Kaon Experiments WG – Summary of activities and roadmap

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Rare Kaon decays provide e a unique opportunity to explore the flavor sector of any extension of the Standard Model (SM). The WG activities focused on two main thrusts:

- Theory: We explored the new-physics discovery potential and model discriminating power of rare K decays. This is essential to establish target precision that should be pursued with Project X at Fermilab.
- Experiment: We had a summary of the landscape of existing and planned Kaon experiments over the next decade, and we discussed experimental opportunities at the various phases of Project X.

1 Theory Summary

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1.1 Rare K decays in the Standard Model: current status and 2020 forecast

The theory discussion focused primarily on the four theoretically cleanest flavor changing neutral current (FCNC) Kaon decays, namely, $K^+ \to \pi^+\nu\bar{\nu}$ $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \pi^0 e^+e^-$, and $K_L \to \pi^0\mu^+\mu^-$. Because of the peculiar suppression of the SM amplitude (loop level proportional to V_{us}^5 which does not have to be present in SM extensions) kaon FCNC modes offer a unique window on the flavor structure of SM extensions. The actual "discovery potential" depends on how well we can predict these rare decays in the SM and how well we can measure their BRs. State-of-the-art predictions are summarized in Table 1 and show that we currently know the BRs $K^+ \to \pi^+\nu\bar{\nu}$ at the 10% level, $K_L \to \pi^0\nu\bar{\nu}$ at the 15% level, while $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$ at the 25-30% level. In the charged lepton modes, the uncertainty is dominated by long distance contributions which are parameterized in terms of the rates of other decays (such as $K_S \to \pi^0\ell^+\ell^-$). In the neutrino modes, the irreducible theoretical uncertainty is a small fraction of the total uncertainty, which is dominated by the uncertainty in the CKM parameters that enter the prediction. It can be forecast that in the next decade progress in lattice QCD combined with progress in B meson measurements (LHCb and Super-Belle) will allow one to reduce the uncertainty on both $K \to \pi\nu\bar{\nu}$ to the 5% level. Substantial improvements in $K_L \to \pi^0\ell^+\ell^-$ will have to rely on lattice QCD computations, requiring the evaluation of bi-local operators. Exploratory steps exist in this direction, but these involve new techniques and it is hard to forecast the level of uncertainty that can be achieved, even in a ten-year timescale. Therefore, from a theory perspective, the golden modes remain both $K \to \pi\nu\bar{\nu}$ decays, because they suffer from small long-distance contamination (negligible in the CP violating K_L mode).

mode	Standard Model	Experiment
$K^+ \to \pi^+\nu\bar{\nu}$	$7.81(75)(29) \times 10^{-11}$	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ E787/949
$K_L \to \pi^0\nu\bar{\nu}$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a
$K_L \to \pi^0 e^+e^-$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 28 \times 10^{-11}$ KTEV
$K_L \to \pi^0\mu^+\mu^-$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 38 \times 10^{-11}$ KTEV

Table 1: Summary of current SM predictions and experimental limits for the four cleanest rare K decays. In the SM predictions, the first error is parametric, the second denotes the intrinsic theoretical uncertainty.

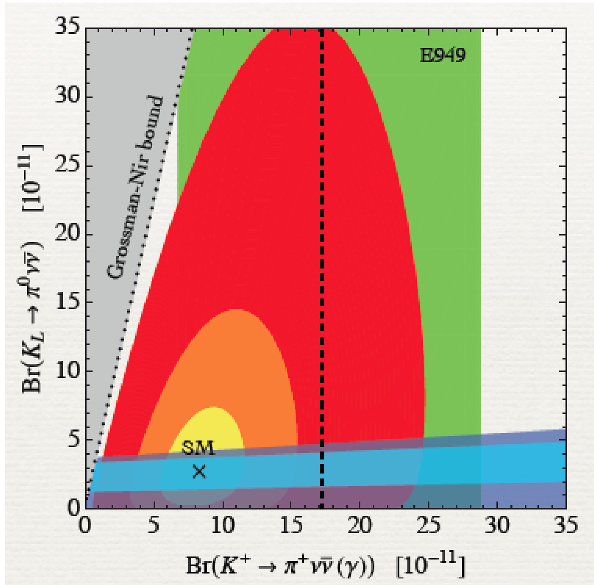

Figure 1: Discovery potential in the $Br(K_L \to \pi^0 \nu\bar{\nu})$ vs $Br(K^+ \to \pi^+ \nu\bar{\nu})$ plane, under the assumption of Z-penguin dominance. The most important constraint is given by the light blue band, corresponding to the requirement that $\epsilon'/\epsilon \in [0.2, 5](\epsilon'/\epsilon)_{SM}$ (from U. Haisch contribution).

1.2 Beyond the Standard Model physics reach

Besides assessing the current theoretical status within the SM, in the WG we have addressed the BSM reach of rare FCNC K decays in some detail. In absence of an emerging candidate for the "New Standard Model" (this might change as more data from the LHC are analyzed) the case for discovery potential and model discriminating power can be presented very efficiently in terms of an effective field theory (EFT) approach to BSM physics. In this approach, one parameterizes the effect of new heavy particles in terms of local operators which carry dimensionful couplings, suppressed by inverse powers of the heavy new physics mass scale: the prototype for this is the Fermi-Lee-Yang theory of beta decay. The important point is that the EFT approach allows us to make statements that apply to classes of models, not just any specific SM extension. In this context, one can ask two important questions: (i) how large of a deviation from the SM can we expect in rare decays, given all the constraints from $\Delta S = 1$ processes? (ii) if a given class of operators dominates, what pattern of deviations from the SM can we expect in various rare K decays? Concerning the golden modes, the main conclusion of this analysis is that assuming the dominance of "Z-penguin" operators (which is realized in many models including MSSM and Randall-Sundrum warped extra dimensions models), then ϵ'/ϵ provides a the strongest constraint on the CP violating mode $K_L \to \pi^0 \nu\bar{\nu}$. This is illustrated in Fig 1, where one can see that the requirement $\epsilon'/\epsilon \in [0.2, 5](\epsilon'/\epsilon)_{SM}$ limits deviations in the $K_L \to \pi^0 \nu\bar{\nu}$ to be at most 50%. On the other hand, larger deviations in the CP conserving mode $K^+ \to \pi^+ \nu\bar{\nu}$ are still allowed. This conclusion holds in all models in which the Z-penguin provides the dominant contribution to rare decays and is one of the main drivers to assess an interesting target sensitivity for $K_L \to \pi^0 \nu\bar{\nu}$ experiments.

We have also had WG presentations summarizing the expectations of rare K decays within well motivated extensions of the SM, such as SUSY and warped extra dimensions (Randall-Sundrum) models. In all cases, deviations from the SM can be sizable and perhaps most importantly the correlations between various rare K decays are essential in discriminating among models. It is also worth stressing that rare $K \to \pi \nu\bar{\nu}$ can also probe the existent of light states very weakly coupled to the SM appearing in various hidden sector models, through the experimental signature $K \to \pi$ plus missing energy and distortions to the pion spectrum.

While the main focus of the WG theoretical talks was on the above FCNC probes, we also discussed some unique probes of the charged-current (CC) sector of SM extensions, namely precise measurements of the ratio $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$, which test lepton universality, and measurements of the transverse muon polarization P_μ^T in the semi-leptonic decay $K^+ \to \pi^0 \mu^+ \nu_\mu$, which is sensitive to BSM sources of CP violation in scalar CC operators. In both cases there is a clean discovery window provided by the precise SM theoretical prediction (R_K) and by the fact that in the SM P_μ^T is generated only by small and theoretically known final state interactions.

2 Experimental Summary

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The kaon working group heard talks on three classes of experiments: those that are approved and scheduled to run, those that are under consideration for later this decade and those that would run in the Project X era. We briefly summarize the experiments that will or might run in the next decade to set the context for a kaon program at Project X.

2.1 Experiments in the Next Decade

NA62. The NA62 experiment at CERN is an in-flight measurement of $K^+ \to \pi^+ \nu\bar{\nu}$. The experiment will have a commissioning run with a partial detector later in 2012. Full commissioning followed by a physics run will begin in 2014. The NA62 goal is a measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio with 10% precision. The NA62 experiment anticipates a very robust and diverse kaon physics program beyond the primary measurement.

KOTO. The KOTO experiment at JPARC is an in-flight measurement of $K_L^0 \to \pi^0 \nu\bar{\nu}$. Significant experience and a better understanding of the backgrounds to this rare decay mode were obtained in E391a, the predecessor of KOTO. The anticipated sensitivity of the experiment is a few signal events (assuming the SM branching ratio) in three years of running with 300kW of beam. A commissioning run will occur later in 2012, but the longer term performance of the experiment will depend upon the beam power evolution of the JPARC accelerator.

TREK. The TREK Experiment (E06) at JPARC will search for T violation in charged kaon decays by measuring the polarization asymmetry in $K^+ \to \pi^0 \mu^+ \nu_m$ decays. TREK needs at least 100 kW (proposal assumes 270 kW) for this measurement. While the accelerator is running at lower power, collaborators have proposed P36, which will use much of the TREK apparatus to perform a search for lepton flavor universality violation through the measurement of $\Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ at the 0.2% level. The P36 experiment requires only 30 kW of beam power and will be ready to run in 2015. The uncertainty of the JPARC beam power profile and potential conflicts for beamline real estate make the long term future of the TREK experiment unclear.

ORKA. The ORKA experiment is proposed to measure $K^+ \to \pi^+ \nu\bar{\nu}$ with 1000 event sensitivity at the Main Injector later this decade. ORKA is a stopped kaon experiment that builds on the experience of the E787/949 experiments at Brookhaven. Like NA62, ORKA offers a wide variety of measurements beyond the $K^+ \to \pi^+ \nu\bar{\nu}$ mode.

2.2 Landscape later this decade

We look at the experimental landscape at the end of this decade under optimistic assumptions. The NA62 experiment will have measured the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio to 10% precision. The KOTO will have measured the $K_L^0 \to \pi^0 \nu\bar{\nu}$ mode with standard model sensitivity. The P36 experiment will have improved precision on lepton flavor universality. The ORKA and TREK experiments would be in progress.

Even under the optimistic scenario spelled out above, progress in the kaon sector would be significant but modest. The physics reach in the kaon sector is well motivated and will continue to be of interest for the foreseeable future. Therefore, there are significant opportunities for important measurements in the kaon sector at Project X.

2.3 Project X Kaon Program

The flagship measurement of the Project X kaon era would be an experiment to measure the $K_L^0 \to \pi^0 \nu \bar{\nu}$ branching ratio with 5% precision. This effort will need to build upon the KOTO experience, benefit from significant detector R&D and take advantage of the beam power and flexibility provided by Stage 2 of Project X. Based upon the $K_L^0 \to \pi^0 \nu \bar{\nu}$ experience at JPARC, it seems likely that an effort to achieve this ultimate sensitivity will take two generations. Depending upon the outcome of the TREK experiment at JPARC, a T violation experiment would be an excellent candidate for Project X, as would a multi-purpose experiment dedicated to rare modes that involve both charged and neutral particles in the final state. This experiment might be able to pursue $K_L \to \pi^0 \ell^+ \ell^-$ as well as many other radiative and leptonic modes.

3 Conclusion

To summarize, rare and not-so-rare K decays are extremely sensitive probes of the flavor and CP-violating sector of any SM extension. The $K \to \pi \nu \bar{\nu}$ remain the golden modes and offer a "win-win" opportunity for the future because: (i) sizable ($O(1)$) deviations from the SM are expected; (ii) even small deviations can be detected due to the precise theoretical predictions. Project X searches should aim for a sensitivity level of 10^3 SM events (few %) in both K^+ and K_L modes, so as to retain plenty of discovery potential in the K_L modes even in presence of the constraint from ϵ'/ϵ. We foresee the search for $K_L \to \pi^0 \nu \bar{\nu}$ as the flagship measurement of the kaon program at Project X, with the potential to uncover novel BSM sources of CP violation. But we also stress the importance of pursuing the broadest possible set of measurements, so as to enhance the model discriminating power of Project X.

The Project X kaon program will benefit greatly from an ongiong R&D effort to produce hermetic, highly efficient low-energy calorimetry; high precision calorimetric timing; particle identification for π/μ and π/K separation at low energies; and very low mass tracking with excellent momentum and spatial resolution. Although R&D can move forward in the near term, there is a significant concern that domestic expertise in kaon physics will be completely depleted if there is no near-term kaon program in the U.S. As a consequence, the ORKA experiment at the Main Injector is an absolutely integral part of the Project X kaon program. If ORKA does not run this decade, there will be little hope of carrying out the extremely challenging kaon program that the science motivates and Project X can facilitate.