Prospects for Measuring $K_L^0 \to \pi^0 \nu\bar{\nu}$ at Fermilab

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1. General considerations and the KOPIO experiment at BNL

Definitively measuring $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay at the few $\times$ 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 any 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. The former is conventionally called "even" and the latter "odd Kπ2 background". 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, has taken this approach (although the KEK-PS limited them to medium energies), and recently released a new 90% CL upper limit, B($K_L^0 \to \pi^0 \nu\bar{\nu}$) < 6.7×10^{-8}. The low energy approach was epitomized by the KOPIO experiment proposed for the Brookhaven AGS. This experiment was part of the RSVP project canceled by the National Science Foundation in 2005. However the experiment passed many technical reviews, and its cancellation was not the result of doubts about its proposed technique.

This technique is illustrated in Fig. 1. It depends upon obtaining the maximum possible information about the events, 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, there is highly efficient hermetic vetoing of 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 25MHz period of the protons. Combined with direction and timing

measurements on the final state γ's, this gives the time of flight and therefore the energy of the incident kaon. The directional measurement of the γ's also gives the decay position. Finally, energy measurement of the γ's allows powerful kinematic constraints to be imposed on candidate events.

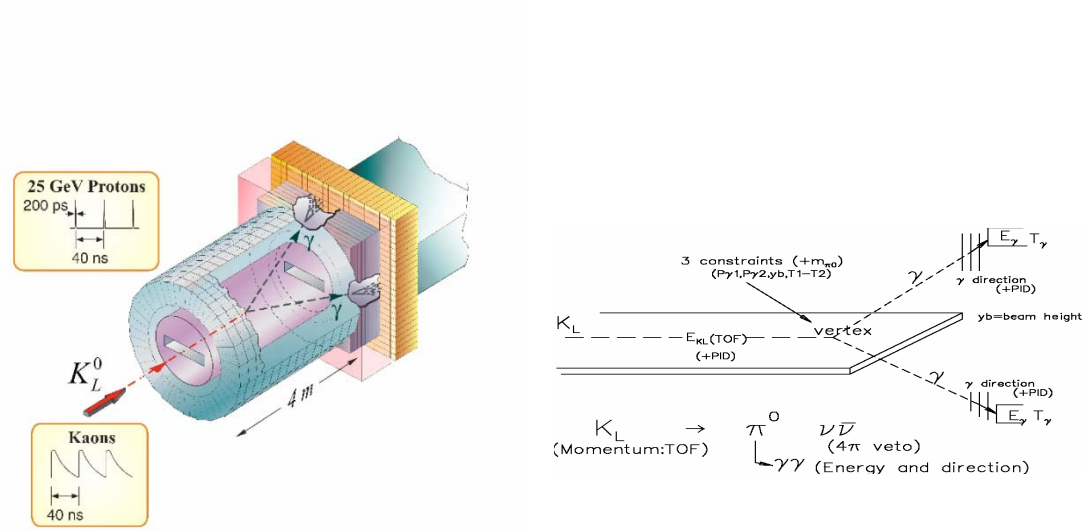

Fig. 1 The principles of the KOPIO experiment.

In order to get the low energy beam (usable K_L's between 0.4 and 1.4 GeV/c) needed for timing the kaons, it was necessary to go to a very large production angle. At this angle, the flux of kaons is much reduced with respect to forward production. Therefore, to obtain the high flux necessary for a measurement at the ~10^{-12}/event level, one was forced to a rather large beam solid angle. To maintain at least one beam kinematic constraint, the beam profile was made extremely asymmetric, narrow in the vertical and extremely wide in the horizontal.

Fiscal and other constraints required that KOPIO running be limited to 6000 hours in total. It was assumed that the AGS could provide 100TP of 24 GeV protons per machine spill. This in turn provided about 300M K_L/spill at a production angle of 42.5^o. It was further assumed that the spill length could be varied arbitrarily. A complex optimization of this length, taking into account accidentals of many varieties, the possibility of extra beam kaon decays spoiling a given microbunch, the AGS interspill time of 2.3s and other factors resulted in an optimum spill length of ~5s. Several topologies of signal with varying degrees of background contamination were considered. Figure 2 shows the result of a simulation of a 6000-hr run under these conditions.

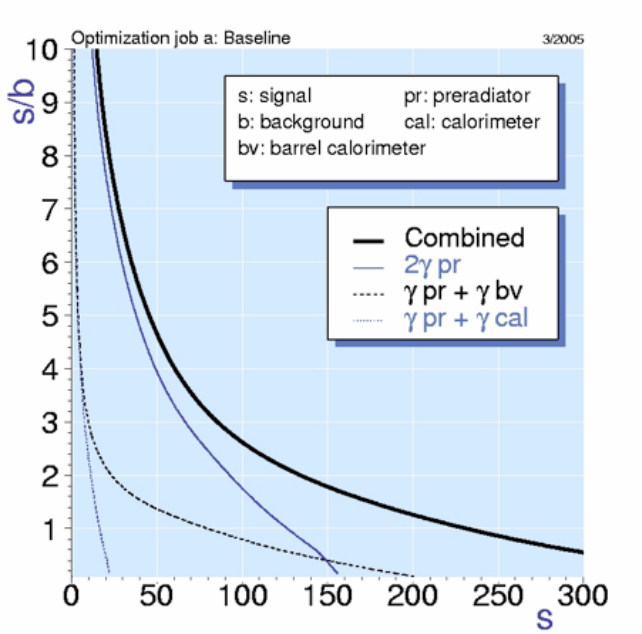

Fig. 2 Signal/background vs number of signal events for 6000-hr run of KOPIO at the BNL AGS. Beyond S:B of ~1:2, the gain in precision is very slow, and the requirements on knowledge of the background become more and more difficult to meet.

Fig. 3 shows the results of a maximum likelihood analysis developed to use events of varying signal to background. After 6000 hours, the precision of a measurement at the Standard Model level would be ~11%.

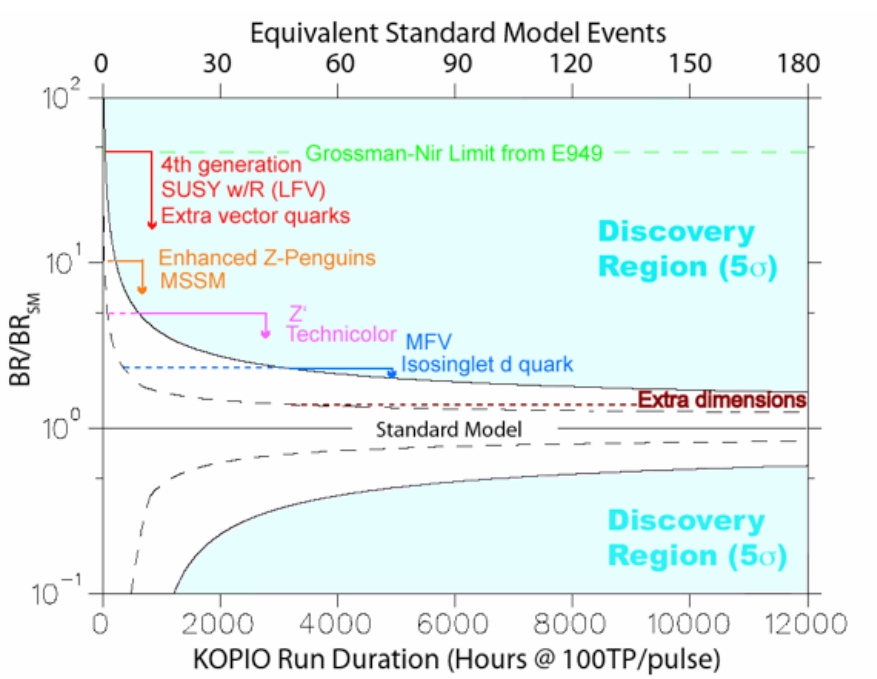

Fig. 3.Reach of KOPIO experiment as a function of running time. Solid lines show the 5σ limits in terms of branching ratio relative to that of the Standard Model (SM). Dashed lines show the corresponding 3σ limits. "Equivalent Standard Model Events" means the number of SM events with no background that would have equivalent reach.

2. Choices for FNAL

Given the possible progression of 8 GeV intensity at Fermilab, a low-energy $K_L^0 \to \pi^0 \nu \bar{\nu}$ experiment is a very appealing possibility. There are several alternatives on how one might proceed. Perhaps the most straightforward would be to launch the KOPIO experiment, more or less as originally conceived, at the Booster. An LOI was submitted to Fermilab some time ago asking that this be considered. The experiment at BNL had progressed to a baseline review commissioned by the NSF in May of 2005. This review was somewhere between what in DOE parlance would be a CD-1 and a CD-2 review. Thus the cost of the experiment was known to be approximately $100M including the beamline and modifications of the accelerator. The cost would be expected to be similar at Fermilab. As will be discussed below, this would be likely to result in an experiment of similar or somewhat better sensitivity, i.e. a 7-10% measurement of the SM branching ratio. The downside of this choice is that the experiment could make only limited use of enhanced intensity of Project-X. A second choice would be to launch an upgraded version of the KOPIO experiment with improved resolutions. As will be discussed below, this might allow an improvement in the sensitivity by a factor as much as a factor 3, but it would make an already expensive experiment even more so, as well as stretch out the time scale of building it. Such an experiment could benefit somewhat from the increased intensity of Project-X, but the KOPIO technique is instantaneous-rate limited, this is unlikely to be a large factor. Another alternative would be to make more substantive changes to the original design. A very appealing idea is to reduce the beam aperture substantially. This would allow the experiment to benefit greatly from any increase in the available proton flux. The problem is that it would also decrease the sensitivity of a near-term Booster-based experiment substantially. However it is so appealing from the technical point of view that one cannot dismiss it. The large beam aperture is the single factor that made KOPIO as technically challenging as it was. One was forced to design a very large, very thin vacuum chamber, and also to deploy veto counters over a very large area downstream of the fiducial region. Thus the effective accidental rates of the experiment were increased by a factor three over those due to decays in the fiducial region alone.

3. KOPIO at the Fermilab Booster

The FNAL LOI assumed that large angle kaon production did not fall very fast with primary beam energy. This was based on the same extrapolation by which the KOPIO group predicted the 24 GeV flux, based on an AGS measurement at 14 GeV. However later work by Striganov cast doubt on this assumption. Thus we assume for present purposes that the effective cross section at 8 GeV is half of that at 24 GeV. In terms of available protons, we use the optimized KOPIO spill of 100TP per 5s every 7.3s and compare with Booster performance of 22.5 TP per 1.3s every 1.4s. The average protons/sec is then 13.7 at the AGS and 16.1 at the Booster. With the above assumption about K cross-section, the ratio of kaons per second is 0.59 for Fermilab/BNL. However

there are other factors based on details of the expected accidental rates that tend to compensate for the higher kaon flux at BNL. When these are taken into account the ratio of effective kaons per second is 0.93. Since the potential running time at the Booster is much greater than what was assumed for the AGS, it's clear one could do as well or better at Fermilab than what was predicted for KOPIO at the AGS. For example a 3-year run at 5500 hrs/year would give 2.5 times the statistics of the latter. Assuming ~ 4% systematic error, this would give about an 8% measurement of the SM branching ratio.

4. KOPIO at Project-X

We assume that 10 times the intensity of the Booster will be available in the first stage of Project-X. As mentioned above, the KOPIO technique is eventually limited by instantaneous rates of various types (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.). However KOPIO is pretty far from the rate limit at the Booster. Figure 4 shows the effective yield relative to that discussed above for the Booster, as a function of the relative proton intensity available.

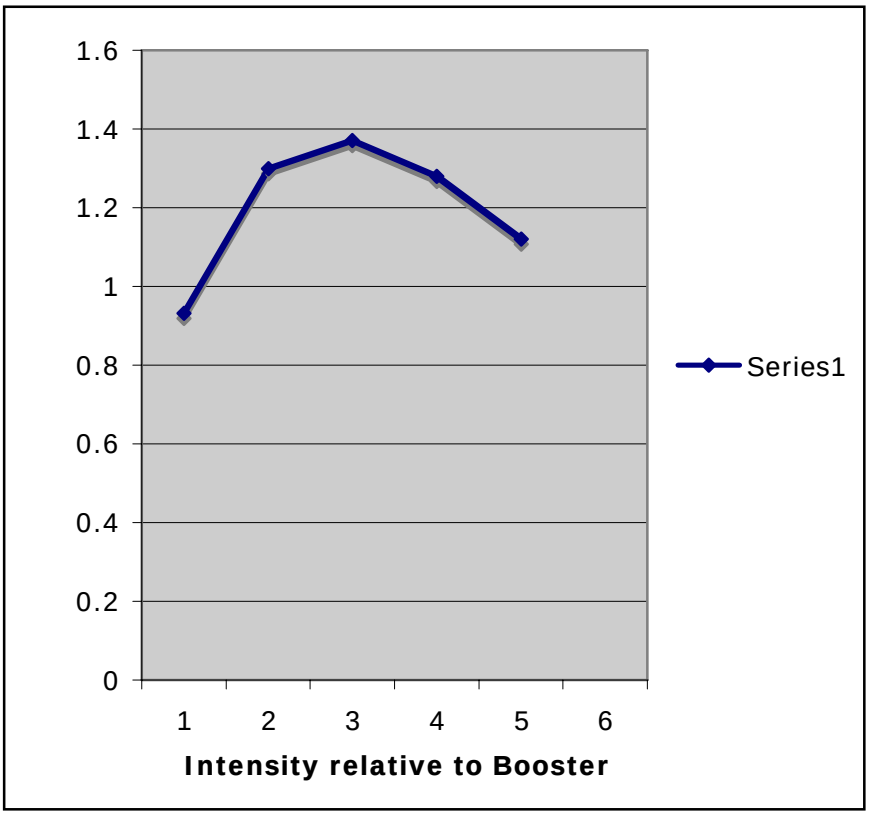

Fig. 4. Relative effective yield of a KOPIO-type intensity at Project-X, as a function of the ratio of the proton intensity relative to that available at the Booster.

It's apparent that above about three times Booster intensity, one starts losing ground. The maximum one can obtain is ~1.37 times that at the Booster. Taking the above example of a 3-year run, one could achieve a total of 334 equivalent events, giving a precision of 7% on the SM branching ratio. At this point, one would benefit significantly by reducing the

systematic error; statistics alone would allow a 5.5% measurement. As mentioned above, work by David Jaffe based on parameter variations studied for the KOPIO CDR indicates one could benefit very significantly by improving on the KOPIO resolutions. But one should keep in mind that KOPIO already assumed very demanding performance. Given that the KOPIO team has dispersed, it would not be trivial just to duplicate the experiment. Perhaps a more fruitful direction would be to find a way to put the entire experiment in vacuum. This would remove the difficult thin vacuum vessel, that is one of the most daunting features of the experiment. The only technology that could not obviously operate in a vacuum is that of the preradiator chambers, so a replacement would need to be found for them. But this still leaves us with at best a ~6% measurement, which could not use the entire intensity available at Project-X.

5. A low-energy Booster experiment with a small-aperture beam.

Reducing the size of the beam would make the experiment much less difficult. The problematical vacuum vessel with its awkward aspect ratio would be eliminated. Many other 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. Symmetrizing the beam would incur a very high price in flux – roughly speaking a factor 20. The loss in effective statistics would be somewhat less because of reduction of accidentals, and of spoilage by additional events in a microbunch, i.e., the factor come out to about 14. The reconfiguration of the experiment that this geometry could result in an increase in geometric acceptance of about a factor 2. Thus the relative loss in statistics would be ~7. The 3-year experiment would yield only 35 equivalent events, for a statistical precision of 17%. If we define the minimum goal of a Booster experiment as a 10% measurement, this would need to be improved. David Jaffe's work indicates improvements up to a factor 4.3 for the best events (S/B ~ 8) and 1.7 for medium quality events (S/B ~ 2). One could conceivably get an equivalent increase in overall yield of a factor 3, which would allow the 10% benchmark to be met. Several other optimization paths could be imagined, including a less radical reduction of the beam aperture.

6. A low-energy Project-X experiment with a small-aperture beam.

If Project-X intensity is assumed, the small aperture approach becomes much easier to exploit. With the assumptions of the last section, the increase in effective statistics is a factor 10. This gives 929 equivalent events, which allows the 3% benchmark to be met.