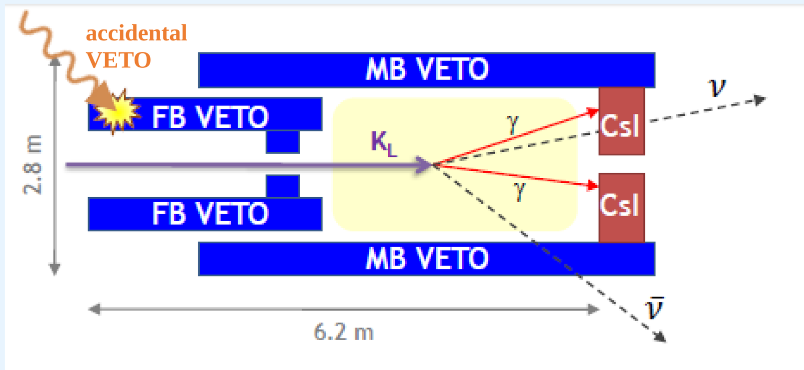
Effect of low-energy neutrons on accidental counting rate in the KOTO experiment

Toru Matsumura (on behalf of the KOTO collaboration), *National Defense Academy of Japan, Yokosuka, Japan* (E-mail: toru@nda.ac.jp)

1. Introduction

KOTO is a high-sensitivity experiment aiming to search for the rare $K_L \to \pi^0 \nu \bar{\nu}$ decay (Br ~10^{-11}). The signal criteria is 2γ detection in the CsI and no hit in the VETO counters (**Fig.1**). Hence, higher accidental rate of the VETO counters causes loss of the rare "signal" due to **accidental VETO**. Typical counting rates are 5 MHz for FB VETO and 2 MHz for MB VETO. In total, ~60% of the SM signal is expected to be lost in the present experimental condition. Therefore, **reduction of the accidental VETO rate is one of the issue to be solved in order to reach higher sensitivity.**

Fig.1 Signal criteria and accidental veto. FB and MB VETO are Lead/Scinti. sandwich counter.



Cause of the accidental rate

In the past few years, we reinforced radiation shield around the experimental area with 30 cm-thick-iron and 10 cm-thick polyethylene. As a result, activity due to high-energy neutrons from the **primary beamline** was drastically reduced. At present, the main source of the accidental counts is stemmed from particles from the **KL beamline**. Our objective is to investigate the origin and mechanism of the accidental activity originated from the KL beamline with a beamline simulation.

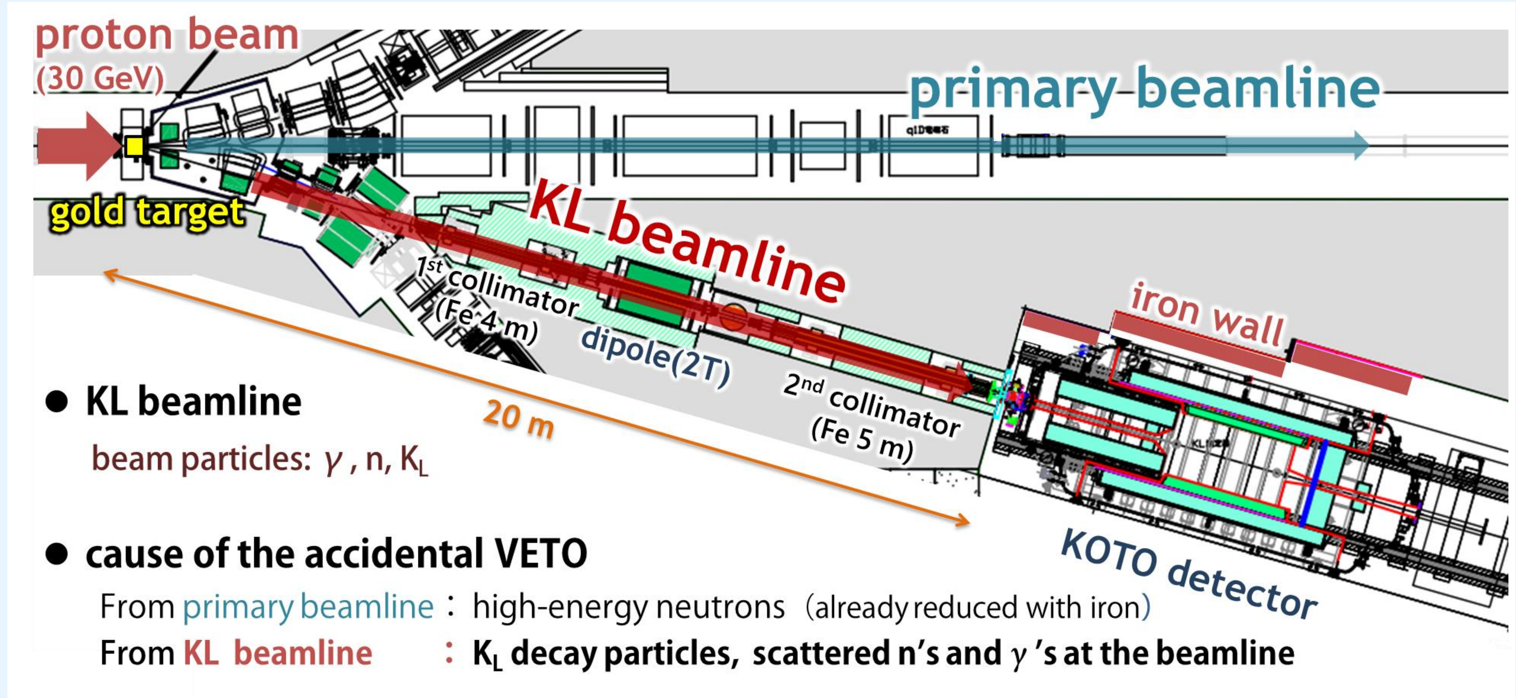


Fig.2 Top view of the KOTO beamline

2. Origin of the accidental hit in FB VETO

Fig.3 shows a histogram of the detection time with energy deposit more than 1 MeV in FB VETO, where the initial time is the start timing of beam transport at 1m downstream of the gold target. There are two major components: sharp peak at around 70-300 ns (**Prompt Component**) and broad bump at around 10 μs-3 ms (**Delayed Component**).

Mechanism of the accidental VETO rate

- **Prompt Component (33%)**
  - K_L-decay particles such as $\pi^{\pm}$, μ, γ
  - Scattered neutrons or γ's at the upstream charged veto counter (UCV)

  These are true-timing hits that should be vetoed.

- **Delayed Component (53%)**
  - Neuron capture: n+^{1}H→^{2}H+ **γ (2.2 MeV)** in the scintillator
  - Neuron capture: n+^{56}Fe→^{57}Fe+ **γ (7.6 MeV)** in the support structure

  Neutrons generated by the $\pi^- p \to \pi^0 n$ reaction are **thermalized** in the KOTO detector; they are captured by the scintillators and stainless steel.

This component is uncorrelated timing hits and should be suppressed !

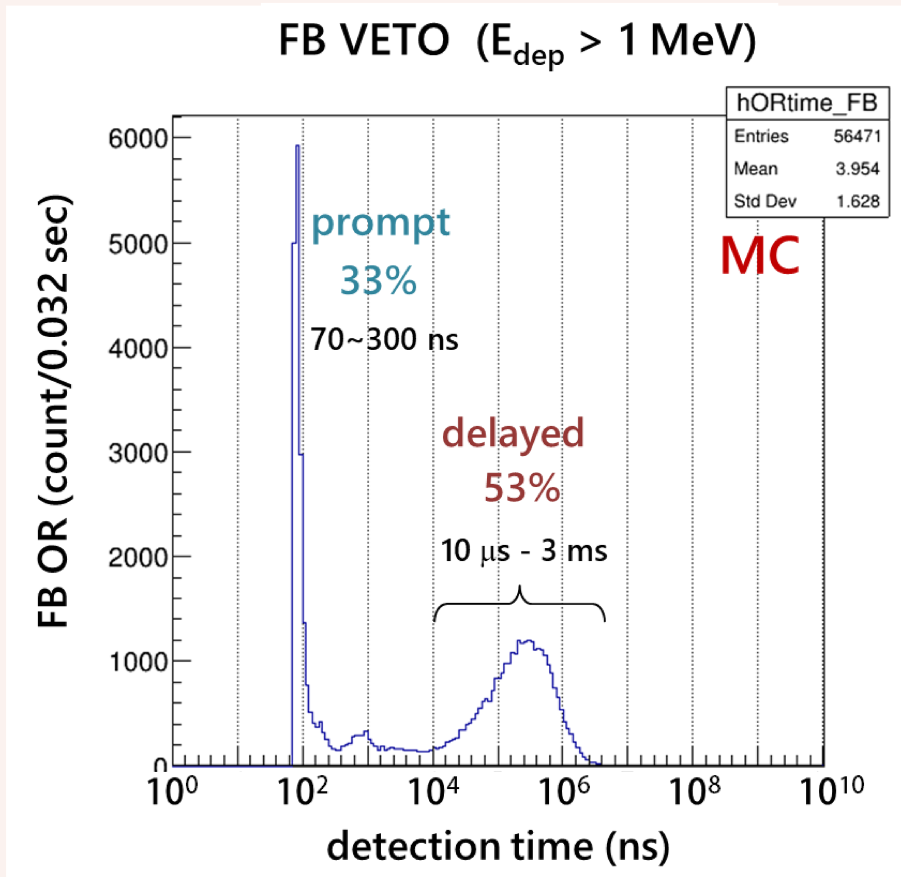


Fig.3 Detection time of FB after the production

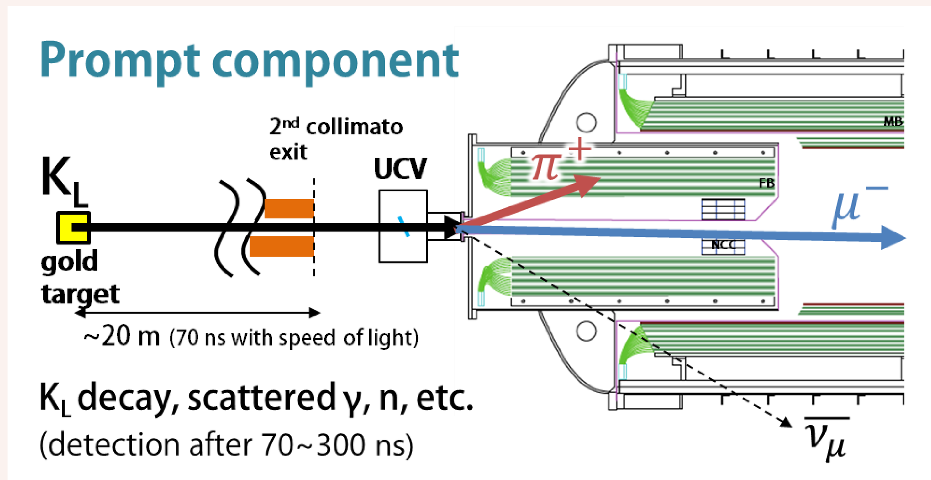


Fig.4 A typical reaction mechanism of the prompt component

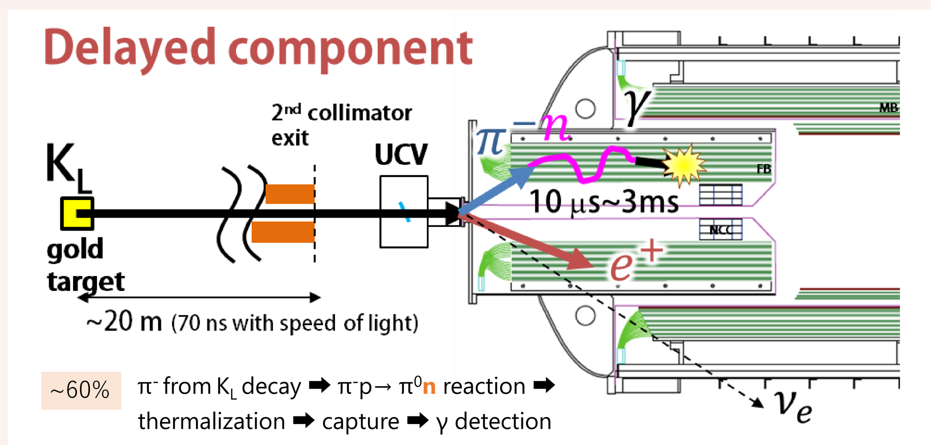


Fig.5 A typical reaction mechanism of the delayed component

3. Data/MC comparison

The accidental rate of FB VETO with 64kW beam was 2.99MHz after subtracting the primary beamline contribution. On the other hand, the Monte Carlo (MC) estimation was 2.3 MHz, which was in agreement with 20% accuracy. The small discrepancy between the data and MC may be due to incompleteness of the hadron package of MC or existence of unaware background source.

Fig.6 shows threshold dependence of the FB accidental rate estimated with MC for all component and only delayed one. Due to the strong effect of 2.2 MeV γ accompanying the neutron capture of ^{1}H, one can see that the delayed component become pronounced (~50%) at low energies. Hence, if we can eliminate the unwanted delayed component in an effective way, drastic suppression of the accidental rate is achievable.

Data (clock trig.) 3.24 MHz – 0.25 MHz (primary beamline contribution) = 2.99 MHz (KL beamline contribution)

MC (this report) 2.3 MHz

assumption : beam power 64 kW = 6.1×10^{13} protons/spill
K_L yield corr. = 1.5 x (GEANT3)

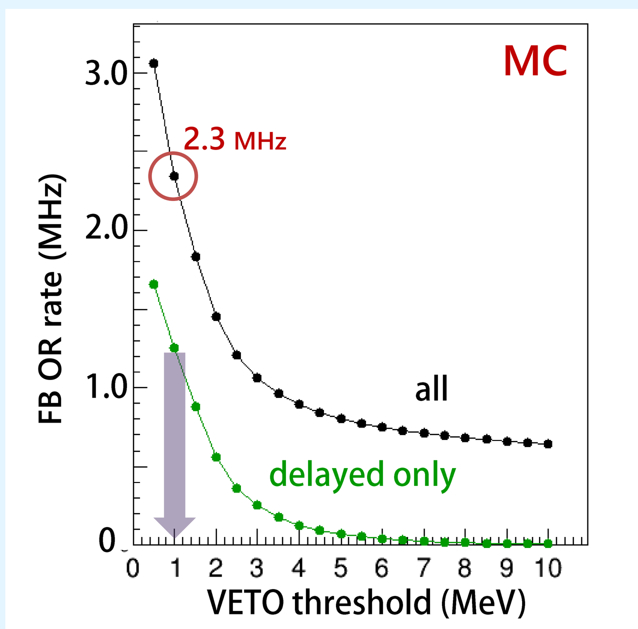


Fig.6 Threshold depemdence of FB counting rate

4. A possible way to suppress the accidental hits

Since thermal neutrons induce the delayed accidental hits, we can suppress them by inserting neutron absorber into the VETO counter. Boron carbide (B_4C) sheet is a good candidate for this purpose because of following reasons.

- Cross-section for the ^{10}B(n,α)^{7}Li* reaction to thermal neutrons is large (3840 b). Most of ^{7}Li residuals (94%) are in excited state and 0.48 MeV γ's are emitted from them; nevertheless, FB VETO with 1 MeV threshold is basically insensitive to the γ's.
- Thin mylar sheet is commercially available (50-100 μm). Thus, we can insert it between lead plate and reflector sheet without major modification of the detector.

The effect of insertion is summarized in Table 1. By inserting 100-μm-thick of B_4C sheet to all the 54 layers of the FB module, the accidental rate reduces from 2.3 MHz to 1.2 MHz (90% reduction in the delayed components). As a result, the accidental loss of FB VETO may be improved from 21% to 12% with 50 ns timing window.

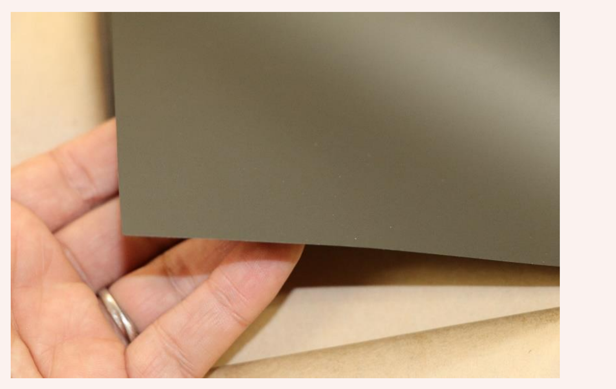


Fig.7 B_4C mylar sheet (100 μm)

Tab.1 Effect of B_4C sheet insertion (64kW)

Condition	rate (MHz)	rate [delayed] (MHz)
No B_4C sheet	2.34	1.25
B_4C sheet 100 μm	1.20	0.11
B_4C sheet 100 μm (Inner 27 layer only)	1.43	0.33
B_4C sheet 50 μm	1.39	0.31

90% reduction

5. Other sources?

In addition to the above mentioned sources, thermal or epi-thermal neutrons that directly come from upstream of the beamline are possible source of accidental counts. Evaluating this by simulation requires a long calculation time and is difficult to reproduce the geometry required for reliable results. Therefore, the presence or absence of low-energy neutrons was investigated by systematic measurements with various neutron counters.

One of such counter is ^{6}LiI(Eu) scintillator covered in front with two layer of the neutron absorber (20%-boric acid mixed polyethylene). The thickness of the absorber makes a big difference in sensitivity to thermal and epithermal neutrons. Fig.9 shows ADC distributions for different absorber thickness measured at 30 cm below the beam axis. No difference was observed in the neutron detection rate, which indicates that **we can exclude the possibility of thermal and epithermal neutrons coming from the upstream of the beamline.**

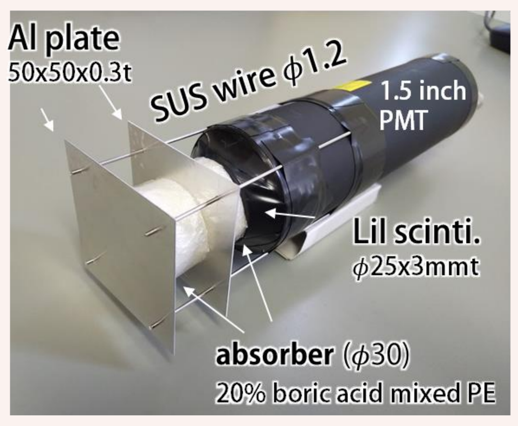


Fig.8 LiI(Eu) scintillator

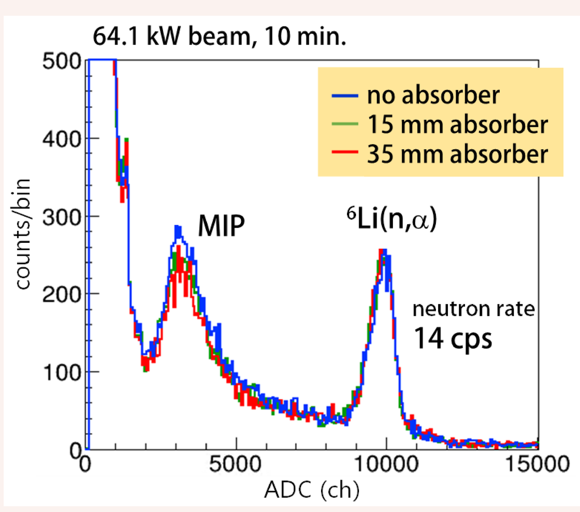


Fig.9 ADC distributions of LiI

Summary

- In the KOTO experiment, reduction of the accidental loss is one of the issue to be solved in order to reach higher-sensitivity.
- We found that more than 50% of the accidental counts of FB VETO are caused by the neutron capture reactions in scintillators (^{1}H) and support structures (Fe isotopes).
- Inserting a B_4C sheet between lead/scintillator layers can reduce 90% of the counting rate caused by thermal neutrons. As a result, the accidental loss of FB VETO can be improved from 21% to 12%.

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