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Beam Hole Photon Veto For J-PARC K^{O}TO experiment

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The Beam Hole Photon Veto counter (BHPV) for the J-PARC K^{O}TO experiment was designed by MC simulation. This detector is required to operate under extremely large flux of neutrons and low energy γs, as placed in the beamline and directly exposed with such particles in the neutral beam. To realize this detector, we proposed an array of Cerenkov counter modules, each of which has a lead sheet as γ converter, a stack of aerogel tiles as Cerenkov radiator, and light collection system consisting of flat mirrors and Winston Cone funnels. We employ the dual readout to reduce the counting rate for each PMT and optimized the design of lead converter and aerogel. Finally, we succeeded in designing BHPV which can operate in K^{O}TO experiment with $\sim$ 2MHz maximum single counting rate while keeping $\sim 0.1\%$ inefficiency for γs ($E_\gamma > 1$GeV) and 3% acceptance loss by the beam particle such as neutrons.

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1. $K_L \to \pi^0 \nu \bar{\nu}$ search and K^{O}TO experiment

1.1 physics of $K_L \to \pi^0 \nu \bar{\nu}$ decay

The neutral kaon rare decay, $K_L \to \pi^0 \nu \bar{\nu}$, is called "the golden mode" since it can give us critical information about CP violation with extremely small theoretical uncertainty. This decay process is caused by Flavor Changing Neutral Current(FCNC) of the second order electro-weak diagram and its branching ratio is proportional to square of the complex parameter η in CKM matrix (shown in Fig. 1.) Thus, $K_L \to \pi^0 \nu \bar{\nu}$ can provide a very sensitive testing ground for the Standard Model(SM) as well as a probe for new physics beyond SM.

1.2 experimental search so far and in K^{O}TO experiment

The current prediction of the branching ratio by SM is $(2.49 \pm 0.39) \times 10^{-11}$ [1]. Due to this extremely small branching ratio, no experiments so far have observed this decay as shown in Fig. 2. The current best upper limit of the branching ratio is 6.7×10^{-8} [2] at 90% C.L. from the result of runII at KEK-PS E391a, which is the first dedicated experiment to this mode. In our K^{O}TO experiment (K^0 at TOkai), we try to make the first observation of this decay by upgrading the E391a detector and using an intense beam in J-PARC.

The preparation is in progress, and we'll begin data taking in 2011 and continue for 3 years.

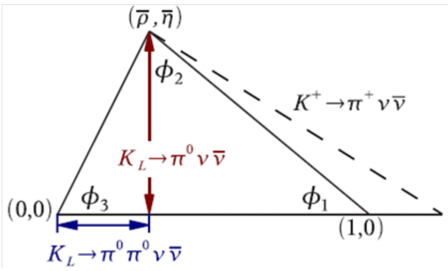

Figure 1: Kaon unitarity triangle. η stands for the height of this triangle.

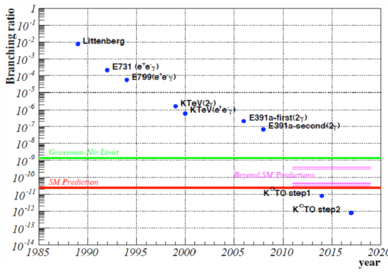

Figure 2: History of improvement in upper limit of the $K_L \to \pi^0 \nu \bar{\nu}$ branching ratio. The final result of E391a will soon plot a new point.

2. experimental method and Beam Hole Photon Veto

2.1 signal detection

In this decay process, a visible particle in the final state is only π^0. So, for the signal identification, we require single π^0 detection with no other activity in our "Hermetic Veto System", which covers the whole decay volume.

The layout of the detectors are shown in Fig. 3. π^0 is detected by pure CsI calorimeters; it measures 2 γ hit positions and energies, from which its z-vertex and transverse momentum are reconstructed. The whole decay volume is surrounded with veto counters such as Front Barrel(FB), Main Barrel(MB) and Neutron Collar Counter(NCC) and extra particles such as γ and $\pi^{\pm}$ are detected with high efficiecncy.

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The BHPV is located the most downstream of the setup, and is one of few detectors placed in the beam. Its role is to veto extra γ from K_L decay escaping into the beam hole. Description of our beam line and requirements for BHPV will be described in the following sections.

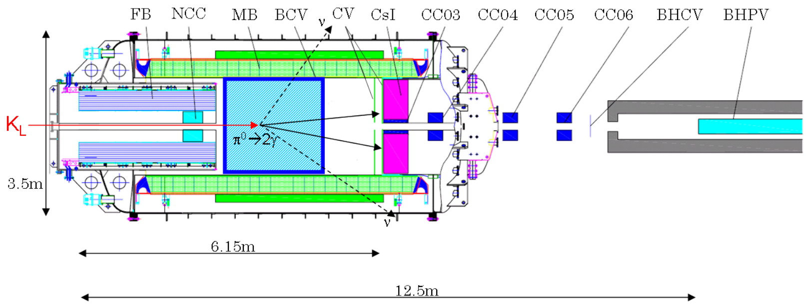

Figure 3: Schematic view of K^{O}TO detectors. Blue hatched region is the decay volume. BHPV is surrounded by some shield to reduce backsplash for upstream detectors such as BHCV, CC05 and CC06.

2.2 neutral beamline

Our neutral beam line, shown in Fig. 4, consists of a nickel (Ni) target, collimation system, lead (Pb) γ absorber and sweeping magnet. First, an intense primary proton beam is bombarded onto the target. Then the secondary particles extracted at 16° are shaped by two sets of collimators. The γ absorber, 7cm-thick lead inserted upstream of the 1st collimator to reduce the beam γs and then make the counting rate of BHPV by these unwanted beam γs smaller. Finally, they pass through the sweeping magnet which bends out all charged particles. The distance between the target and the downstream edge of the 2nd collimator is 20m, long enough for short-lived particles like K_S to decay completely. Estimated fluxes of the remaining particles at the exit of the beam line are listed in Table 1. As seen, our neutral K_L beam contains much more neutrons and γs than K_L. Thus any detector installed in the beam must be able to cope with these particles.

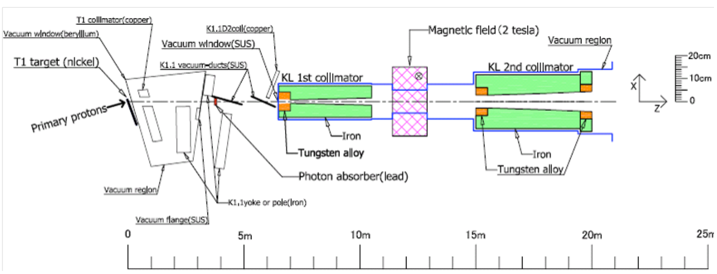

Figure 4: Schematic drawing of the K^{O}TO beamline.

Table 1: Flux of beam particles. The energy thresholds for neutron and γ are 100MeV and 2MeV, respectively.

particle	flux[/spill]
K_L	7.79×10^6
neutron	7.16×10^8
γ	4.20×10^8

2.3 requirements for BHPV

In our experiment, the main backgrounds to the $K_L \to \pi^0 \nu \bar{\nu}$ signal come from the $K_L \to \pi^0 \pi^0$ mode, in which 2 γs are detected by the CsI calorimeter but the ohter 2 γs escaped from detection by one reason or another. The BHPV's main role is to minimize such background events, namely to detect and veto γs coming down in the neutral beam. Fig. 5 shows the energy distribution of such γs entering BHPV. As shown, events with high energy γs ($>$ 1GeV) are dominant. Thus the prime requirement to the detector is a high detection efficiency ($>$ 99.9%) above 1 GeV.

Another important issue is low sensitivity to neutrons and low energy γs in the beam core. This is due to the 2 reasons; single counting rate and accidental signal loss. As for the former, you can easily expect the high counting rate by the large flux of these beam particles and whether the detector can operate properly is a big problem. This is especially serious for the beam γ because this is a kind of particle that should be detected. Though the flux of the beam γ can be controlled by the γ absorber thickness as mentioned, further increase of its thickness would result in decrease of K_L yield, and thus it is desirable for BHPV to be capable of operating in as large a flux as possible. The latter accidental signal loss comes from false veto by these neutrons and γ by accidental coincidence when they are mistaken as hits by γ from K_L decay.

In the following section, the actual design of this detector is discussed.

3. design of BHPV

3.1 design concept

As for BHPV, we proposed to employ an array of aerogel Cerenkov detectors. Fig. 6 shows a schematic layout of one detector module. We plan to install 25 modules along the beam line, as shown in Fig. 7. In one module, an incident γ creates an electromagnetic shower in a lead converter, and, in turn, electrons and positrons radiate Cerenkov lights in the aerogel tile. The lights are collected by 2 sets of a flat mirror and light funnel (Winston Cone), and are read out by 2 5-inch PMTs (HAMAMATSU R1250) from both sides of the module. As opposed to γs, neutrons tend to generate slow particles by hadronic interactions in materials. Thanks to the low refractive index of the aerogel ($n \simeq 1.05$), they don't radiate Cerenkov lights. Thus BHPV is much less sensitive to neutrons than γs.

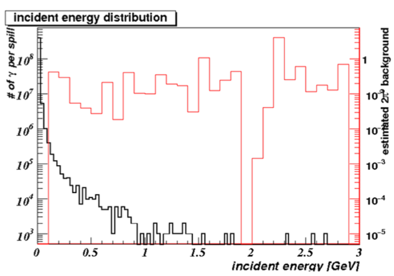

Figure 5: Energy spectrum of the beam γ (black) and one BHPV should detect(red). The latter is scaled to the number of $K_L \to 2\pi^0$ background after the 3 snowmass year run.

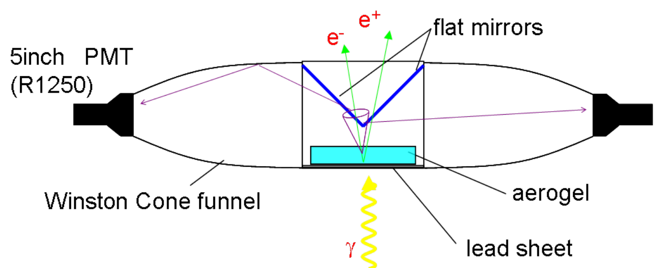

Figure 6: Design of single module of BHPV (top view). The size of aerogel is 30cm × 30cm.

3.2 γ detection condition

As mentioned, we use 25 modules placed along the beam line. In order to identify high energy γs, we demand a condition that 3 consecutive modules have a hit in each event. This is our logical definition of γ that should be vetoed. We note that electromagnetic showers tend to spread forward while hadronic showers isotropically. Thus this condition helps further separation between γs and neutrons, and reduce the accidental signal loss by neutrons. The number of modules, 25, is determined to achieve enough efficiency for high energy γs while keeping each module thin enough.

3.3 reduction of single counting rate

In designing BHPV, one remaining issue was single counting rate; the maximum counting rate was expected to much as high as 10MHz in our original design which employed one PMT to read out Cerenkov lights, and equal lead converter and/or aerogel thickness for all 25 modules. Below, we discuss several optimizations to reduce single counts.

As mentioned previously, we use 2 PMTs for one module in the present design. This change alone has reduced the counting rate to 65% of the original design. As a side bonus, uniform light collection in wider geometrical region (especially along the horizontal direction) and better γ detection efficiency are expected.

The thickness of lead converter and aerogel is optimized for further counting rate reduction. Ideas in this optimization are summarized as follows:

- to employ thinner aerogel in front layers, where the single counting rate is too high
- to make lead converter thinner in layers with thinner aerogel to recover efficiency of the low energy γ
- to conserve total radiation length($8.9X_0$) for high energy γ detection

We note that inefficiency for high energy γ stems mainly from the punch through effect; thus the total radiation length of the whole BHPV should be kept same. Thus, we employ thinner (or no) lead sheet and aerogel in the first 10 modules and thicker lead converter in the rest.

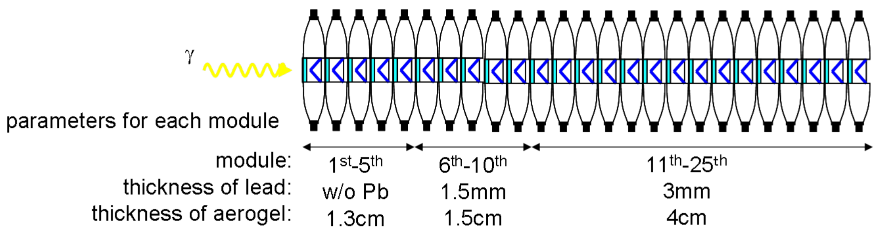

Figure 7: Configuration of optimized design. Even without lead sheet, there're several numbers of aluminum sheet as support structures, and conversion is possible.

3.4 expected performance

We studied in detail the detector performance by Geant4 MC simulation. The detector configuration in our preset design is shown in Fig. 7. Fig. 8 (left) shows the expected counting rate for each module. In this study, we used the profile and energy spectra of γ, neutron and K_L obtained by a beam line simulation. The maximum rate by the present design, shown in green, is less than 2MHz. Fig. 8 (right) shows the γ inefficiency (1-"efficiency") vs incident energy. In this case, γ was injected perpendicularly to 15cm square of the detector surface uniformly. Above 1GeV, its efficiency is around 99.9%.

Accidental loss by various beam particles is also estimated, and is summarized in Table 2. It shows that the total signal loss is less than 3%, proving that we could successfully design the BHPV with high efficiency to γs, and low enough sensitivity to unwanted particles at the same time.

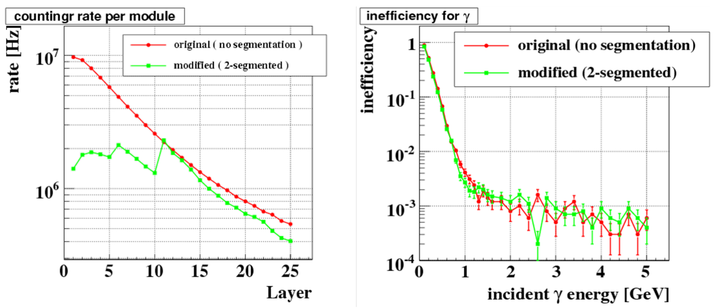

Figure 8: Expected single counting rate for each module(left) and inefficiency for γ (right) by the original design (25 identical modules with 2mm-thick lead converter and 5cm aerogel) and the optimized design. The threshold is 4p.e.

Table 2: Expected accidental loss by beam particles.

particle	accidental loss [%]
γ	0.92
neutron	1.5
K_L	0.52
total	2.9

4. summary and prospect

The Beam Hole Photon Veto counter(BHPV) for the J-PARC K^OTO experiment was designed, which can work in our neutral beam with extremely large neutron and low energy γ flux of nearly GHz order. To detect extra γ from K_L decay effectively while excluding neutron hits in the beam core, we designed the Cerenkov detector using lead γ converter and aerogel. Though high single counting rate at each PMT was a big problem, after the study on performance of dual readout by 2 PMTs and optimization of thickness of lead converter and aerogel, the maximum rate was reduced to $\sim$ 2MHz keeping inefficiency to γ with $E_\gamma >$ 1GeV around 0.1%.

For further development of this detector, we plan to manufacture some prototype modules with the real size and check the performance by positron beam and actual K_L beam in J-PARC.

References

[1] F. Mescia and C. Smith, Phys. Rev. D 76, 034017 (2007).

[2] J. K. Ahn et al. (E391a Collaboration), Phys. Rev. Lett. 100, 201802 (2008).