STUDIES ON RARE K DECAYS

Including results presented up to
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P r e l i m i n a r y

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The CKMfitter Group

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1 Theoretical status

Theoretically clean constraints on the CKM matrix can be obtained from rare kaon decays with two neutrinos in the final state, as they can only arise via second-order weak transitions (Z-penguins and box) within the Standard Model (SM), and light-quark loops are strongly GIM-suppressed. Moreover, the $K \to \pi\nu\bar{\nu}$ decay amplitudes are sensitive to potential contributions from BSM physics, which could provide sizeable deviations with respect to the SM.

Within the SM, the $K^+ \to \pi^+\nu\bar{\nu}$ decay rate is given by [1–5]:

$$\mathcal{B}[K^+ \to \pi^+\nu\bar{\nu}]_{\rm SM} = \kappa_+ \left(1 + \Delta_{em}\right) \left[\left(\frac{Im\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{Re\lambda_c}{\lambda} \left(P_c + \delta P_{c,u}\right) + \frac{Re\lambda_t}{\lambda^5} X_t \right)^2 \right], \quad (1)$$

where the isospin-breaking parameter κ_+ can be extracted from semileptonic K decays with a correction Δ_{em} for the photon cut-off dependence, the X_t functions contain the top-quark contributions, and the light-quark contributions are given by P_c and $\delta P_{c,u}$, which are the dominant theoretical uncertainties. Similarly, the SM decay rate for the $K_L \to \pi^0\nu\bar{\nu}$ mode is given by [1, 5]:

$$\mathcal{B}[K_L \to \pi^0\nu\bar{\nu}]_{\rm SM} = \kappa_L \left(\frac{Im\lambda_t}{\lambda^5} X_t \right)^2, \quad (2)$$

with only small residual uncertainties from the isospin-breaking parameter κ_L and scale invariance.

In terms of CKM parameters, a measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ provides a quasi-elliptical constraint in the $(\bar{\rho}, \bar{\eta})$ plane, with a cener close to the vertex of the unitarity triangle located at $(1, 0)$. This can also be interpreted as an indirect constraint on the $|V_{td}|$ CKM matrix element. For the $K_L \to \pi^0\nu\bar{\nu}$ decay mode, a measurement of its branching ratio would provide a clean constraint on the absolute value of the CKM $|\bar{\eta}|$ parameter.

The current SM prediction for the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio is $(0.882^{+0.092}_{-0.098}) \times 10^{-10}$. For $K_L \to \pi^0\nu\bar{\nu}$, the corresponding prediction is $(0.314^{+0.017}_{-0.018}) \times 10^{-10}$. Table I lists the inputs and parameters used in the analysis of $K \to \pi\nu\bar{\nu}$ decays with CKMfitter.

2 Experimental statuts

2.1 $K^+ \to \pi^+\nu\bar{\nu}$

The BNL-E787 experiment [7] identified two $K^+ \to \pi^+\nu\bar{\nu}$ candidates in their data sample. Given the smal expected background rate (0.15 ± 0.03 events) the null hypothesis was already strongly disvafoured by this result. The BNL-E949 experiment [8] identified in a first step an additional candidate near the upper kinematic limit, and added three additional candidates in the analysis of their final data sample [9, 10]. For the combined E787+E949 results, the estimated total background amounts to $0.93 \pm 0.17^{+0.32}_{-0.24}$ events, and the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio is measured to

Name	Value	Ref.	Comment
$\overline{m}_t(m_t)$	$165.95 \pm 0.35 \pm 0.64$ GeV	[6]	Top quark mass ($\overline{\text{MS}}$ scheme)
$\overline{m}_c(m_c)$	$1.286 \pm 0.013 \pm 0.040$ GeV		Charm quark mass ($\overline{\text{MS}}$ scheme)
$\alpha_S(m_Z)$	$0.1185 \pm 0 \pm 0.0006$		Strong coupling constant
η_X	0.994	[2]	QCD correction factor to the top contribution
δP_{cu}	$0.04 \pm 0 \pm 0.02$		Charm quark contribution combined with long-distance contribs. at the charm quark scale
κ_{ν^+}	$(0.5173 \pm 0.0025) \times 10^{-10}$	[5]	Higher-order EW corrs. to matrix element
κ_{ν_L}	$(2.231 \pm 0.0013) \times 10^{-10}$		Higher-order EW corrs. to matrix element
Δ_{EM}	-0.003	[3]	Long distance QED corrections
κ_{10}	1.6624		Expansion coefficient in linearized formula for P_c
κ_{01}	-2.3537		Expansion coefficient in linearized formula for P_c
κ_{11}	-1.5862		Expansion coefficient in linearized formula for P_c
κ_{20}	1.5036		Expansion coefficient in linearized formula for P_c
κ_{02}	-4.3477		Expansion coefficient in linearized formula for P_c

Table 1: Numerical values of parameters used as input for the analysis of rare kaon decays. When indicated, the total uncertainty is splitted into two components: the first one is statistical in nature and the second one is theoretical in nature, and is treated following the RFit approach.

be $1.73^{+1.15}_{-1.05} \times 10^{-10}$. The probability of a background fluctuation is 0.001 and a 90% C.L. upper limit at 3.35×10^{-10} is set.

The NA62 experiment at CERN is currently taking data (for recent status reports, see e.g. [11] and references therein), and aims at collecting a data sample containing some $\mathcal{O}(100)$ signal candidates by 2017, with a background rate controlled to the level of a few percent. NA62 therefore aims at measuring the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio with a $\pm 10\%$ accuracy.

2.2 $K_L \to \pi^0\nu\bar{\nu}$

The $K_L \to \pi^0\nu\bar{\nu}$ decay has not been observed yet. The best current limit on its branching ratio is provided by the KEK-E391a experiment [12], and is 2.6×10^{-8} at 90% C.L. The KOTO experiment (see e.g. [13] and references therein) is currently taking data, and has already achieved 1.1×10^{-8} single-event sensitivity. At a first stage, KOTO aims at surpassing SM sensitivity with their ongoing data-taking, which would translate into a $\sim 3\sigma$ constraint on the branching ratio. At a second stage, KOTO expects to measure the $K_L \to \pi^0\nu\bar{\nu}$ branching ratio with a $\pm 10\%$ accuracy.

2.3 Prospective studies

In the context of this note, the future NA62 measurement is assumed to be in agreement with the SM prediction, namely $BR(K^+ \to \pi^+\nu\bar{\nu})_{\text{NA62}} = (8.50 \pm 0.85) \times 10^{-11}$. In a similar spirit, the future KOTO results are assumed to be in agreement with the SM prediction, with an accuracy expected to be reached in two steps, namely $BR(K_L \to \pi^0\nu\bar{\nu})_{\text{KOTO1}} = (2.8 \pm 0.9) \times 10^{-11}$ at the first stage, and $BR(K_L \to \pi^0\nu\bar{\nu})_{\text{KOTO2}} = (2.78 \pm 0.28) \times 10^{-11}$ for the final KOTO result.

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