Direct CP Violation in Kaons and Kaon Rare Decays

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Abstract. Recent results on direct CP violation in kaons are presented and future experiments aiming to perform precise measurements of rare kaon decays are briefly reviewed.

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INTRODUCTION

There are two independent ways of exploiting frontier research in particle physics: one is the higher energy challenge, to access directly new information, the other is the indirect way of the high precision measurements of rare processes. Both experimental methods are essential to address a comprehensive investigation of fundamental interactions from different perspectives and in a complementary way. In this respect, kaons are a compelling example of the latter approach.

The study of the features of the K mesons system and of kaon decays has been a powerful tool to achieve results of unique importance in the development of particle physics. The concept of strangeness led to the quark model and to the basic issues of QCD; the first evidence of parity violation showed the way to the chiral nature of weak gauge forces; the suppression of Flavor Changing Neutral Currents (FCNC) suggested the charm quark and the GIM mechanism; the discovery of CP violation established matter-antimatter asymmetry and the three generation structure of matter; basic investigation of lepton flavour and CPT symmetries have been possible; tests of theoretical techniques such as chiral lagrangians which account for the low energy behaviour of QCD became feasible thanks to kaon decays dominated by long distance contributions. This richness of results is partly due to the fact that kaons are a rather simple system of the lightest mesons containing a quark flavour of a generation

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beyond the first, they have rather long lifetimes, with a broad hierarchy between K_L and K_S, and they are produced in large quantity.

Many decades after their first observation in cosmic rays [1], kaons still keep their capacity to provide a deep insight into Nature. Aside from being crucial for the present knowledge of the Standard Model (SM), as already described, they hold an unquestionable importance as tester of its possible deviation and explicit violation, thus allowing to precisely address also the issue of the physics beyond it.

CP Violation in Kaons

CP violation was discovered in $K\to\pi\pi$ decays in 1964 [2]. The same mode provided also the evidence for direct CP violation [3-5].

All three types of CP violation are observed in neutral kaons. The phenomena of neutral kaons mixing accounts for the indirect CP violation, measured with the parameter $Re(\varepsilon)$, where ε represents the asymmetric mixing of the CP eigenstates into the mass eigenstates occurring with $\Delta S=2$. Direct CP violation is due to an asymmetry in the amplitude of K^0 decays into two pion final states with different isospin values. This effect is quantified by the measurement of the parameter $Re(\varepsilon')$. A non-zero value of ε' arises naturally in the SM from the complex phase of the CKM matrix. The violation of CP symmetry takes also place in the interference between decays with and without mixing, where it is represented in terms of the parameters $Im(\varepsilon)$ and $Im(\varepsilon')$.

Only direct CP violation occurs in charged kaons, since mixing is not allowed.

Direct CP Violation in Neutral Kaons

Direct CP violation was finally established in 1999 with the results of the precision experiments E832 (KTeV) at FNAL [4] and NA48 at CERN [5]. This confirmation has been the most important result obtained with kaons in the recent past.

The quantity which is measured is the double ratio

$$\mathrm{R} = \frac{\Gamma(K_L \to \pi^0\pi^0)\cdot\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)\cdot\Gamma(K_L \to \pi^+\pi^-)} = \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \cong 1 - 6\cdot Re(\varepsilon'/\varepsilon) \qquad (1)$$

The measurement of R requires counting experiments where K_L and K_S are produced concurrently and the four $\pi\pi$ decay modes, which coincide in space, are measured simultaneously. The two above experiments exploit similar concepts in their detector, with a high performance calorimetry for the $\pi^0\pi^0$ measurement – pure CsI crystals for KTeV and a liquid Krypton ionization chamber for NA48 – and high quality magnetic spectrometers for the $\pi^+\pi^-$ detection.

The schemes of the KTeV and the NA48 detectors are shown in figure 1. Important differences were also present in the two experimental approaches. The K_S beam was produced at a close target in NA48, and in a regenerator in KTeV; K_S and K_L decays were distinguished with a proton tagging technique in NA48 and using displaced beams in KTeV; the acceptance corrections applied to take care of the differences between K_S and K_L decay distributions were calculated with an accurate Monte Carlo simulation in KTeV, while a statistical method of weighting events was used in NA48.

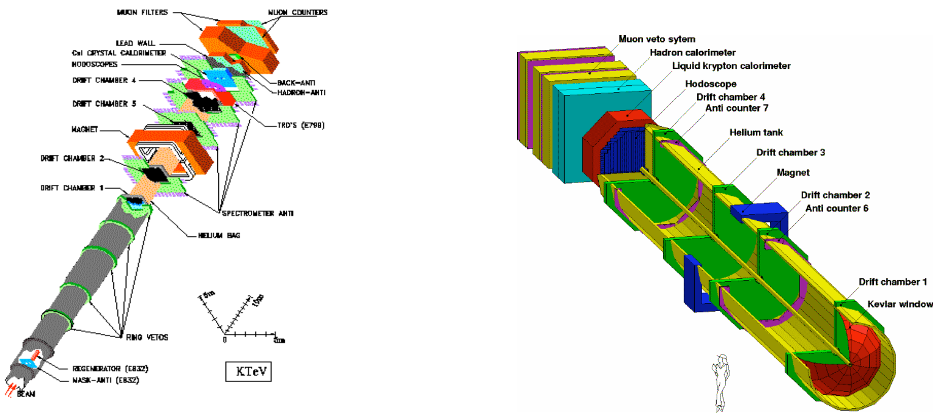

FIGURE 1. Scheme of the KTeV detector at FNAL (left) and the NA48 detector at CERN (right)

Figure 2 summarizes the current experimental situation and some recent theoretical calculations of the direct CP violation parameter $Re(\varepsilon'/\varepsilon)$. The present world average, quoted in figure 2 according to the PDG procedure [6], has a significance of more that 7 standard deviations. This result is compatible with the SM predictions. Despite the impressive progresses in recent years, theoretical difficulties still prevent $Re(\varepsilon'/\varepsilon)$ to be a quantitative test of the SM, due to non perturbative calculations of hadronic physics. Progresses in the lattice QCD should eventually overcome such problems. A review of the status of theoretical predictions for $Re(\varepsilon'/\varepsilon)$ can be found in [8]

The KLOE experiment at the Frascati DAΦNE Φ Factory exploits the correlated decays of $K_S - K_L$ and $K^+ - K^-$ from the Φ resonance produced in e^+e^- collisions. They are measured in a magnetic detector with a lead-scintillator electromagnetic calorimeter and a large drift chamber. Figure 3 shows a view of the KLOE detector.

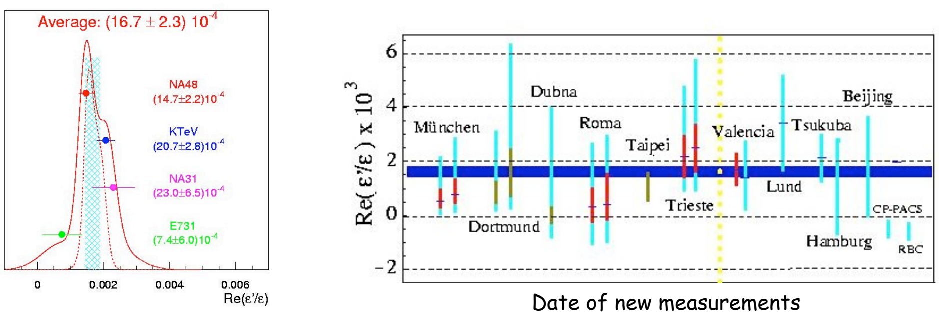

FIGURE 2. Left: summary of recent experimental results on the direct CP violation parameter *Re(ε'/ε)*. The curves show probability distributions according to the PDG procedure (solid line) [6] or a Bayesian approach (dashed line) [7]. The hashed band is the ±1 standard deviation around the world average. Right: recent theoretical calculations of *Re(ε'/ε)* by several groups along the years. The horizontal band is the measured value with its error; the vertical dotted line marks the year 1999, when the first experimental results from KTeV and NA48 became available

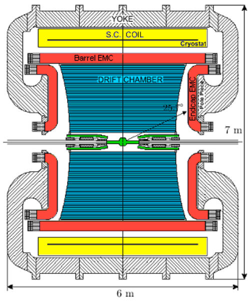

FIGURE 3. Scheme of the KLOE detector at the Frascati DAΦNE Φ Factory.

Pure kaon beams are reconstructed in KLOE by tagging the companion K decays. Thanks to its unique K_S beam, KLOE is very well suited to study K_S decays, and, in particular, the CP violating process $K_S \rightarrow 3\pi^0$, allowed by SM, but never observed so far. A direct search for $K_S \rightarrow 3\pi^0$ was carried out which achieved, with the analysis of a sub-sample of the collected data, the best limit presently available [9] of

$$BR(K_S \rightarrow 3\pi^0) < 1.2 \cdot 10^{-7} \quad (90\%\ CL) \tag{2}$$

An improvement of about one order of magnitude is expected after the analysis of the complete data sample.

Direct CP Violation in Charged Kaons

Direct CP violation in $K^\pm$ is expected to induce different decay amplitudes for K^+ and K^- decays into the same three pions final states. Since the three-body decay has a low Q value, the matrix elements M can be expanded in powers of the Lorentz-invariant Dalitz variables $u=(s_3-s_0)/m_\pi^2$ (odd pion coordinate) and $v=(s_1-s_2)/m_\pi^2$ (even pion coordinate), where $s_i = (p_k-p_i)^2$. If $|M(u,v)|^2 \propto 1+g\cdot u+O(u^2,v^2)$, the asymmetry

$$A_g = \frac{g(K^+)-g(K^-)}{g(K^+)+g(K^-)} = \frac{g^+ - g^-}{g^+ + g^-} \neq 0 \tag{3}$$

of the slope parameter g would be a signal of direct CP violation. The SM predictions for such effect are rather small, with asymmetries at the level of 10^{-5} [10]. Higher values of A_g would possibly imply the presence of new physics beyond the SM [11].

The NA48/2 collaboration [12] at CERN accomplished a high precision study of direct CP violation in charged kaon decays into three pions, using a modified NA48 experimental setup and a new unique design of simultaneous narrow band (60 GeV/c ± 5% momentum) non separated $K^\pm$ beams, at high intensity ($\sim 10^7$ particle per second). Figure 4 shows the layout of the NA48/2 beam line and of the detector.

The NA48/2 experiment aims to measure the slope asymmetry A_g in $K^\pm \rightarrow 3\pi^\pm$ events with a sensitivity of $\sim 2\cdot 10^{-4}$, more than one order of magnitude better than the best available measurements [13-16]. The simultaneous data taking with $K^\pm$ beams of similar momentum spectra, associated to the regular reversal of the polarity of magnets along the beam line and of the spectrometer magnetic field, allows the cancellation of most systematic effects due to asymmetries in the setup and equalize local effects due to the electric charge on the acceptances.

The measurement of the slope asymmetry A_g is based on the comparison of the reconstructed u spectra $N^+(u)$ and $N^-(u)$ of the K^+ and K^- decays. The presence of direct CP violation effects can be possibly obtained from a fit to the ratio $N^+(u)/N^-(u)$ of the distributions, which depends on the difference $\Delta g= g^+ - g^-$ of the slope parameters. Several data sample are collected in four different configurations, according to all the possible combinations of beam line and spectrometer magnet polarities, in order to define "supersamples" of events, each given by data collected in all the configuration for a periods of 2 weeks. This procedure allows to accomplish further cancellation of systematic biases due to possible differences in the beam rates, in the beam line geometry and in the asymmetries of the detector.

The method is independent on the K^+/K^- flux ratio and on the size of the samples collected under different conditions. The results is only sensitive to time variation of the asymmetries in the experimental conditions which have characteristic times smaller than those of the magnetic field inversions, and, in principle, should be free of systematic biases. No Monte Carlo corrections to the acceptance are required.

Based on a total of 3.1×10^9 $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ decays (2.0 K^+ and 1.1 K^-) and 9.1×10^7 $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ decays (5.9 K^+ and 3.2 K^-), collected in the years 2003 and 2004, the final results of the NA48/2 measurements of the CP violating "charged" A_g^c and "neutral" A_g^n asymmetries are

$$A_g^c = (-1.5 \pm 1.5_{stat} \pm 1.4_{syst}) \cdot 10^{-4} = (-1.5 \pm 2.2) \cdot 10^{-4} \quad (4)$$
$$A_g^n = (1.8 \pm 1.7_{stat} \pm 0.5_{syst}) \cdot 10^{-4} = (1.8 \pm 1.8) \cdot 10^{-4} \quad (5)$$

The precision achieved in NA48/2 in the final measurements of the A_g asymmetries is one order of magnitude better than the previous measurements. Similar precisions have been obtained for both $\pi^\pm\pi^+\pi^-$ and $\pi^\pm\pi^0\pi^0$ decays, despite a factor 30 in the data statistics, due to the fact that the population density of the Dalitz plot is more favorable in the neutral mode. The results are compatible with the SM, an no hints of CP violation have been found. However the high precision achieved could be effectively used to constrain SM extensions which predict enhancements of the asymmetries.

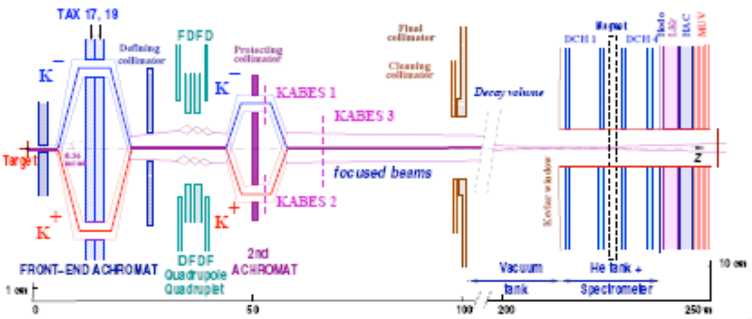

FIGURE 4. A view of the NA48/2 simultaneous charged kaon beams and of the detector

Rare Kaon Decays

The study of rare kaon decays has several motivations. Physics beyond SM (BSM) can be addressed through the search for explicit lepton flavour violation, predicted at some level in many theoretical models. Lepton flavour violation can be pursued to remarkable sensitivity in kaon leptonic and semileptonic processes which violate the lepton number conservation, with excellent signature. Measurements of kaon rare decays, proceedings through FCNC, allowed but strongly suppressed in SM, are also potentially very sensitive to BSM physics. Kaon decays dominated by long-distance contributions are useful tools to sharpen theoretical techniques, such as Chiral Perturbation Theory, aimed to describe the low energy behavior of QCD. The Unitarity Triangle (UT) derived from $V^*_{ub}V_{ub}+V^*_{cb}V_{cb}+V^*_{tb}V_{tb}=0$ can be completely settled with measurements of rare K decays [17].

A renewed interest in rare kaon decays appeared in the recent years, focusing the attention to the rare decays $K \to \pi\nu\bar{\nu}$. These processes are theoretically very clean, since they are dominated by short-distance contributions. The main transition involved at the quark level in these modes is $s \to d\nu\bar{\nu}$, which proceeds through Z penguins and box diagrams. Contributions from heavy c and t quarks dominate the decay amplitudes [18] and the hadronic matrix element can be precisely derived from the well measured $K^+ \to \pi^0 e^+ \nu$ process, using isospin asymmetry [19]. Direct CP violating short distance contributions, from t quark, dominates the $K_L^0 \to \pi^0\nu\bar{\nu}$ mode.

The accurate measurement of the branching fractions of the $K \to \pi\nu\bar{\nu}$ modes leads to the precise determination of the height and the hypotenuse of the above UT, represented in the (η, ρ) complex plane, in a completely independent way from B meson measurements. The uncertainty on the theoretical calculation of the branching fractions is at the level of a few percent; improvements are expected in the next future thanks to NNLO calculations. The measurement also gives important information on BSM physics, since any deviation from SM would contribute to it with remarkable effects, at the level of 10%-20% in MSSM [20] and up to 50% in Minimal Flavour Violation models [21]. Together with a few observable in the B sector, these decay modes are optimal probes for the precision study of flavour physics.

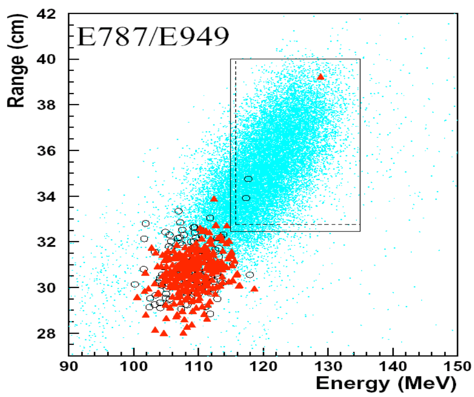

FIGURE 5. The three $K^+ \to \pi^+\nu\bar{\nu}$ events detected by the E787 and the E949 experiment al BNL. The distribution of events as a function of the pion range in the scintillator stack and its measured energy, together with the signal boxes, is shown.

All the above reasons strongly motivate new experiments aiming to measure the branching ratio of the $K \rightarrow \pi\nu\bar{\nu}$ decays at an accuracy of at least 10%. However, the experimental difficulties to detect such decay modes are overwhelming. In fact, the final state is not kinematically constrained, due to the presence of two undetected neutrinos, which is a serious issue for decays with an amount of background events 10^{10} times larger than the signal ones.

The $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay is the only one which has been already measured among the rare decays being considered here. The first observation of this decay has been done by the E787 experiment at BNL, with a stopped kaon technique [22]. Together with the next generation experiment, E949, a total of 3 signal events was found [23], shown in figure 5. A value slightly higher than the SM expectation is obtained for the branching ratio

$$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (14.7\ ^{+13.0}_{-8.3}) \cdot 10^{-11} \quad \textit{(90\% CL)} \tag{6}$$

In order to reach an accuracy of the order of 10%, any new experiment should observe $O(100)$ events. The installation of an improved version of the E949 detector at the J-PARC facility in Japan has been proposed aiming to enlarge the signal events sample. Since no dedicated kaon beam-line is currently foreseen in the first phase of the J-PARC complex, the project could not possibly start before an upgrade of the accelerator facility.

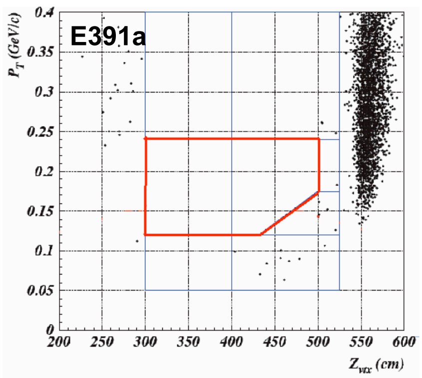

FIGURE 6. The search for the $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ process in the pilot project E391a at KEK: distribution of events after all the selection cuts as a function of the transverse momentum and of the longitudinal vertex coordinates, together with the signal box.

The search for the $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ decay, never observed so far, represents an even harder experimental challenge. The E391a pilot project is under way at the KEK PS [24]. Based on the 10% of the data sample, they quote the best available limit [25]

$$BR(K_L^0 \rightarrow \pi^0\nu\bar{\nu}) < 2.1 \cdot 10^{-7} \quad \textit{(90\% CL)} \tag{7}$$

The distribution of all the selected events as a function of the transverse momentum and of the longitudinal vertex coordinates is shown in figure 6, together with the signal box. The number of observed events is compatible with the expected background.

An improvement of one order of magnitude on the above limit is expected with the analysis of all the available data statistics. The E391a project is the first step toward a more ambitious experiment at J-PARC, which aims to collect 300 SM events in 3 years. The evolution of this concept depends on the results of the pilot project and the availability of a neutral kaon beam line at J-PARC.

The P326 proposal at CERN

An alternative approach, with kaon decays in flight, has been proposed in the project P326 at CERN, aiming to collect about 80 SM $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events with a 10% background, using a 75 GeV/c intense beam of not separated K^+ [26]. A background rejection factor of 10^{12} is required to fulfill this purpose. This is achieved with a substantial upgrade of the NA48 detector and some changes in the existing beam line. With this approach the challenges are not only the hermetic vetoing of photons, the requirement of redundant measurements and the high quality of the particle identification, but also the difficulty of tracking kaons in the ~ 1 GHz charged beam.

In $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events, the charged pion is the only observable particle in the final state. For this reason, both the pion and the kaon momenta should be measured independently. Assuming that the observed charged particle in the final state is a π^+ and that the decaying particle is a K^+, the missing mass squared m^2_{miss} distribution can be built from the measured p_k, p_π and $\theta_{k\pi}$. This distribution can be used to distinguish between the signal and the background decays, as shown in figure 7 for the signal and the three dominant background modes $K^+ \rightarrow \mu^+ \nu$, $K^+ \rightarrow \pi^+ \pi^0$ and $K^+ \rightarrow \pi^+ \pi^+ \pi^-$, which amount to the 92% of the total. Additional rejection power from veto detectors is mandatory to get rid of the residual background events, mainly due to kinematically unconstrained decays. Excluding the zone around the $\pi^+\pi^0$ peak in the m^2_{miss} distribution (see figure 7), the signal can be selected within two regions defined by the missing mass resolution.

The P326 experimental technique requires primary kaons to be positively identified with a Cherenkov differential counter and their momentum to be measured in a dedicated low mass, fast and high resolution spectrometer. A silicon pixel detector with integrated fast read-out (Gigatracker) is used to track primary hadrons at a rate of ~ 1 GHz. Minimum material budget and redundant measurements are the main requirements for the downstream spectrometer, tracking the pion in the final state. An innovative technique based on straw tubes operated in high vacuum is used in this case. Efficient and hermetic photon vetoes and muon identification capability are required in order to suppress the kinematically irreducible background and the events surviving the kinematic selection. Several detector elements are used to identify photons and reject the $\pi^+\pi^0$ background at the level of 10^{-8}: the NA48 Liquid Krypton calorimeter; a set of new photon detectors at larger angles, all along the decay region; a small angle calorimeter made with lead/scintillator sandwiches and wave-length shifting fibers readout, to cover the acceptance gap around the beam axis. A large RICH counter is foreseen in order to achieve a good π/μ separation in a wide momentum range. The detector layout proposed in P326 is illustrated in figure 7.

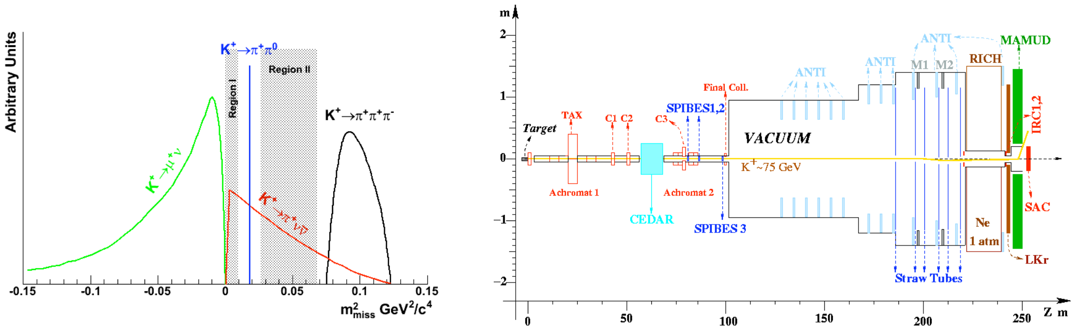

FIGURE 7. Experimental concepts in the P326 project: the m^2_{miss} distribution for the signal events and for the main background decays (left) and the layout of the proposed detector (right).

Conclusions

Kaon sector is quite lively and active and has still large potential to provide crucial quantitative information on the flavour sector of particle physics. Rare kaon decays are highly sensitive probes of the SM, particularly well suited to address BSM physics in addition to B meson measurements and in a completely independent way.

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