PROCEEDINGS OF SCIENCE

Kaons at Project-X

David E. Jaffe∗†
Brookhaven National Laboratory
E-mail: djaffe@bnl.gov

The potential for kaon experiments at Project-X is reviewed.

2013 Kaon Physics International Conference,
29 April-1 May 2013
University of Michigan, Ann Arbor, Michigan - USA

∗Speaker.
†This is BNL-101013-2013-JA.

PoS(KAON13)036

1. Introduction

Flavor physics experiments have the potential to discover and elucidate new physics (NP) effects. If NP is discovered at the LHC, flavor physics experiments will be crucial in sorting out the flavor- and CP-violating (CPV) couplings. If NP is not found at the LHC, precision flavor physics experiments can probe mass scales beyond the reach of LHC through virtual effects. Among the flavor physics experiments that have special status due to their small standard model (SM) uncertainties and large NP reach are $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$. Project-X at Fermilab could enable huge gains in sensitivity for these decays to reach the level of the SM uncertainties.

Table 1 lists rare kaon processes that could be accessible with Project-X. Planned and running experiments are listed in the table.

I assume that a successful pre-Project-X ORKA [4] $K^+ \to \pi^+ \nu\bar{\nu}$ experiment will promote interest and generate expertise in kaon physics to help enable the premium Day One Project-X experiment to measure $K_L^0 \to \pi^0 \nu\bar{\nu}$. After ORKA discovers NP in $K^+ \to \pi^+ \nu\bar{\nu}$, it can move to the Project-X Kaon campus. My presentation was focused on the $K_L^0 \to \pi^0 \nu\bar{\nu}$ experiment at Project-X [5]. Possibilities for other processes are briefly mentioned.

	Current experiment
$K^+ \to \pi^+ \nu\bar{\nu}$: Wide range of New Physics accessible	NA62 [1]
$K_L^0 \to \pi^0 \nu\bar{\nu}$: Wide range of NP including pure CPV effects	KOTO [2]
$K^+ \to \pi^0 \mu^+ \nu$: Transverse polarization, T violation	TREK [3]
$K^+ \to e^+ \nu / K^+ \to \mu^+ \nu$: Universality, LFV	TREK
$K^+ \to \mu^+ \nu_H$: Heavy neutrinos	TREK
$K_L^0 \to \pi^0 \ell^+ \ell^-$: CP violation	
$K \to \mu e(X)$: LFV	
K^0-interferometry (Planck scale physics)	

Table 1: Rare kaon physics possibilities at Project-X. Planned and running experiments are indicated.

2. The challenge of a precision measurement of $\mathscr{B}(K_L^0 \to \pi^0 \nu\bar{\nu})$

- In the SM, the $K_L^0 \to \pi^0 \nu\bar{\nu}$ branching fraction is approximately 3×10^{-11}. To set the scale, observation of 1000 signal events with an experiment with 1% efficiency requires $\sim 3 \times 10^{15}$ K_L^0 or three years of ~ 100 MHz of K_L^0.
- The experimental signature is very weak with no charged particles in the initial or final state and no definitive kinematic signature, such as a mass peak.
- The background-to-signal ratio is approximately $\mathscr{B}(K_L^0 \to \pi^0 X)/\mathscr{B}(K_L^0 \to \pi^0 \nu\bar{\nu}) \approx 10^{10}$ with the CP-violating $K_L^0 \to \pi^0 \pi^0$ as the most troublesome when two photons are undetected.
- The experiment must be able to veto on extra particles with inefficiency $\leq 10^{-4}$.
- As most neutral kaon beams have K_L^0/neutron $\approx 10^{-2}$, the design of the neutral kaon beamline and detector must suppress $n + \text{gas} \to \pi^0 X$ with high vacuum, have a small and well-

controlled neutron halo, and achieve hermiticity by placing photon veto detection in the neutral beam.

- The experiment must have convincing measurements of all backgrounds, preferably obtained from data.

The experiment concept for a $K_L^0 \to \pi^0 \nu \bar{\nu}$ experiment at Project-X builds on the KOPIO [6] experiment originally proposed to run at the BNL AGS as illustrated in Figure 1. The experiment

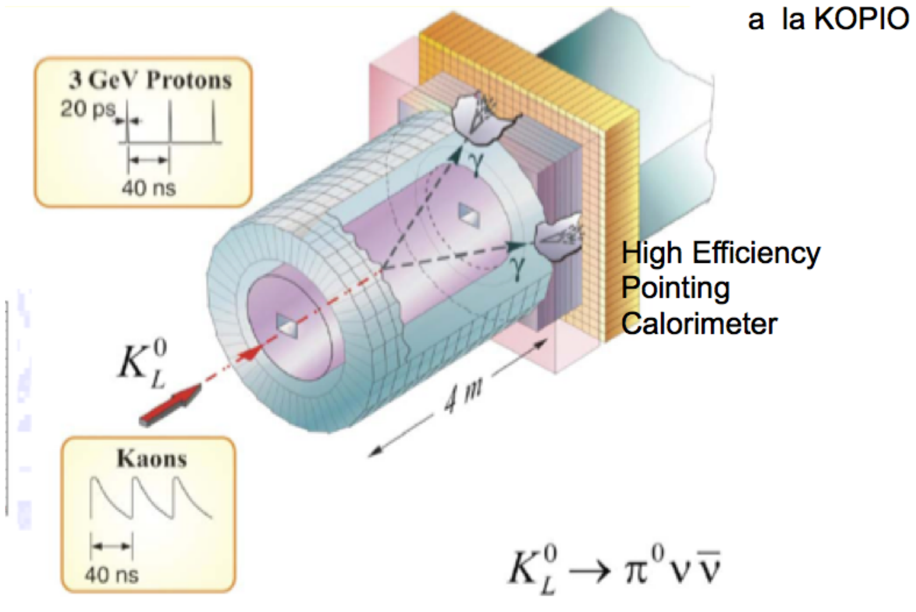

Figure 1: Illustration of the KOPIO experimental concept for $K_L^0 \to \pi^0 \nu \bar{\nu}$.

uses a bunched 3 GeV proton beam with $\sim$40 ns bunch spacing to produce a low momentum K_L^0 beam ($\overline{p_K} \approx 750$ MeV/c). The $\pi^0 \to \gamma\gamma$ decay is reconstructed using a high efficiency pointing calorimeter that allows reconstruction of the gamma directions and the K_L^0 decay point. The decay vertex, in concert with the bunched beam, allows time-of-flight (TOF) to be used in order to work in the kaon center-of-momentum system (CMS) to identify and eliminate the main 2-body background from $K_L^0 \to \pi^0\pi^0$ ($K_{\pi 2}$). The $K_{\pi 2}$ decay forms a background when 2 γs, either from a single π^0 or one from each π^0, avoid detection. In the K_L^0 CMS, the $K_{\pi 2}$ background populates distinct kinematic regions that can be efficiently rejected. Backgrounds are identified and rejected using high efficiency 4π photon and charged particle vetos. The KOPIO technique allows the energy, position, direction and time of the decaying K_L^0 to be measured for maximal signal-to-background.

A 1 mA continuous 3 GeV from a CW Linac would provide the beam at Project-X for KOPIO. Although the kaon yield at Project-X is reduced by $\times 1/10$ with respect to the 24 GeV AGS beam, the $\times 300$ increase in proton beam intensity yields an overall $\times 30$ increase in kaon flux.

Some advantages of a Project-X for a KOPIO-style experiment are as follows:

- The 20ps wide proton bunches with $\ll 10^{-3}$ extinction would allow
  - The K_L^0 production time distribution to be determined by target size, and

  - Suppression of interbunch background. (Protons not in the 20 ps bunches produce kaons that spoil the TOF technique.)

- The higher kaon flux permits a “pencil” beam that allows
  - A simpler beam-line,
  - A more hermetic detector,
  - An increase in acceptance because the beam hole size decreases and detector size increases,
  - Improvement in the kinematic constraint and subsequent increase in signal-to-background and
  - Reduction in background from decays upstream and downstream of the fiducial volume.

- The narrower momentum spread of the kaon reduces high momentum kaons that have poor velocity resolution.

The attendant challenges at Project-X are

- A higher neutron rate due to the lower K/n production ratio,
- Handling the higher beam power on the target, and
- The need for a relatively dense target to be able to design a neutral beam line to fully exploit the 20 ps proton bunches.

These considerations lead to an estimated SM signal event rate of ~ 200 events/year with a signal-to-background of ~ 5 or more for a KOPIO-style experiment at Project-X which would yield a 5% measurement of $\mathscr{B}(K^0_L \to \pi^0 \nu\bar{\nu})$ in a few years.

3. Other kaon physics at Project-X

An ORKA-style stopped K^+ beam, driven by Project-X, could increase the statistics of a TREK-style experiment by over $\times 20$ and allow such an experiment to search for T-violation in $K^+ \to \mu^+\pi^0\nu$ decays near the 10^{-5} level.

Measurement of direct CPV $K^0_L \to \pi^0\ell^+\ell^-$ decays could discover NP; however, these decays suffer from irreducible $K^0_L \to \gamma\gamma\ell^+\ell^-$ background and from indirect CPV and non-CPV amplitudes. These problems could be mitigated by superb π^0 mass resolution and huge statistics. Alternatively an experiment could measure $\mathrm{Im}(V^*_{ts}V_{td})$ using $K^0_S - K^0_L$ interference in $K^0 \to \pi^0 e^+e^-$ decays [7]. This would require a compact detector due to the K^0_S lifetime as well as a huge proton flux ($\sim 5 \times 10^{23}$ or ~ 10 years at 1.5MW Project-X) for a 5% measurement of $\mathrm{Im}(V^*_{ts}V_{td})$. For $K^0_L \to \pi^0\mu^+\mu^-$, one could measure muon polarization asymmetries, branching ratio and lepton energy asymmetry to disentangle the CP-conserving, indirect CPV amplitudes and $K^0_L \to \gamma\gamma\mu^+\mu^-$ background [8]. An even bolder approach would be to combine the interference and polarization techniques for $K^0_L \to \pi^0\mu^+\mu^-$ and $K^0_L \to \mu^-\mu^+$.

4. Conclusion

Project-X provides an unprecedented opportunity to discover new physics with rare kaon decays. The measurement of $\mathscr{B}(K_L^0 \to \pi^0 \nu\bar{\nu})$ and $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with high precision would build on past and current experiments at BNL, CERN, J-PARC and Fermilab, achieve the ultimate precision covering all accessible non-SM physics, and discover NP in flavor interactions at high mass scales. Additional possible Project X discoveries in rare kaon processes include new CP- and T-violating processes, exploration of lepton universality and lepton flavor violation as well as searches for scalar and pseudoscalar interactions and new particles.

References

[1] G. Ruggiero, "Status and Prospects for $K^+ \to \pi^+ \nu\bar{\nu}$ observation at CERN", NA62, these proceedings.

[2] M. Togawa, "Status and Future Prospects for the KOTO Experiment", these proceedings.

[3] S. Strauch, "Searches for New Physics with the TREK Detector", these proceedings.

[4] E. Worcester, "ORKA, The Golden Kaon Experiment: Precision Measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ and other Ultra-rare Processes", these proceedings.

[5] The Project X Kaon Physics Research Program, Editors: D. Bryman& R. Tschirhart, August 31, 2010

[6] KOPIO Conceptual Design Report, 2005, `https://pubweb.bnl.gov/~litt/e926/kopio_cdr2005_nsf.pdf`

[7] H.Nguyen, Fermilab-TM-2438-PPD.

[8] M.Diwan, H.Ma, L.Trueman, Phys.Rev. D**65** 054020 (2002).