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Rare Kaon Decays $K \longrightarrow \pi\nu\bar{\nu}$ and $K_L \longrightarrow \pi^0\ell^+\ell^-$

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Over the next years, the Flavour Physics community will be looking for inconsistencies of the Standard Model (SM) by exploiting new and precise measurements. In these “indirect new physics” searches, the key strategy is to concentrate on observables, which are theoretically clean and preferably suppressed in the SM. In this respect, the four golden modes $K^+ \rightarrow \pi^+\nu\bar{\nu}$, $K_L \rightarrow \pi^0\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\ell^+\ell^-$ are very promising.The pollution from hadronic uncertainties in these decays is at present under control with good accuracy, thanks to the interplay between theory information (Chiral Perturbation Theory and OPE) and experimental inputs (KTeV, NA48). Their measurements might thus give rise to some unexpected scenario. Here, we briefly review the present situation for these four exclusive rare decays.

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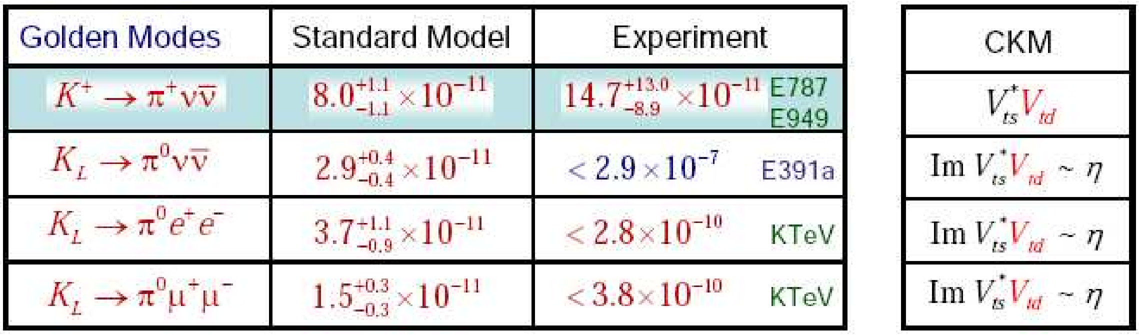
1. Introduction

The present theoretical and experimental scenario for the four modes discussed here is sketched in the table below:



Golden Modes	Standard Model	Experiment		CKM
$K^+ \to \pi^+ \nu\bar{\nu}$	$8.0^{+1.1}_{-1.1} \times 10^{-11}$	$14.7^{+13.0}_{-8.9} \times 10^{-11}$	E787 E949	$V_{ts}^* V_{td}$
$K_L \to \pi^0 \nu\bar{\nu}$	$2.9^{+0.4}_{-0.4} \times 10^{-11}$	$< 2.9 \times 10^{-7}$	E391a	$\mathrm{Im}\, V_{ts}^* V_{td} \sim \eta$
$K_L \to \pi^0 e^+ e^-$	$3.7^{+1.1}_{-0.9} \times 10^{-11}$	$< 2.8 \times 10^{-10}$	KTeV	$\mathrm{Im}\, V_{ts}^* V_{td} \sim \eta$
$K_L \to \pi^0 \mu^+ \mu^-$	$1.5^{+0.3}_{-0.3} \times 10^{-11}$	$< 3.8 \times 10^{-10}$	KTeV	$\mathrm{Im}\, V_{ts}^* V_{td} \sim \eta$

Even though difficulties to measure these decays (with missing energy and branching ratios below 10^{-10}) are very high, three events for $K^+ \to \pi^+ \nu\bar{\nu}$ have been already observed at BNL by the E787-E949 experiments [1]. The corresponding measure turns out to be twice higher than the SM, but compatible within the large error. For the future, experimental progress is connected to the recent NA48 proposal. Their project is to collect about 80 $K^+ \to \pi^+ \nu\bar{\nu}$ events in two years starting from 2010. For the other modes, the experimental situation is less settled down. For the $K_L \to \pi^0 \nu\bar{\nu}$ decay, the E391a Collaboration has improved, this summer [2], the upper limit fixed earlier by KTeV. They have analyzed 10% of their first run and the third one is being finished. At the end, they plan a 10^{-10} sensitivity close to the SM limit and to possible surprises. Moreover, E391a is intended to be a pilot experiment at JPARC for a more ambitious project of $\mathcal{O}(100)$ $K_L \to \pi^0 \nu\bar{\nu}$ events. For the two other modes, the best experimental knowledge is from KTeV but no new experiments are planned yet. The advantage of these decays is that all the decay products can be detected and this should not be ignored.

From the theoretical point of view, these decays arise from FCNC one-loop transitions. For this reason, they provide an independent scrutiny of V_{td} from unexplored sectors: $\Delta S = 1$ at one-loop level. Indeed, the flavor dynamics [3] has been mostly investigated on the $\Delta B = 1, 2$ and $\Delta S = 2$ transitions. Due their theoretical cleanness, they could also shed light on the nature of new physics [4–7], when new particles will be directly observed at LHC.

In what follows, we will review the theoretical status of these decays, with emphasis on recent progress to reduce the hadronic uncertainties.

2. Hadronic uncertainties: Long Distance effects and power Corrections

The short-distance (SD) contributions to these decays are described at leading order [8] by

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_{q=u,c,t} \lambda_q \left(c_\nu^q (\bar{s}d)_{V-A} (\nu\bar{\nu})_{V-A} + c_V^q (\bar{s}d)_{V-A} (\ell^+\ell^-)_V + c_A^q (\bar{s}d)_{V-A} (\ell^+\ell^-)_A \right) \qquad (2.1)$$

with $\lambda_q = V_{qs}^* V_{qd}$. c_ν^q and c_A^q encode W-boxes and Z-penguins, whereas c_V^q Z- and $\gamma-$ penguins.

Due to the power-like GIM enhancement in Z- and W-mediated processes, top loops represent the leading contributions to eq. (2.1) and are computable in perturbation theory with high precision. The hadronic uncertainty then due to $\langle \pi | (\bar{s}d)_{V-A} | K \rangle$ in eq. (2.1) is accurately determined by the $K_{\ell 3}$ rates (modulo isospin corrections). According thus to the relative strength of the top contribution, these decays are more or less theoretically clean. Being for example $K_L \to \pi^0 \nu\bar{\nu}$ a CP-violating

(CPV) process, the GIM mechanism along with the CKM hierarchy makes CPV effects from charm and up completely negligible [9], $\leq 1\%$, and the corresponding decay turns out to be the cleanest of these four modes. Unlike $K_L \to \pi^0\nu\bar{\nu}$ charm and up loops can however contribute to the others through CPV-effects mediated by γ [1] and/or CP-conserving (CPC) effects mediated by γ and Z. In this case, for both $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\ell^+\ell^-$ charm and up can induce hadronic uncertainties in terms of $\mathscr{O}(G_F)$ electro-weak corrections to the non-leptonic $\Delta S = 1$ operators. At present, all these contributions are small and/or under good theoretical control. Moreover, their present knowledge could be also improved by means of lattice QCD [10].

In the case of CP-conserving transition $K^+ \to \pi^+\nu\bar{\nu}$ for example, the top enhancement with respect to the charm is partially compensated by the CKM coefficient ($|V_{cs}^*V_{cd}| \approx 10^3 \times |V_{ts}^*V_{td}|$) and the charm then amounts to about 35% of the total magnitude. Due to the low value of the charm mass, close to the non-perturbative regime, either NNLO QCD corrections for the coefficient y_ν^c in (2.1) or subleading terms $\propto 1/m_c^2$ not described by the Hamiltonian in eq. (2.1) cannot be completely neglected. The NNLO calculation has been recently performed in [12] and y_ν^c is now known with a relative precision of about 9%. This translates into an error of about 5% in the SM estimate of $Br(K^+ \to \pi^+\nu\bar{\nu})$. For the subleading terms, we have both dimension-eight four-fermion operators generated at the charm scale, and genuine $\Delta S = 1$ long-distance contributions which can be described within the framework of Chiral Perturbation theory (ChPT). In [13], we have shown that a consistent treatment of the latter contributions, which turn out to be the dominant effect, requires the introduction of new chiral operators already at $O(G_F^2 p^2)$. Using this new chiral Lagrangian, an approximate matching between short- and long-distance components has been performed and from the numerical point of view, these corrections enhance the SM prediction of $Br(K^+ \to \pi^+\nu\bar{\nu})$ by about 6%. A residual

Finally, in the case of $K_L \to \pi^0 l^+ l^-$, the SD Hamiltonian in (2.1) takes into account only the direct CPV effects from top ($\sim i\lambda^5 m_t^2/m_W^2$) and charm ($\sim i\lambda^5 \log(m_c^2/m_t^2)$) loops. However, because of the presence of the up contributions mediated by photon penguins, the $K_L \to \pi^0 l^+ l^-$ modes receive also two long-distance contributions: indirect CP-violation (ICPV) and CPC contributions. In addition, DCPV and ICPV components interfere with each other and the sigh of this interference contribution (INTF) has to be fixed as well. More specifically, through the $K^0 - \overline{K^0}$ mixing, the CPC decay $K_1 \to \pi^0 l^+ l^-$ gives rise to a ICPV contribution to the $K_L \to \pi^0 l^+ l^-$, computable in ChPT [11] using the recent measurements of the $K_S \to \pi^0 l^+ l^-$ modes [14]. A constructive interference is favored now by two works [15, 16].

The CPC contribution instead proceeds through two virtual photons and has been recently determined [15, 17] by a precise study of the decay $K_L \to \pi^0\gamma\gamma$ [18]. Finally, the pattern for the *BR*'s in the SM ($\mathrm{Im}\lambda_t \sim 1.36\,10^{-4}$) is:

$$BR(K_L \to \pi^0 e^+ e^-)_{SM} \approx (23_{ICPV} + 10_{INTF} + 4_{DCPV}) \times 10^{-12}\,, \tag{2.2}$$

$$BR(K_L \to \pi^0 \mu^+ \mu^-)_{SM} \approx (5.4_{ICPV} + 2.5_{INTF} + 2_{DCPV} + 5_{CPC}) \times 10^{-12}\,, \tag{2.3}$$

where the irreducible theoretical error on the various contributions is around 10%. The INTF term is portional to $\mathrm{Im}\lambda_t$, whereas the DCPV to $\mathrm{Im}\lambda_t$ squared. This means that despite of dominance

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[1] For the γ-penguins, the GIM mechanism is only logarithmic, so that up and charm can be sizable, namely $\log(m_q/M_W) \gg \log(m_t/M_W)$.

of the long-distance indirect CP-violating contribution we are still able to uncover with relatively good accuracy the short-distance part related to λ_t (and possibly sensitive to new physics).

3. Summary and Prospects

In conclusion, estimating all the hadronic uncertainties (LD effects) with good accuracy, SD contributions and thus potential new physics effects can be clearly unveiled. In perspective, these decays are as promising as $\sin 2\beta$ from $B \to J/\psi K_S$ in the B-factory era.

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