ORKA: MEASURING $K^+ \to \pi^+ \nu\bar{\nu}$ AT FERMILAB

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ABSTRACT

Using the Fermilab Main Injector to produce low energy kaons, the decay $K^+ \to \pi^+ \nu\bar{\nu}$ can be measured with sensitivity corresponding to about 1000 events at the level of the Standard Model prediction. The recently proposed ORKA experiment would explore the full range of non-SM physics possibilities accessible to $K^+ \to \pi^+ \nu\bar{\nu}$, unambiguously signaling the existence of New Physics or severely constraining a wide variety of hypothetical models involving high mass scales. Project-X beams would then substantially drive the experiment to the ultimate sensitivity for this process.

INTRODUCTION

Rare K decay studies, particularly the "golden" decays $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$, are competitive with, and in many cases surpass in sensitivity, other experimental searches for New Physics. Some examples of the types of New Physics that could be uncovered include heavy fourth-generation quark mixing, supersymmetric loop effects, dynamical symmetry breaking, multi-Higgs bosons, and extra dimensions---a broad and well-motivated set of scenarios.

The predicted SM branching ratios for $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ carry little theoretical uncertainty and are very sensitive to New Physics; they can actually explore short-distance scales beyond $O(1000\ \mathrm{TeV})$! Considerable theoretical effort has gone into refining the SM predictions which form a baseline with which to compare precise measurements. Multi-loop QCD corrections, electroweak radiative corrections and m_d-m_u isospin-violating effects have been computed. Most recently, leading two-loop electroweak corrections were improved, thereby reducing the electroweak theory uncertainty in $K \to \pi\nu\bar{\nu}$ to below 1%. The SM predictions now stand at (1)

$B(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81 \pm 0.69 \pm 0.29) \times 10^{-11}$, and

$B(K_L \to \pi^0 \nu\bar{\nu}) = (2.43 \pm 0.37 \pm 0.11) \times 10^{-11}$,

where the first error stems from current CKM parameter uncertainties (which will be further reduced in time) and the second error is a quadrature sum of current theory input uncertainties. Here we focus on $K^+ \to \pi^+ \nu\bar{\nu}$ which is amenable to study with existing accelerator facilities at Fermilab; another contribution will deal with the prospects for measuring $K_L \to \pi^0 \nu\bar{\nu}$.

Experimental Study of $K^+ \to \pi^+ \nu\bar{\nu}$

The E787/E949 experiments at the BNL Alternating Gradient Synchrotron (AGS) reported a combined result (PDG) of $B(K^+ \to \pi^+ \nu\bar{\nu}) = 17.3^{+11.5}_{-10.5} x 10^{-11}$, based on the observation of seven events. Compare this result with the SM prediction (1) $B(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81 \pm 0.69 \pm 0.29) \times 10^{-11}$. Today, the CERN experiment NA62 (2) is pursuing the next step beyond discovery with a promising new technique, driven by the SPS proton facility, that aims for 100 event sensitivity at the SM level. However, the proven techniques developed at the AGS could be further exploited with the existing Fermilab accelerator complex to reach the 1000-event level achieving comparable uncertainty to the precise SM prediction.

ORKA: Using the Fermilab Main Injector

The BNL E787/E949 experiments used high-purity, high-flux, low-energy K^+ beams transported to a stopping target where the rare decays were observed. Recent studies suggest that the rate capability and acceptance of the stopped-K^+ technique can be improved substantially over BNL E787/E949 with straightforward detector upgrades and by lowering the kaon momentum on the stopping target from 710 MeV/*c* (used at BNL) to 600 MeV/*c*. Such a stopped-K^+ source driven by the Fermilab Main Injector would be an order of magnitude brighter than at BNL and would enable a very high statistics experiment that could precisely determine both the rate and the form factor of the $K^+ \to \pi^+ \nu\bar{\nu}$ process. In addition, the detector sensitivity can be improved by an order of magnitude using higher levels of detector segmentation to reduce accidental losses and larger acceptance detection elements leading to an expectation of acquiring approximately 210 events/yr at the SM level. This concept has been presented in the "ORKA" (3) proposal which has recently been submitted to Fermilab (P-1021).

The Main Injector can sustain a 44% slow-spill fraction at 95 GeV together with a balance of fast-spill cycles at 120 GeV for the NOvA and LBNE programs. This slow-spill component corresponds to 75 kW of average slow-spill power. Eventual slow-spill operations would also directly benefit the planned muon physics program at the Fermilab Booster which could receive additional Booster beam during the Main Injector slow spill.

A preliminary optimization of ORKA beam conditions for the $K^+ \to \pi^+ \nu\bar{\nu}$ measurement favors the Main Injector running at 95 GeV with a 40-45% duty factor using p_k=600 MeV/c. With these conditions, a 5 year run of the experiment would yield ~1050 $K^+ \to \pi^+ \nu\bar{\nu}$ events at the SM level, and the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio would be measured with precision 5%, comparable to the theoretical uncertainty. The experiment can be carried out using an existing superconducting solenoid magnet and hall at Fermilab.

All the many approaches to non-SM physics predicted for $K^+ \to \pi^+ \nu\bar{\nu}$ will be fully explored by ORKA, opening the possibility of a major discovery. If initiated promptly, the experiment would operate as a contemporary of the CERN NA-62 experiment slated to begin production running following the 2012-2013 LHC shutdown --aiming at 50 events per year using the new in-flight technique.

CONTINUING STUDY OF $K^+ \to \pi^+ \nu\bar{\nu}$ AT PROJECT X

If Project-X is initiated on an appropriate timescale, the proposed measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ would be a natural Day-1 experiment due to the solid physics case and the well established technique which would undergo further refinement. By operating ORKA for some period prior to the inception of Project X beams e.g. 3-4 years using the Main Injector, the fully debugged experiment with possible improvements would be capable of producing an enhanced physics result very early in the Project-X research program. We estimate that a sensitivity of approximately 340 events/yr at the SM level would be achieved with initial Project-X beam power. ORKA at the Main Injector would spur the development of a Project-X kaon community and promote techniques necessary for the early development of the neutral channel measurement ($K_L^0 \to \pi^0 \nu\bar{\nu}$) which is sensitive to additional physics effects, particularly new CP-violating effects which occur in many models. The ratio of the neutral and charge mode branching fractions with high statistics is a particularly sensitive probe of new physics due to further cancellation of already small theoretical uncertainties.

COST ESTIMATE AND TIME SCALE

Driving ORKA with the Main Injector would represent an incisive experiment with 1000-event SM capability. It would also be a relatively low-cost battle tested "Day-1" flagship experiment early in the Project-X research program. The experiment total project cost (TPC) estimate is ~$50M. When Project-X beams and experimental areas and targets are ready, ORKA could be relocated to the Project-X 3 GeV campus and continue with substantially enhanced sensitivity.

References

(1) J. Brod, M. Gorbahn, and E. Stamou, Phys. Rev. D83, 034030 (2011) [arXiv:1009.0947 [hepph]].

(2) The CERN NA62 experiment:

http://na62.web.cern.ch/na62/Home/Home.html

(3) ORKA proposal:

http://projects-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1365

(4) Project-X white paper on kaon physics:

https://indico.fnal.gov/getFile.py/access?resId=1&materialId=0&confId=3579