Measuring $K_L^0 \to \pi^0 \nu \bar{\nu}$ at Fermilab Project X

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1. Introduction and Theory

High precision measurements of the ultra-rare decay $K_L^0 \to \pi^0 \nu \bar{\nu}$ would be among the most incisive probes of quark flavor physics. Particularly when combined with similarly precise measurements of the closely related decay $K^+ \to \pi^+ \nu \bar{\nu}$ it has dramatic reach for uncovering new physics, due to several important factors:

- The branching ratios are sensitive to most new physics models that extend the Standard Model to solve its considerable problems.
- The Standard Model predictions for the $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ branching fractions are broadly recognized to be theoretically robust at the 5-10% level. Only a precious few accessible loop-dominated quark processes can be predicted with this level of certainty.
- The $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ branching fractions are highly suppressed in the Standard Model to the level 10^{-11} to 10^{-10}. This suppression allows physics beyond the SM to contribute dramatically to the branching fractions with enhancements of up to factors of 5 and 30 above the SM predictions for the charged and neutral modes respectively, based on current experimental results.
- The certainty with which the Standard Model contributions to $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ can be predicted would permit a 5σ discovery potential for new physics even for enhancements of the branching fractions as small as 35%.

This sensitivity is unique in quark flavor physics and allows probing essentially all models of new physics that couple to quarks within the reach of the LHC. Furthermore, high precision measurements of $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ are sensitive to many models of new physics with mass scales well beyond the direct reach of the LHC.

The hallmark of the $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ decays is their clean separation of the QCD scale from the electroweak and higher scales. If the Standard Model (SM) suffices, then measurements of the branching fractions of the charged and neutral modes yield constraints on the CKM unitarity triangle with 2-4% precision. However, experiments may well observe a rate substantially different than the SM predictions [1], $B_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (7.81 \pm 0.80) x 10^{-11}$ and $B_{SM}(K_L^0 \to \pi^0 \nu \bar{\nu}) = (2.43 \pm 0.11) x 10^{-11}$ where the uncertainties stem from the CKM matrix, other input parameters $(\alpha_s, \mathrm{m_t}, \mathrm{m_c}, \sin^2\theta_\mathrm{W})$, the truncation of electroweak and QCD perturbation theory, and the (isospin-corrected) Kl3 normalization; this would be a highly significant discovery in its own right. The charged mode is sensitive to both CP-conserving and CP-violating interactions whereas the neutral mode is purely CP-violating.

If TeV-scale particles are observed at the Large Hadron Collider, much of high-energy physics research will start to focus on the interplay of direct observation, data-driven model building, and constraints from measurements such as these rare kaon decays. For the current SM predictions, the largest uncertainties stem from the CKM matrix but, by folding in foreseeable improvements, the Standard Model predictions of the branching fractions will likely be known to 7-9%.

There is now a substantial literature on the subject of new physics effects on $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ [2]. In this discussion we will focus mainly on recent examples. In fact, the majority of the models studied can accommodate effects that would be significant in $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ experiments with 5% precision. This is true in large part even in models that incorporate the very restrictive Constrained Minimal Flavor Violation (CMFV) assumptions [3], *i.e.* that there are no new sources of flavor violation and no new effective dimension-six flavor-changing operators beyond the Standard Model ones. With a further assumption that charged leptons and neutrinos couple in the same way, in terms of the experimental precision discussed here, the possible range of B($K^+ \to \pi^+ \nu\bar{\nu}$) is [-9:6σ; +4:5 σ] with respect to the Standard Model [4]. Without this extra assumption [5], B($K^+ \to \pi^+ \nu\bar{\nu}$) is constrained only by experimental bounds on B($B^+ \to K^+ \nu\bar{\nu}$), which are a few times the SM expectation [6, 7].

Examples where excursions from the SM value of B($K^+ \to \pi^+ \nu\bar{\nu}$) could easily be more than 3 σ from the SM value include the general MSSM [8, 9], the Minimal 3-3-1 Model (in which the weak SU(2)L gauge group is extended to SU(3)L) [10], a Littlest Higgs model with T-parity [11], models incorporating a warped extra dimension with custodial protection [12], an extra down-type isosinglet quark model [13], and a 5-dimensional split fermion model [14], among others. In many cases, non-SM effects could be observable in B($K^+ \to \pi^+ \nu\bar{\nu}$) even though the superficially similar B($B^+ \to K^+ \nu\bar{\nu}$) remains consistent with the SM.

In other cases, rather than explicit predictions of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay rate, the current result from BNL E787/949 is used to limit the parameters of models of new physics. Examples include R-parity violating supersymmetry [15], extended technicolor [16], anomalous charm couplings [17], singlet and triplet leptoquarks [18], a fourth quark generation [19,20,21], non-standard neutrino interactions [22], and more generic semi-phenomenological schemes [23]. A more precise value for B($K^+ \to \pi^+ \nu\bar{\nu}$) would serve to eliminate many of these models, or to refine or confirm them. Note that the already considerable power of $K^+ \to \pi^+ \nu\bar{\nu}$ to probe new physics would be significantly enhanced by the availability of a measurement of $K_L^0 \to \pi^0 \nu\bar{\nu}$. This point has been wellexplored, most recently by Blanke [24]. Fig. 2.3 gives a sense of the possibilities for several popular theoretical approaches [25]. Similar results have been found by other authors [26].

It is also important to note that the experimental signature of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ a π emerging from a K decay with missing energy, is shared by other, non-SM, processes. Perhaps the smallest excursion from the SM is the case in which the process is still $K \to \pi\nu\bar{\nu}$ but the neutrino flavor is not conserved. Such models include versions of supersymmetry [27] and new effective four-fermion interactions involving neutrinos [22]. As in the case of most examples of lepton flavor violation in kaon decay, the effects tend to be small, although there are exceptions.
A second category is reactions in which a single unseen particle recoils against the pion. These cases include species of axions [28], the familon [29], light scalar pseudo-Nambu Goldstone bosons in models of meta-stable SUSY breaking [30], sgoldstinos [31], a gauge boson corresponding to a new U(1)0 gauge symmetry [32, 33], and various light-mass dark-matter candidates [34,35,36]. In general these models do not predict branching ratios; rather they use limits on $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ to constrain their parameters.

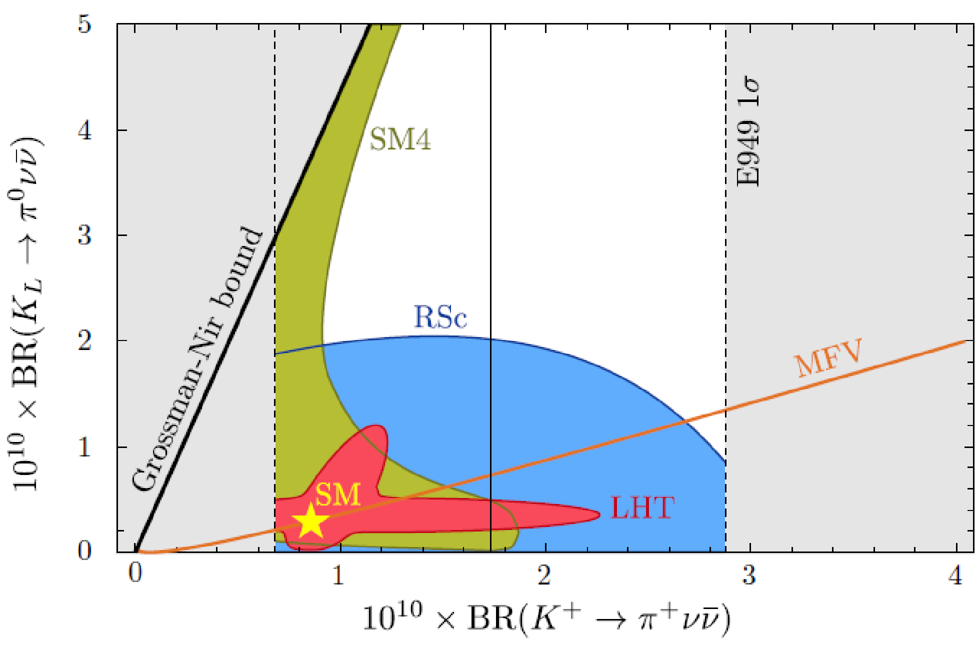

Figure 2.3: Predictions of different physics models for the branching ratios of the charged and neutral versions of $K \to \pi\nu\bar{\nu}$. The SM prediction is indicated by a yellow star. The gray regions indicate the 68% CL limits from the BNL E787/949 experiments, and the exclusion from the Grossman-Nir bound. The orange line indicates the tight constraint of minimal-flavor violation. (Other models predict similarly strong correlations between the two modes.) The red lobes show the region preferred by the Littlest Higgs model with T parity (LHT) [11]; the blue shoulder shows the region preferred by the Randall-Sundrum

model with custodial protection (RSc) [12]; and the olive-green boomerang shows the region preferred by the Standard Model with a fourth sequential generation (SM4) [20]. The MSSM (with pre-LHC limits) populates most of the rest of the experimentally allowed region [26]. From Ref. [25].

There are also examples of models with two or more unseen BSM particles recoiling against the pion. For example, if the lightest superpartner is neutral and light enough (*i.e.*, a neutralino $\tilde{\chi}_1^0$), the decay $K^+ \to \pi^+ \tilde{\chi}_1^0 \tilde{\chi}_1^0$ is allowed. As shown in Fig. 2.4 [37], the spectrum depends sensitively on the neutralino mass, although the predicted rates are small unless squark-mass dfference are nearly as large as possible to remain consistent with bounds on other FCNCs. In general, the shape of pion spectrum could be distorted in a measurable way. An especially exotic example of this phenomenon is the unparticle model of Wu and Zhang [38]. This is an example of a process whose parameters are constrained by the BNL E787/949 results. This brief summary is necessarily incomplete, but should give an accurate impression of the wide range of BSM possibility that can be accessed via measurements of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$

2. General considerations and the KOPIO proposal at BNL

Definitively measuring $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay at the few × 10^{-11} branching ratio level represents a significant experimental challenge. The poorly defined signal consists of a neutral kaon followed by a neutral pion, $K_L \to \pi^0$, with the pion immediately decaying into two γ's with no other observed particles. Potential backgrounds from other K decays at branching ratios many orders of magnitude higher have similar signatures. In addition neutrons, which are inevitably present in a neutral beam, can create π^0s off material in or near the beam. Therefore, the experimental strategy involves proving that candidate events have low probabilities of being due to background. The principal intrinsic source of background is $K_L \to \pi^0\pi^0$ with branching ratio 8.64×10^{-4}. This can fake signal either when one of the two π^0s is missed entirely by the detector, or when one γ from each of the π^0s is missed and the two odd γs happen to reconstruct to a π^0 to within the resolution of the detector. Another kaon-induced background comes from $K_L \to 3\pi^0$ which is much less likely to be mistaken for the signal but which has a much higher branching ratio. Other backgrounds can be induced by $K_L \to \pi^+\pi^-\pi^0$ to the extent that charged particle vetoing is imperfect, and $K_L \to \pi^- e^+ \nu$ if charged particle vetoing fails and the two charged particles manage to make or appear to be γs. There are many other possible background processes.

Any attempt to detect $K_L^0 \to \pi^0 \nu\bar{\nu}$ must rely on extremely efficient charged and neutral particle vetoing and very good resolution for γ's. There have been two basic approaches suggested, basically a high and a low energy approach. The former relies on a small, intense forward beam of kaons, high resolution γ detection and the highly efficient neutral and charged vetoing possible at high energies. The one dedicated $K_L^0 \to \pi^0 \nu\bar{\nu}$

experiment, KEK-391a completed so far, took this approach (although the KEK-PS was limited to medium energies), and recently released a new 90% CL upper limit, B($K_L^0 \to \pi^0 \nu\bar{\nu}$) < 2.6 × 10^{-8}. This experiment has been upgraded and moved to JPARC where the KOTO experiment seeks sensitivity of a 3.5 events at the SM level with a signal-to-noise ratio of 1.4; a future stage, presently unspecified, would aim for sensitivity of more then 100 SM events. The low energy approach that we will discuss here was originally proposed for the KOPIO experiment at the Brookhaven AGS which aimed at accumulating several hundred events. [1]

The low energy technique is illustrated in Fig. 1. It focuses upon obtaining the maximum possible information about each event, *i.e.* the direction, energy, production time and decay position of the K_L, and the directions, energies and times of the γ's. In addition, it requires highly efficient hermetic rejection of events (vetoing) with extra particles. A low energy neutral beam is created by protons tightly bunched in time, so that the production time of the kaons is known, modulo the 25 MHz period of the proton μ-bunches. Combined with direction and timing measurements on the final state γ's, this gives the time-of-flight (TOF) and therefore the energy of the incident kaon. The directional measurement of the γ's also gives the kaon decay position, assuring that the photons originated in a $\pi^0 \to \gamma\gamma$ decay. Finally, energy measurement of the γ's allows powerful kinematic constraints to be imposed on candidate events in the K_L^0 CM system.

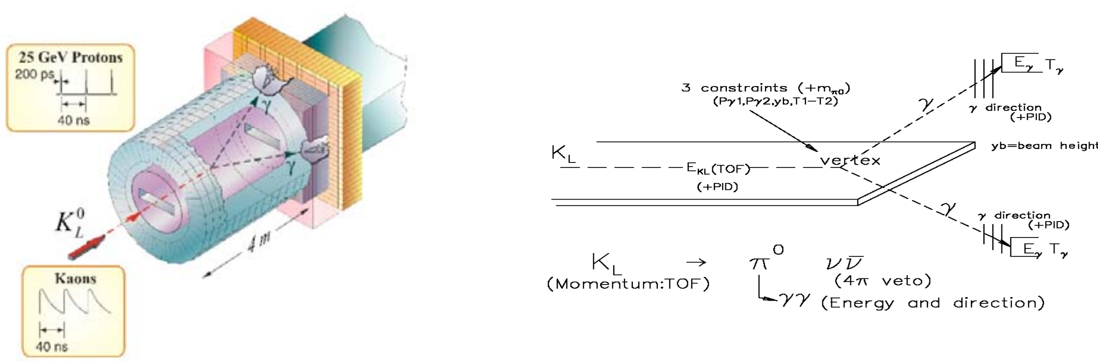

Fig. 1. (Left) The principles of the low energy approach to measuring $K_L^0 \to \pi^0 \nu\bar{\nu}$. (Right) Kinematic measurements.

In order to optimize the low energy beam to enable the TOF technique described above (with usable K_L's between 0.4 and 1.4 GeV/c), it was necessary to go to a very large production angle. To obtain the high flux necessary for a measurement at the

[1] KOPIO passed all technical reviews and had progressed to a baseline review commissioned by the NSF in May of 2005. The RSVP program (KOPIO and MECO) was canceled for financial reasons relating to NSF and DOE funding issues.

$\sim 10^{-12}$/event level, KOPIO was forced to use a rather large beam solid angle and to maintain at least one beam kinematic constraint; the beam profile was made very asymmetric, (narrow in the vertical and extremely wide in the horizontal).

3. $K_L^0 \to \pi^0 \nu\bar{\nu}$ at Fermilab Project X

An experiment at the SM-level precision ~3% appears to be feasible for Project X beams. Perhaps the most attractive approach is a version of the low energy experiment in which the beam aperture is substantially reduced compared to KOPIO. This would allow the experiment to benefit greatly from any increase in the available proton flux. Moreover it would be much easier to mount, and more robust than KOPIO. The large beam aperture was the single factor that made KOPIO as technically challenging as it was due to the very large, very thin vacuum chamber required. Many other aspects of the experiment would be improved by the smaller beam including the need for very large elaborate downstream vetoes.

With Project X beams the technique may be eventually limited by instantaneous rates of various types (accidental spoiling of events by other kaon decays in the same microbunch, accidentals due to stopped muons, accidentals due to neutron interactions in the beam veto, etc. A possible approach for a Fermilab $K_L^0 \to \pi^0 \nu\bar{\nu}$ is to put the entire experiment in vacuum (like KEK E391a) and to use a small symmetric beam aperture. Placing all detectors in vacuum would completely remove the difficult thin vacuum vessel,but would require vacuum operation of the preradiator photon tracking chambers.

Reducing the size of the beam would make the experiment much less difficult. Many mechanical issues would be made easier and the experiment could be reconfigured to have a considerably higher acceptance. Moreover, many types of background would be diminished or eliminated. As mentioned above, the spoiling of event candidates by additional decays in the same μ-bunch would be much reduced. The loss in effective statistics due to the small beam acceptance would be somewhat mitigated because of the reduction in accidentals, and in spoilage by additional events in a μ-bunch. However the reconfiguration of the experiment that this geometry allows could result in an increase in geometric acceptance of a factor 2 or even more. At Project-X intensity, 200 SM level equivalent events would be observed per year which would allow a 3% measurement to be made for $K_L^0 \to \pi^0 \nu\bar{\nu}$.

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