from the predicted value would be a sign of CP violation beyond the complex phase present in the CKM matrix.

### 4. Test of CKM unitarity

With lattice QCD now able to reliably calculate decay constants and form factors of light mesons, the precise testing of unitarity of the up-quark coupling to the down-type quarks can be performed with great precision testing the unitarity relation  $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ . In this relation, the coupling of the up to down quark is obtained from super-allowed  $0^+ \rightarrow 0^+$  transitions, while the coupling of the up quark to the strange one is measured from the study of leptonic and semi-leptonic kaon decays. Following the analysis presented by Marciano and Blucher for the PDG, we can conclude that the unitarity is respected to a precision of  $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9995 \pm 0.0005$ , providing a test of the SM radiative correction with a precision of a few % [4].

### 5. Rare kaon decays

The holy grail of kaon physics is represented by the  $K \rightarrow \pi \nu \bar{\nu}$  decays. The neutrino–antineutrino pair in the final state guarantees that long-distance contributions from electromagnetic interactions and hadronic uncertainties are small. This is in contrast with respect to the final states with pairs of charged leptons.

Rare decays proceeding through flavor changing neutral currents such as  $K \rightarrow \pi \nu \bar{\nu}$  are important because their Standard Model contribution appears only at loop level and it is strongly suppressed. Thus, any contribution due to undiscovered particles can affect the measurement but not the Standard Model prediction. Therefore, a discrepancy between the observed rate and the predicted one would signal something interesting beyond the Standard Model.

The SM prediction [13] reads

$$\begin{aligned}\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= (8.39 \pm 0.30) \times 10^{-11} \times \left( \frac{V_{cb}}{0.0407} \right)^{2.8} \times \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} \\ &= (8.4 \pm 1.0) \times 10^{-11}.\end{aligned}$$

As it can be seen in the formula above, it is noteworthy that the precision of the prediction is dominated by the uncertainty of a combination of CKM elements. Those elements will be better determined in the future (by experiments such as LHCb and Belle II). Therefore, the ultimate impact of the test will be defined by the achievable experimental precision and not by the purely theoretical error which is very small.

Evidence for this decay was obtained by experiments BNL-E787/E949 made with stopped kaons. The final result of these experiments is [14]

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 17.3_{-10.5}^{+11.5},$$

which is consistent with the SM prediction but it is affected by a large error, still allowing large effects beyond the standard to be present. The probability that all the candidate events reported are due to background is not negligible and was quoted to be  $10^{-3}$  [14].

To bridge the gap between the theory and the experimental error, the NA62 experiment [15] at CERN has been built. It exploits the decay in flight technique and it has started data taking in 2016. Details about the experiments can be found in [15] and here only the main features are recalled. Protons accelerated by the CERN super proton synchrotron (SPS) to 400 GeV are slowly extracted and directed onto a 40 cm long Be target. A secondary beam of hadrons is selected with a mean momentum of 75 GeV/c and a momentum bite of 1%. About 6% of the hadrons are kaons, while the majority of the rest is composed by pions and protons. The beam is debunched in order to have as little as possible of the memory of the SPS RF structures. To tag the incoming kaons, the beam passes through a differential Cherenkov counter adjusted to give a positive response to kaons of 75 GeV/c. While only a small fraction of the beam is made of kaons, each particle has to be tracked because there is no way to distinguish the kaons that will decay from any other beam particle. To do so, a novel Si pixel detector (gigatracker) with 100 ps time resolution has been developed. After being tracked, the particles enter a long decay tank surrounded by large angle vetoes (LAVs) that veto photons from  $K^+ \rightarrow \pi^+ \pi^0$  decays. The useful decay region is approximately 60 m long depending on fiducial cuts. To avoid excessive multiple scattering, the tracking detectors (Straws) are installed and operated inside the decay tank under vacuum. Pion/muon separation is provided by a Ring Imaging Cherenkov (RICH), while hermetic coverage

to photons in the forward region is provided by a liquid krypton calorimeter (LKr) and smaller shashlik calorimeters (IRC and SAV). Coverage is completed by a hadron sampling calorimeter (HASC).

The in-flight technique has the advantage to avoid the material of the stopping target and the disadvantage that only a small fraction of the beam kaons (10%) usefully decays. An additional bonus of the in-flight technique is the excellent control of backgrounds and a much larger useful detector acceptance.

The commissioning of the experiment was completed in 2016 and physics data taking is in progress and will last at least towards the end of 2018 when CERN enters a two-year long shutdown (LS2).

Data from the first physics run in 2016 have been analyzed and a first result of the search for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  in flight was recently reported [16, 17]. Based on one candidate event and a background expectation of  $0.15 \pm 0.09$  background events, the upper limit  $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \leq 14 \times 10^{-10}$  at 95% C.L. is placed. This is based on a statistics of only about 1% of the total expected NA62 statistics and already places competitive bounds on the kinematical region contained between the  $\pi\pi$  and  $\pi\pi\pi$  thresholds. NA62 has accumulated already 20 times more data and assuming a successful 2018 data taking should have about 20 SM events on tape before the CERN long shutdown 2 (LS2).

As ultimate measurement of  $K$  rare decays, one should mention  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ . Currently this decay is studied by the KOTO experiment at J-PARC. The best limit still comes from the predecessor experiment E391a at KEK [18], which placed an upper limit of  $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 2.6 \times 10^{-8}$  at 90% C.L.

## 6. Lepton universality and lepton flavor violation

Hints of lepton non-universality have emerged from the analysis of  $B$  decays. More generally, a lot of investigations have taken place in the study of angular resolutions, effective operators and ratio of branching fractions of  $B$  decays in pairs of electrons and muons. While updates on the analyses are eagerly awaited, the questions stand out to which extent deviations are seen in other systems. In kaon physics, a good test is made comparing the ratio

$$R_K = \frac{\Gamma(K^+ \rightarrow e^+ \nu)}{\Gamma(K^+ \rightarrow \mu^+ \nu)}.$$

The most precise determination to date has been obtained by NA62 [19]:  $R_K = 2.488 \pm 0.010 \times 10^{-5}$ . This result is in a good agreement with the SM prediction and it will be further improved with new NA62 data. The main systematics of the measurement will be reduced thanks to the presence of a RICH detector and the absence of material in between the tracking stations.

With the discovery of neutrino oscillations, which implies that the lepton flavor is not conserved, the question arises whether the lepton flavor violation is also violated in the sector of charged leptons. Although the origin of possible flavor violation could be totally different between the case of neutral and charged leptons (in the case of the neutrinos, it is observable because the almost degenerate nature of neutrino masses), all efforts devoted to improve the experimental situation are worth pursuing. The data sample collected by NA62 promises to increase the existing limits of lepton flavor violation in kaon decays by an order of magnitude.

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