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Flavour physics and CP violation / Physique de la saveur et violation de CP

Role of kaon physics, present–future

Rôle de la physique des kaons, présent–futur

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ABSTRACT

The main issue for kaon physics in the next decade is a systematic study of the rare decay modes to test the unitarity of the quark flavour mixing matrix, the global symmetries of the Standard Model and new physics with the highest possible precision.

RÉSUMÉ

L'objectif central pour la physique des kaons dans la prochaine décennie est l'étude systématique des modes de désintégration rares, afin de tester l'unitarité de la matrice de mélange des saveurs de quarks, les symétries globales du Modèle Standard et de la nouvelle physique avec la plus grande précision possible.

1. Introduction

In 2008, Kobayashi and Maskawa (KM) received the Nobel Prize "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature". In fact, their key observation made in the early 1970s was simply based on a general theorem for the decomposition of any $N \times N$ unitary matrix [1]. To illustrate this theorem, let us consider the special case of unitary matrices V with equal elements in modulus. For $N = 2$, V can always be written as a $\frac{\pi}{4}$ rotation:

$$V = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ \nu & 1 \end{pmatrix}, \quad \nu = \exp(i\pi) \tag{1}$$

with $1 + \nu = 0$, known as the Euler relation and considered (together with the Maxwell's ones) as "the greatest equation ever" [2]. But for $N = 3$, one phase has to be introduced and

$$V = \frac{1}{\sqrt{3}}\begin{pmatrix} 1 & 1 & 1 \\ \omega & 1 & \omega^2 \\ \omega^2 & 1 & \omega \end{pmatrix}, \quad \omega = \exp\left(\frac{2i\pi}{3}\right) \tag{2}$$

with $1 + \omega + \omega^2 = 0$ ensuring unitarity, is a possible choice.

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The original KM link between a well-known mathematical property of $N \times N$ unitary matrices and the rather unexpected [3] observation of a broken CP symmetry in the K^0–$\bar{K}^0$ system [4] was the hypothetical existence of up-to-down flavour transitions between three generations of quarks ($N = 3$). Very briefly, CP-violation is equivalent to T-violation because of the CPT theorem in Quantum Field Theory. Also, the presence of a factor i in the commutation relations

$$\left[p^j, q^k\right] = -i\hbar\delta^{jk} \tag{3}$$

tells us that any complex numbers like the phase ω in the 3×3 transition matrix would imply time-reversal (T) non-invariance.

Such a T-violation is most naturally associated with the familiar arrow of time. Yet, one should not confuse T-violation in weak interactions [5], namely an asymmetry under the interchange of in-states and out-states

$$\mathrm{Prob}\left\{\bar{K}^0(t=0) \to K^0\left(t \approx 10^{-9}s\right)\right\} \neq \mathrm{Prob}\left\{K^0(t=0) \to \bar{K}^0\left(t \approx 10^{-9}s\right)\right\} \tag{4}$$

with macroscopic irreversibility due to very special boundary conditions. In General Relativity, for example, the classical equations at the basis of cosmology are invariant under the T-transformation ($t \to -t$) but the late expansion expected for our Universe

$$a(t) \propto \exp\left(\sqrt{\frac{\Lambda}{3}}t\right) \tag{5}$$

is due to a very special initial condition: Lemaître's "primeval atom" (with a Big Bang) and not Newton's "array of needles" (with a Big Crunch).

2. Role of kaon physics, present–past

The 3×3 unitary matrix V in Eq. (2), first considered by Cabibbo [6] in the context of $(\nu_e, \nu_\mu, \nu_\tau)$ oscillations, allows us [7] to easily display the useful geometrical connection between the *shape* of unitarity triangles (UT) and the *relative size* of CP-violation. Indeed, its associated unitarity conditions $(V^\dagger V)_{ij} = \delta_{ij}$ graphically represent a single equilateral triangle in the complex plane such that mixings and CP-violation are equally optimal in all favour changing processes. However this democracy turns out to be quite unrealistic for the relative strength V_{kj} of the quark charged currents.

In fact, an enigmatic misalignment of the weak eigenstates with respect to the strong (u, c, t) and (d, s, b) ones in the quark sector of the Standard Model rather implies off-diagonal KM matrix elements scaling (roughly) as powers of the Cabibbo angle λ [8] defined by the u-to-s flavour transition:

$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \propto \begin{pmatrix} 1 & \lambda & -\lambda^3\omega \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3\omega & -\lambda^2 & 1 \end{pmatrix}, \quad \lambda \approx 0.22 \tag{6}$$

In their paper [9], KM were "not concerned with higher states with the new quantum number". However, the discovery of a third (beautiful) flavour b with $-1/3$ electric charge in the late 1970s led to numerous ways to successfully test their model. Indeed, the only UT visible and directly accessible at $\vartheta(\lambda^3)$ is also (roughly) equilateral. Corresponding to the product of the first and third columns of the matrix in Eq. (6), namely $(V^\dagger_{\mathrm{CKM}} V_{\mathrm{CKM}})_{bd} = 0$, it is directly associated with B^0_d and not with K^0 physics.

At the beginning of the 21st century, the first results from the BABAR and BELLE B-factories turned out, indeed, to be in pretty good agreement with the KM theory for CP-violation in weak interactions. Nowadays, the CKM ansatz Eq. (6) with a single phase (roughly ω) is supported by the most precise data. Given the fact that CP-transformations in Quantum Field Theory simply amount to interchanging particles with anti-particles (see Eq. (4)), these data can be re-expressed in terms of a single time-dependent CP asymmetry

$$A^M_f(t) \equiv \frac{\mathrm{Prob}\{\bar{M}^0(t) \to f_{\mathrm{CP}}\} - \mathrm{Prob}\{M^0(t) \to f_{\mathrm{CP}}\}}{\mathrm{Prob}\{\bar{M}^0(t) \to f_{\mathrm{CP}}\} + \mathrm{Prob}\{M^0(t) \to f_{\mathrm{CP}}\}} \tag{7}$$

with f_{CP}, a common CP eigenstate. The following experimental data

$$A^K_{\pi\pi}(t = \infty) = +(3.32 \pm 0.04) \times 10^{-3} \tag{8}$$

$$A^K_{\pi\pi}(t = 0) = -(5.0 \pm 0.8) \times 10^{-6} \tag{9}$$

$$A^B_{J/\Psi K}\left(t \approx 310^{-12}s\right) = 0.673 \pm 0.023 \tag{10}$$

correspond, respectively, to three types of CP-violation, namely indirect CP-violation in mixing ($+2\,\mathrm{Re}\,\varepsilon$), direct CP-violation in decay ($-2\,\mathrm{Re}\,\varepsilon'$) and time-dependent CP-violation in the interference between mixing and decay ($\sin 2\beta$) [10]. These numbers, covering five orders of magnitude, can (again roughly) be understood from the CKM mixing matrix (6) with a pretty flat UT defined by the product of its first and second columns, namely the condition $(V^\dagger_{\mathrm{CKM}} V_{\mathrm{CKM}})_{sd} = 0$ clearly related to K physics. Furthermore, the CKM ansatz ensures the absence of tree-level flavour changing neutral currents (FCNC). This remarkable property invoked in the past to explain the following long-lived kaon rare decay and tiny K_L–K_S mass splitting [10]:

$$\mathrm{Br}\big(K_L \to \mu^+\mu^-\big) = (6.84 \pm 0.11) \times 10^{-9} \tag{11}$$

$$\Delta m_K = (3.483 \pm 0.006) \times 10^{-15}\ \mathrm{GeV} \tag{12}$$

is at present also nicely displayed in semi-leptonic K decays with, for example,

$$\vartheta\big(10^{-10}\big) = \mathrm{Br}\big(K^+ \to \pi^+\bar{\nu}\nu\big)^{\mathrm{exp}} \ll \mathrm{Br}\big(K^+ \to \pi^0 e^+\nu\big)^{\mathrm{exp}} = (5.08 \pm 0.05)10^{-2} \tag{13}$$

So, why is kaon physics still needed in the future?

- At the theoretical level, a primordial baryo-genesis would require a new source of CP-violation beyond the Standard Model (SM) to explain the matter–antimatter asymmetry in our present Universe and, eventually, our very existence. This may affect kaon physics entering now a precision era with the help of powerful tools such as chiral perturbation, $1/N$ expansion or lattice. These tools allow us to relate quark transitions to observed hadron transitions.
- At the phenomenological level, the observation of CP-violation is yet another compelling piece of evidence for a single elementary Higgs field which guarantees that the zero photon mass is not a mere accident [7]. However, its Yukawa interactions with the quarks at the source of the KM mixing matrix are arbitrary, leaving the hierarchical patterns of fermion masses and mixings unexplained in the SM. The resulting suppression of CP-violation in kaon physics is thus very peculiar and far from being automatic beyond the SM.
- At the experimental level, the CKM paradigm uniquely relates K to B physics and, in particular, Eq. (8) to Eq. (10). However, the impressive accumulation of more precise data regularly leads to tensions at the $(2\text{–}3)\sigma$ level when confronting them [11]. These anomalies trigger new and interesting works on possible physics beyond the SM, in a way similar to the "anomalous" precession of Mercury's perihelion with respect to Newton's gravity that has been a continuous guideline for Einstein in his attempts to formulate a covariant theory. But until now, they might simply be due to under-estimated experimental uncertainties or (and) unjustified theoretical approximations.

To illustrate this last point, let us consider the helicity-suppressed $B^+ \to \tau^+\nu_\tau$ decay whose probability appears to be larger than its SM expectation. This might of course indicate new physics with, for example, one extra (charged) Higgs field. Preferentially coupled to the heavy quarks and leptons, this new field would not affect the now well-measured K^+ (and π^+) leptonic decays. However, at the experimental level the first observation of $B^+ \to \tau^+\nu_\tau$ is quite recent, while at the theoretical level its weak annihilation amplitude is proportional to the B-meson decay constant f_B (numerically estimated in a space–time lattice) and the KM matrix element V_{ub} (extracted from challenging inclusive and exclusive semi-leptonic $b \to u\ell\nu$ transitions). But remember lessons from π and K physics in the past....

In 1958, Feynman and Gell-Mann [12] acknowledged the fact that their universal V–A theory for the Fermi interaction (i.e., the hypothetical equality between the vector coupling constant G_V in nuclear beta decays and the coupling constant G_μ in the muon decay) was "at variance with the fact that fewer than 10^{-4} pion decay into electron and neutrino". Indeed, the ratio R_π of $\pi \to e\nu$ to $\pi \to \mu\nu$ was then measured to be smaller than 2×10^{-5} at the 99% confidence level [13]. Today, the rather precise value for this ratio is $R_\pi^{\mathrm{exp}} = (1.230 \pm 0.004) \times 10^{-4}$, in agreement with the V–A theory.

In 1963, Cabibbo [8] carefully reanalysed this universal theory in the light of the kaon leptonic decay amplitude ($K^+ \to \mu^+\nu_\mu$) proportional to f_K and V_{us}. Assuming equal K and pi-meson decay constants ($f_K = f_\pi$) to extract the value $V_{us} = 0.26$, he had to admit that his hypothesis $G_V V_{ud} = G_\mu$ with $(V_{ud})^2 + (V_{us})^2 = 1$ would still leave a few percent discrepancy to be solved. Nowadays, we know that $f_K \approx 1.2 f_\pi$ such that the Cabibbo hypothesis is tested at the level of 0.06% with $V_{us} \approx 0.22$ (see Eq. (6)).

Tensions also arise now with new data on the B_s^0–$\bar{B}_s^0$ system, leading again to wild speculations about physics beyond the SM. For example, extra (neutral) Higgs fields with complex Yukawa couplings again proportional to the quark masses might be responsible for large tree-level FCNC (and CP-violation) effects in B_s mixing, but medium (small) ones in $B_d(K)$ mixing. This reminds us of one of the first theoretical attempts to explain the observed indirect CP-violation (8) in the K^0–$\bar{K}^0$ system, namely the hypothesis of a new "superweak" interaction [14] only efficient in the neutral $\Delta S = 2$ mixing. This model has been definitely ruled out by the remarkable measurement of a direct CP-violation (9) in $K^0 \to \pi\pi$ decays, with [10]

$$\mathrm{Re}\big(\varepsilon'/\varepsilon\big) = (16.5 \pm 2.6) \times 10^{-4} \tag{14}$$

and later on by the direct CP asymmetry in $B^0 \to K\pi$ decays with [10]

$$A_{CP}\big(B^0 \to K^+\pi^-\big) \equiv \frac{\mathrm{Prob}\{\bar{B}^0 \to K^-\pi^+\} - \mathrm{Prob}\{B^0 \to K^+\pi^-\}}{\mathrm{Prob}\{\bar{B}^0 \to K^-\pi^+\} + \mathrm{Prob}\{B^0 \to K^+\pi^-\}} = (-9.8 \pm 1.3)\% \tag{15}$$

Eqs. (14) and (15) constitute triumphs for high-precision experimentalists, but remain real challenges for theorists. On the one hand, despite tremendous efforts, large uncertainties on the hadronic matrix elements involved in ε' do not allow us to compute it so accurately. On the other hand, the observed relative sign between the $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ asymmetries remains puzzling from an isospin viewpoint.

3. Role of kaon physics, future

Very schematically based on the upcoming NA62 K^+-factory at CERN, KOTO K_L-factory at J-PARC, KLOE-2 K_S-factory at Frascati, as well as on proposed experiments at Fermilab, the main issue for kaon physics in the next decade is a systematic study of the rare decays to test the unitarity of the V_{CKM} mixing matrix (6) with the highest possible precision. With these forthcoming experiments, discovery physics as well as tests of global symmetries in the SM or beyond are also possible.

3.1. Rare decays (at NA62, P996, KOTO and KLOE-2)

Within the SM, the $s \to d$ FCNC's are fully absent at tree-level. Consequently, they are only induced via quantum loops and thus quite sensitive to either new physics beyond the Fermi scale (TeV) or to non-perturbative physics below the QCD scale (GeV). From this viewpoint, we may distinguish two classes of rare K decays [15]:

(1) Rare K decays dominated by short-distance (SD) effects (c and t quark loop contributions proportional to $V_{sc}^{\dagger} V_{cd}$ and $V_{st}^{\dagger} V_{td}$, respectively). They provide quite interesting information on the complex V_{td} matrix element in Eq. (6) and are obviously sensitive to new physics beyond the SM. The golden mode in this class of rare decays is definitely the neutral decay $K_L \to \pi^0 \bar{\nu}\nu$. It is essentially free of hadronic uncertainties and dominantly CP-violating via an interference between mixing and decay, providing thus a measure of the V_{td} phase within the convention of Eq. (6). The related charged mode $K^+ \to \pi^+ \bar{\nu}\nu$ already mentioned in Eq. (13) is also under control at the theoretical level since its hadronic matrix element can be safely extracted from semi-leptonic decays like $K^+ \to \pi^0 e^+ \nu$, using isospin symmetry. Few of those events have already been observed so that the error on the branching ratio determination is large. More precise data on this mode would thus provide a quite interesting constraint on the modulus of V_{td} this time.

(2) Rare K decays dominated by long-distance effects (LD) (virtual up quark contributions proportional to $V_{su}^{\dagger} V_{ud}$). They are mostly radiative modes but should not be forgotten since they may help to disentangle potentially interesting SD contributions from the LD ones in rare decays like $K_L \to \pi^0 \ell^+ \ell^-$ if more precise measurements of the channels $K_S \to \gamma\gamma$, $K_L \to \pi^0\gamma\gamma$ and $K_S \to \pi^0 \ell^+ \ell^-$ are available. Other radiative channels like $K_L \to \gamma\gamma$, $K^+ \to \pi^+\gamma\gamma$ and $K_S \to \pi^0\gamma\gamma$ would also be useful to get further information about the SD physics behind the well-known $K_L \to \mu^+\mu^-$ process and K_L–K_S mass splitting given in Eqs. (11), (12).
Radiative K-decays are also sensitive to SD top contributions and hypothetical new physics via direct CP asymmetries analogous to Eq. (15). The first ones for charged $|\Delta S| = 1$ transitions might possibly be observed in $K^+ \to \pi^+\pi^0\gamma$ and $K^+ \to \pi^+ \ell^+ \ell^-$.

There are different experimental programs that aim at improving the experimental knowledge of rare Kaon decays.

Concerning $K^+ \to \pi^+ \nu\bar{\nu}$, two very different approaches are possible: the in-flight technique (NA62), requiring an extended decay region in high-vacuum and excellent vetoing capabilities, or the stopped-Kaon technique (P996), ensuring high purity thanks to electro-magnetic static separators:

- At CERN, the NA62 experiment has been approved and will start data-taking around year 2013, with a detector re-using the beam-line and the liquid Krypton calorimeter of the NA48 experiment. An intense unseparated hadron beam will produce 10^{13} Kaon decays per year. High-efficiency photon and muon vetoing capabilities, as well as full kinematic reconstruction of the mother K and daughter π with exceptional time resolution, will ensure a 10% acceptance for $\pi^+\nu\bar{\nu}$ decays. About 80 SM events per year are expected. The veto detectors, together with the over-constrained kinematical reconstruction, will ensure a signal to background better than 10.
- At Fermilab, the P996 experiment has been proposed in the framework of the Project-X high-intensity proton complex under evaluation by the U.S. DoE, using the Main injector protons and the Tevatron as stretcher (construction 2015–2019). The aim is of collecting 200 SM events using the E949 stopped-Kaon technique with a 10 times improved acceptance and improved photon veto detectors.

Concerning $K_L \to \pi^0 \nu\bar{\nu}$, the E14 proposal at J-PARC (KOTO experiment) plan is to improve the E391a pilot experiment sensitivity by a factor 3000, thus reaching a single event sensitivity at the level of the SM expectation in 3 years with 2×10^{14} protons on target. This can be achieved with a dedicated neutral kaon beam-line in the J-PARC complex, a superior photon veto performance by a CsI calorimeter, and reduced neutron halo. A first run aiming at reaching the Grossman–Nir isospin bound (inferred from the observed $K^+ \to \pi^+\nu\bar{\nu}$) is planned before the summer 2012 shut-down. Another K_L experiment at Fermilab, with a detector capable of determining the kaon energy with time-of-flight technique and a 4π coverage of neutral and charged particles, has been also presented in the framework of the Project-X proposals.

Concerning K_S rare decays, KLOE will resume data taking in 2011 with the same detector. An upgrade of low-theta calorimeters and tracker is planned after having collected 5 fb^{-1}. About 20 fb^{-1} should then be collected, so that the error on $K_S \to \gamma\gamma$ would go down to 1%, with a few $K_S \to \pi^0 \ell^+ \ell^-$ events expected.

3.2. Test of lepton flavour conservation (at NA62, KLOE-2 and J-PARC P36)

As we have recalled above, very precise measurements of leptonic decays played a central role in our understanding of the weak interactions. In the highly helicity-suppressed $K^+ \to e^+\nu$ decay, the neutrino flavour is undetermined experimentally. So, small contaminations from ν_τ due to lepton flavour violation beyond the SM cannot be ruled out. The presently measured $K^+ \to e^+\nu$ to $K^+ \to \mu^+\nu$ ratio [16]

$$R_K^{\text{exp}} = (2.486 \pm 0.013) \times 10^{-5} \tag{16}$$

is consistent with the SM expectation proportional to m_e^2/m_μ^2, though one order of magnitude less precise.

Considering $10^{13} K^+$ decays/year, an improvement of at least a factor 2 can be expected from another two-years run at the NA62 experiment.

With a 20 fb^{-1} data-sample, KLOE-2 could also reach a 0.3% statistical error.

A dedicated experiment, using a stopped-Kaon technique similar to the Brookhaven E949 experiment, has been proposed at J-PARC (P36 proposal), aiming to 0.1% accuracy, using a new low-energy, electro-statically separated K^+ beam currently being commissioned. The P36 is under evaluation and data-taking could start in a few years after experiment approval and construction.

3.3. Test of CPT (and Lorentz) invariance (at KLOE-2)

Another early attempt to explain the CP asymmetry given in Eq. (8) was a violation of CPT via a long-range vector field coupled to hypercharge [17]. This T-invariant source of CP-violation assigned to a local preponderance of matter over anti-matter has been ruled out because the expected velocity dependence of the decay rate due to the violation of Lorentz invariance did not show up. But more recently, attempts to merge the Standard Model with General Relativity into a (non-local) unified theory (e.g., strings or loop quantum gravity) suggest departures from the CPT invariance at energies below the Planck scale. The present lower limit [10]

$$\left|M_K - M_{\bar{K}}\right| < 4 \times 10^{-19}\ \text{GeV} \tag{17}$$

on the mass difference between K^0 and $\bar{K}^0$ is not so far away from the naïve expectation $M_K^2/M_{\text{Planck}} \approx 0.2 \times 10^{-19}$ GeV based on simple dimensional considerations.

The KLOE-2 experiment aims at reaching the 10^{-19} range by improving the measurement of the time-dependent asymmetries of the decays $\phi \to K_S K_L \to$ four pions, improving the acceptance of low-theta particles, and profiting of the higher luminosity of the DAFNE collider.

3.4. Search for a light neutral boson (at NA62 and KLOE-2)

Very light, long-lived X^0 particles associated with spontaneously broken global symmetries beyond the SM could, in principle, be produced in the rare $K^+ \to \pi^+ X^0$ process, but the sensitivities that can be reached depend on the trigger efficiency. In fact, the original Peccei–Quinn axion can be excluded on the sole basis of the present lower bound such that the strong theta (θ_S) puzzle, namely P- and T-violations in strong interactions, remains unsolved at the weak scale. At this point, it is worth warning that the Two-Higgs-Doublet Models often invoked to relax tensions in flavour physics generically induce a (too) large θ_S at one-loop level, in conflict with the present limit on the P- and T-violating neutron electric dipole moment.

4. Conclusion

Elementary particles are mostly interesting for the fundamental laws they may reveal through their interactions at small distances. In particular, the four known basic forces of nature turn out to proceed from a universal gauge principle, and the mechanisms put forward to prevent long-range nuclear forces (namely, spontaneous symmetry breaking and confinement) form nowadays the cornerstone of the Standard Model. Such subtle ways to get round gauge invariance are highly suspected to be responsible for an explicit violation of the invariance under time-reversal in weak ($\delta_{\text{KM}} \neq 0$) and strong ($\theta_S \neq 0$) interactions, respectively. In other words, T-violation appears to be peculiar to short range nuclear forces. This striking interplay between gauge invariance and time-reversal symmetry challenges us for decades. A systematic and precise study of K rare decays would be a unique probe for testing simultaneously flavour conservation in neutral currents, CP-violation in charged currents and lepton universality in weak interactions. Any deviation from these intrinsic properties of the Standard Model would be evidence for new physics to be seen directly at colliders.

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