FORMATTING INSTRUCTIONS – KOPIO CONCEPTUAL DESIGN REPORT *

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1 Signal and background estimates

A measurement of $\mathrm{K}^0_\mathrm{L} \rightarrow \pi^0\nu\bar{\nu}$ requires suppression of background by $\sim 10^{-11}$ or more. KOPIO combines kinematic and charged particle or photon vetoing to obtain a measurement of $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \rightarrow \pi^0\nu\bar{\nu})$ with a precision of $\sim 10\%$ assuming the SM value of $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \rightarrow \pi^0\nu\bar{\nu})$. In this section the techniques and assumptions used to make these estimates are described as well as the methods of signal detection and background suppression. The organization of this section is as follows. Subsection 1 describes the simulation tools used to make these estimates, 1 and 1 describe the assumptions concerning the K^0_L flux, the veto inefficiency and the resolution. The signal detection methods are described in 1 and the background mechanisms and expected rates are described in 1, 1 and 1. Signal losses aside from analysis cuts are described in 1. The expected sensitivity of a $\mathcal{B}(\mathrm{K}^0_\mathrm{L} \rightarrow \pi^0\nu\bar{\nu})$ measurement is described in 1.

Tools

The signal and background estimates in this section are primarily based on a 'fast' Monte Carlo simulation (FastMC) that uses parametrization of the detection response and event weighting. These calculations are supplemented by a GEANT3.21-based simulation to assess potential signal loss due to trigger and reconstruction algorithms, and vetoing due to accidentals.

The FastMC[1] approximates the KOPIO detector with a simplified geometry consisting of rectangular parallelopipeds with no magnetic fields. K^0_L are generated from the target using the expected time structure of the incident proton beam[2] and target dimensions. The angular and momentum dependence of the KL beam is taken from extrapolation of measurements from proton-nucleus reactions at 14.6 GeV/c[3]. All known K^0_L, $\pi^\pm$, π^0, $\mu^\pm$ decay modes and their matrix elements with branching fractions from[4] as well as decay-in-flight are included in the simulation.

The impact position, angle, energy and time of photon trajectories which project to the photon detectors are 'smeared' according to the expected resolution of the Preradiator (PR) and Calorimeter (CAL) system. The position resolution is taken to be $0.45/\sqrt{E\ \mathrm{GeV}}\ \mathrm{cm}$, the energy resolution is $2.7\%/\sqrt{E\ \mathrm{GeV}}$[5], and the time resolution is 0.2 ns. The angular resolution is taken from[6] which takes into account the angular- and energy-dependence of the angular resolution. When the possibility of detecting signal photons in other detector elements, such as the PR outer veto (OV) or barrel veto (BV), is studied, the energy resolution is taken to be $x.x\%/\sqrt{E\ \mathrm{GeV}}$, the position resolution is taken to be $w/\sqrt{12}$ where w is the width of a veto module and the time resolution is taken to be x.x ns[7].

Two sequential sequential kinematic fits are attempted for each pair of signal candidate photons. The first fit does not impose the π^0 mass constraint, and the second fit does impose the mass constraint. Additional constraints placed on both fits are a common vertex in space and time as well as constraining the vertex to lie within the vertical beam envelope. The vertex of the second fit is used to construct a K^0_L candidate assuming production from the target center at the center of the microbunch. Physically valid ($\beta(\mathrm{K}^0_\mathrm{L}) < 1$) candidates are accepted for further scrutiny.

Flux assumptions

The total useful K^0_L flux is determined as follows. We expect 7.38×10^8 K^0_L for 100×10^{12} protons per spill on a 10.6cm Pt target into 500 μsr centered at 42.5°[3] using a thin target approximation. Taking into account the effects of target length and secondary production, the flux is reduced by a factor of 0.75[8],[9].

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The 7 cm lead spoiler reduces the flux by an additional factor of 0.527[10]. Combining all these factors gives $7.38 \times 10^8 \times 0.75 \times 0.527 = 2.917 \times 10^8$ K_L^0 exitting the spoiler per spill.

The length of the spill is set to maximize the sensitivity while taking all sources of veto into account[9]. Other sources of vetos are K_L^0 in the same and neighboring microbunches[11], stopped muons[12] and neutrons[13]. When all these factors are taken into account, a loss factor of 0.492 is expected[9] with a spill length of 5.635s and we assume a 2.3s interspill[14]. Combining this factors yields $(2.917 \times 10^8 \times 0.492)/(5.635 \text{ s} + 2.3 \text{ s}) = 1.809 \times 10^7$ "useful" K_L^0 exitting the spoiler per calendar second.

To attain an integrated flux of 1.27×10^{15} K_L^0 thus requires ~ 19500 hours of running.

Veto inefficiency and resolution

Detection methods

As mentioned earlier, the primary signal detection method comprises both photons converting in the PR with the energy accumulated in the PR and CAL. This method is labelled 2γPR/CAL and has the best overall position, angle and energy resolution. The second method also requires that both photons convert in the PR with the energy accumulated in the PR, CAL and OV. The first method is a subset of this method This method is labelled 2γPR/CAL& OV and should have comparable position and angular resolution and slightly degraded energy resolution.

The next three methods only require a single photon conversion in the PR with the other photon converted in the CAL, OV or BV and are labelled PR/CAL, PR/OV and PR/BV, respectively. Taken together, these methods could potentially add twice the number of signal events as 2γPR/CAL albeit with a reduced signal-to-background due to the poorer resolution.

Background mechanisms

Five potential background mechanisms were identified and studied. Three are distinguished by the production time of K_L^0 relative to the center of the microbunch. The other two mechanisms are related to mis-identification of accidental activity in the detector as photon activity or merging of nearby photon showers. The expected rates of these backgrounds will be discussed in detail in the following sections. A brief description of each mechanism is given here.

Microbunch timing of the neutral beam is defined with respect to the time that the center of the proton beam crosses the midpoint of the production target. This is taken as $t = 0$ ns. K_L^0 produced at this time are referred to as "in-bunch" and are by far the largest component of the background. K_L^0 produced in the previous microbunch at $t = -40$ ns are a potential source of "wrap-around" background. This background occurs when a slow K_L^0 produced at $t = -40$ ns is reconstructed and mistakenly assumed to be from the microbunch at $t = 0$ ns. The third mechanism is due to K_L^0 production in between the 40 ns interval of the "in-bunch" production. This is referred to as "interbunch" bunch background. Given the measured rates of interbunch protons[2], interbunch backgrounds are negligible.

Another background mechanism is due additional activity in the photon detectors due to stopped muon decays or neutron-induced showers that is mistakenly identified as a photon-induced shower. Backgrounds due to this mechanism can be suppressed to a negligible level by requirements on timing, shower energy and the χ^2 of the two photon fit. The final background mechanism is due to incorrect reconstruction of two photon showers as a single shower.

Background due to K_L^0 decays

The main source of background to $K_L^0 \to \pi^0 \nu \bar{\nu}$ is due to other K_L^0 decays. Background from other sources can be suppressed to negligible rates.

$\mathrm{K^0_L} \to \pi^0\pi^0$ background

The largest single source of background is due to $\mathrm{K^0_L} \to \pi^0\pi^0$ ($K_{\pi 2}$), branching fraction $(9.32 \pm 0.12) \times 10^{-4}$, when two of the photons are undetected and the detected photons mimic the kinematics of $\mathrm{K^0_L} \to \pi^0\nu\bar{\nu}$.

Non-$\mathrm{K^0_L}$ Backgrounds

Signal losses

$\mathcal{B}(\mathrm{K^0_L} \to \pi^0\nu\bar{\nu})$ sensistivity

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7. Need reference for OV, BV energy, position and time resolution.
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10. TN064
11. TN107
12. TN099, TN109.
13. TN059, TN091.
14. TN113