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Ultra-fast Small Angle Calorimeter for photon detection at KOTO II

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Abstract: KOTO-II at J-PARC is proposed to extend the search for the ultra-rare decay $K_L \to \pi^0 \nu\bar{\nu}$ by operating at substantially higher beam intensity than KOTO. In this regime, the Beam Hole Photon Veto (BHPV) must provide excellent timing performance and excellent γ/hadron discrimination to identify background photons and beam-induced activity. Given the time resolution of the lead-aerogel Cherenkov BHPV used in KOTO, a ∼19% nominal beam loss is expected under KOTO-II conditions.

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As an alternative, we propose a compact and highly granular Small Angle Calorimeter (SAC) based on ultra-fast lead-tungstate crystals read out with fast photomultiplier tubes, aiming to improve timing and reduce accidental veto losses. A SAC prototype consisting of two 3×3 PWO-UF crystal layers was tested at the CERN PS T9 beamline with Hamamatsu R9880 and R14755 metal-channel photomultipliers. In parallel, the crystals were characterized with high-resolution X-ray diffraction to quantify their orientation and enable measurements with aligned crystals. We present an overview of the detector R&D and the first beam test results on energy response and time resolution.

Keywords: Calorimeter methods; Calorimeters; Particle detectors; Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc)

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1 The KOTO experiment and the KOTO II upgrade

The KOTO experiment at J-PARC in Japan is searching for the ultra-rare decay $K_L \to \pi^0 \nu \bar{\nu}$. This transition is a Flavour Changing Neutral Current (FCNC) process, with a $s \to d$ transition, mediated by loop-level penguin and box diagrams. Within the Standard Model, this decay is predicted with a branching ratio of $\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) \simeq 3 \times 10^{-11}$ [1], and with a theoretical uncertainty at the $\sim 2\%$ level, since the amplitude is dominated by short-distance physics. Because it is an FCNC decay strongly suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism and by the hierarchical structure of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, any observed deviation from the Standard-Model prediction would constitute a clean signature of new physics. Moreover, $K_L \to \pi^0 \nu \bar{\nu}$ is a purely CP-violating decay: the K_L state is predominantly CP-odd, while the $\pi^0 \nu \bar{\nu}$ final state is CP-even. The process is therefore also highly sensitive to new sources of CP violation.

The KOTO experiment has achieved excellent performance in this search, setting the current best upper limit with a sensitivity of $\mathrm{BR} < 2.2 \times 10^{-9}$ at 90% C.L. [2]. To reach the sensitivity required to test the Standard-Model prediction, the KOTO experiment demands an upgraded experimental setup, motivating the proposed KOTO II upgrade.

The KOTO II experiment is designed to reach a sensitivity below the level required to probe the Standard-Model prediction. This sensitivity would enable the first observation of the decay with a significance above 5σ if the rate is consistent with the Standard Model, and/or reveal a deviation indicative of physics beyond the Standard Model.

Beyond the $K_L \to \pi^0 \nu \bar{\nu}$, the KOTO II experiment can also explore the decays $K_L \to \pi^0 \ell^+ \ell^-$, which are among the most informative rare decays in kaon physics. They provide stringent tests of new-physics scenarios of Lepton Flavour Universality (LFU), by delivering complementary information for interpreting the $K \to \pi \nu \bar{\nu}$ measurements.

KOTO II can study additional rare decays such as $K_L \to \pi^0 \gamma \gamma$, improving the precision of the current branching ratio determination, and $K_L \to \pi^0 \pi^0 \nu \bar{\nu}$, setting a more stringent upper limit.

Finally, KOTO II also offers opportunities to probe the dark sector through searches for dark photons and axion-like particles (ALPs) produced in K_L decay final states [3].

The KOTO-II setup is largely based on the KOTO design, optimized for the search for the decay $K_L \to \pi^0 \nu \bar{\nu}$, but it incorporates major upgrades to operate with substantially higher intensity.

Protons with an energy of 30 GeV, provided by the J-PARC Main Ring, impinge on a gold target and produce neutral secondaries; in KOTO II these are extracted into a new neutral beamline at 5° with respect to the primary beamline (compared to 16° in KOTO), which increases the K_L yield and hardens

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the K_L momentum spectrum. At a primary beam power of 100 kW, corresponding to 2×10^{13} protons on target per second, the resulting K_L flux in the neutral beam is expected to reach ~24 MHz per spill. The neutral beam is then collimated, selecting a K_L component that enters the decay volume; in KOTO II the fiducial region will be extended to approximately six times larger than in KOTO, which, after accounting for the higher K_L momentum, increases the decay acceptance by about a factor of three.

In the decay region, a CsI electromagnetic calorimeter at the downstream end measures the energies and positions of photon clusters and selects events consistent with boosted $\pi^0 \to \gamma\gamma$. The decay region is surrounded by veto detectors, which, together with the calorimeter, reject events with extra activity, in particular those with a number of photons different from two. Among the veto detectors, in the forward direction along the K_L beam axis, a dedicated Beam Hole Photon Veto (BHPV) is installed to detect photons escaping through the beam hole; it must be transparent to neutral hadrons. In KOTO, the BHPV is implemented as 16 modules, each consisting of a lead converter followed by an aerogel Cherenkov detector [4].

2 Small Angle crystal Calorimeter as beam hole photon veto

Although the BHPV has performed well in KOTO, an upgrade is required in KOTO II in order to cope with the substantially higher K_L flux. The KOTO II proposal therefore foresees an increase of the BHPV from 16 to 25 modules [3]. However, due to its timing resolution (~600 ps), the BHPV must operate with a veto window of about 6 ns, which translates into an expected ~19% loss of the nominal K_L flux for KOTO II.

To mitigate this limitation, we propose an alternative approach inspired by the HIKE proposal (a conceptually similar but not approved experiment for rare K_L decays), based on a granular Small Angle Calorimeter (SAC) built from oriented ultra-fast lead tungstate crystals (PWO-UF). PWO-UF crystals retain several key features of standard PWO, including strong radiation hardness (up to 10^{13}–10^{14} n/cm^2 and 10^5–10^6 Gy), a short radiation length (X_0 = 0.89 cm), and a favourable ratio $\lambda_{\text{int}}/X_0 = 22.8$. When used in configuration with high granularity, these properties make them well suited for neutral-hadron beamlines, to have an efficient photon detection and γ/hadron discrimination. In addition, PWO-UF provides a light yield of about 7 p.e./MeV with a scintillation decay time of 640 ps [5]; compared to standard PWO, this corresponds to a lower light output but significantly faster emission, a combination that is advantageous for improving the timing performance and, consequently, reducing beam losses associated with accidental vetoes.

A first SAC prototype was therefore constructed and tested. It consists of two stackable layers, each built as a 3×3 matrix of crystals produced by the Crytur facility each with dimensions $18 \times 18 \times 40$ mm^3. The crystals were specified to have the $\langle 100 \rangle$ axis perpendicular to the front face within 6 mrad; for each crystal, the residual misalignment angle with respect to the front face was measured using a high-resolution X-ray diffractometer (XRD).

To preserve good time resolution while maximizing light collection, each crystal is read out individually by a photomultiplier tube (PMT) with a diameter of 8 mm, coupled through a Winston-cone light concentrator lined with ESR foil, increasing the photon-collection acceptance from about 15% to 79%. The PMTs are mounted on a dedicated single-PCB plane for each layer. Two variants of the sensor board were developed and tested, based on the Hamamatsu R9880 and R14755 PMTs, which share nearly identical external dimensions. The R9880 features 10 dynodes and reaches a gain of 4×10^6 at V_{max}, while the R14755 has 6 dynodes and a maximum gain of 6×10^5. The R14755

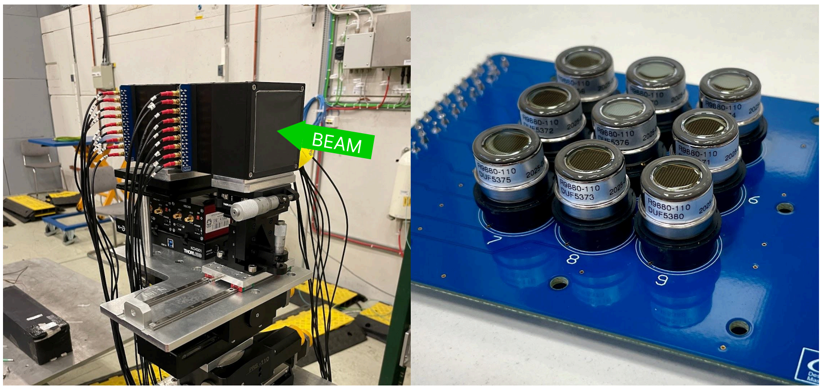

Figure 1. Left: Photograph of the SAC prototype mounted on a high-precision goniometer for alignment. The beam direction is indicated by a green arrow. Right: Single PCB sensor plane populated with nine Hamamatsu R9880 PMTs.

provides a slightly faster response (pulse width 680 ps versus 1250 ps FWHM), and both tubes have a quoted transit-time spread of 200 ps. For the R9880 board, the high-voltage divider follows the Hamamatsu reference design, with additional removable 51 Ω resistors on the last two dynodes to suppress ringing due to parasitic inductance when needed. For the R14755 board, a custom divider was implemented, including ballast capacitors and the same option of removable damping resistors on the last dynodes. To achieve a stable optical response, reducing optical cross-talk between crystals, and to enhance internal light collection via diffuse reflections, the 18×18 mm^2 end faces of the crystals were polished, whereas the lateral faces were left unpolished and wrapped with ESR foil. The upstream end faces were covered with black electrical tape to suppress light returning away from the PMTs. Figure 1 shows photographs of the SAC prototype mounted on the goniometer and the sensor PCB populated with the PMTs R9880.

3 Beam test preliminary results

The SAC prototype was tested in a CERN PS T9 beamline using a focused positron beam in the 1–6 GeV energy range and a parallel beam of minimum-ionizing particles (MIPs) and electrons at 5 GeV. A schematic of the beam test setup and its main components is shown and described in figure 2. The goals of the beam test were to compare and test the two PMT models, study the energy response, measure the time resolution, and assess the calorimeter performance as a function of the crystal alignment. For these studies, the tracking system was used to select events in which the beam positron was incident on the central 14×14 mm^2 area of the central crystal. Figure 3(A) shows the pulse-height distributions used to characterize the energy response of the prototype for the focused electron beam, as well as for the parallel MIP beam (at 10x gain), for the R9880 PMT configuration. The MIPs peak is observed at 392 mV in pulse height and at about 50 pC in the corresponding charge distribution. Using the laboratory calibration factor of 0.82 pC/p.e. and assuming an average ionization energy loss of $\sim$ 80 MeV for a MIP traversing 8 cm of PWO, we estimate a light yield of approximately 0.75 p.e./MeV of deposited energy.

The timing performance of the R9880 PMTs was evaluated with two independent methods. In the first approach, the mean time is measured by the central crystals in the front and back layers and

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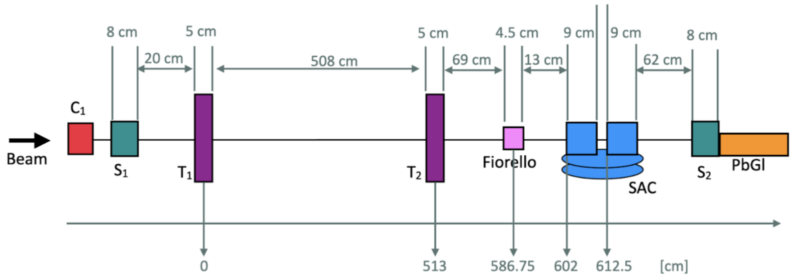

Figure 2. Beam test setup: The beam particles were tracked over a 10×10 cm^2 active area using two double-sided silicon microstrip tracking stations (T1 and T2). Two scintillators (S1 and S2) were used to form the trigger, while a Cherenkov detector (C1) provided offline e/MIP separation.For the timing studies, a dedicated reference counter (Fiorello) was employed: it provides a time resolution of about 35 ps and covers a 2 cm^2 area at the centre of the setup. The prototype (SAC) was mounted on a high-precision goniometer to perform its alignment with respect to the beam. The fraction of the electromagnetic shower not contained in the SAC was measured by a downstream lead-glass calorimeter (PbGl) with a thickness of about 37 cm (24.7 X_0), located at the end of the beamline.

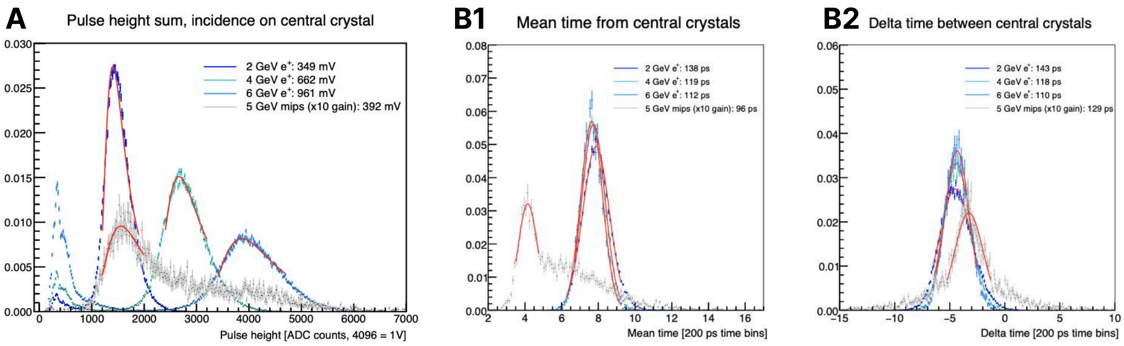

Figure 3. Results from the SAC beam test with focused electron beams at 2, 4, and 6 GeV and a 5 GeV parallel beam of MIPs. (A) Pulse-height spectra summed over all channels. (B) Timing-resolution studies using two independent methods: (B1) distributions of the mean signal time measured by the central crystals in the front and back layers with respect to the reference time; (B2) distribution of the time difference between the central crystals in the front and back layers.

compared to a reference time provided by the t_0 detector; the contribution of the reference detector resolution ($\sigma_{t_0} \simeq 36$ ps) is subtracted. In the second approach, the time difference between the central crystals in the front and back layers is used. Under the assumption of equal time resolution for the two layers, one obtains $\sigma_t = \sigma(\Delta t)/2$. The two methods yield consistent results for both positrons and MIPs (see figure 3(B1) and (B2)). For the positron data, the time resolution is well described by the parameterization $\sigma_t = 140\ \text{ps}/\sqrt{E\ (\text{GeV})} \oplus 95$ ps.

4 Outlook

The present results highlight the potential of a prototype granular ultra-fast calorimeter based on PWO-UF crystals to enhance timing resolution in the small angle veto region of the KOTO II experiment and, consequently, to mitigate accidental veto losses estimated to be at the ~19% level for

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the nominal KOTO II K_L flux with the baseline lead-areogel BHPV timing window. However, we did note some non-linearities in the correlation between the curve of charge and pulse height, possibly indicating some issues with the light collection, which are still under study; in particular, we suspect that light reflected back into the crystal by the short light-collection cones contributes to the observed degradation. For this reason, the cone geometry is being re-optimized through dedicated simulations. Once this activity is completed, a new set of beam tests with electrons and MIPs is planned.

In addition, the data collected with the R14755 PMT option are still under detailed investigation. Because of its lower maximum gain, this configuration requires a more careful calibration and analysis. Nevertheless, its intrinsically faster response suggests that it may ultimately provide improved timing compared to the R9880 option.

Finally, the calorimeter has been conceived to allow an independent alignment of the crystallographic axis of the central crystal in each layer with respect to the beam direction. This feature enables studies of coherent effects in oriented crystals for improved performance. In the specific case of KOTO II, where photons from K_L decays typically have energies below ~2 GeV, the impact of crystal orientation is expected to be limited. However, the alignment capability becomes particularly attractive for higher-energy applications (e.g. HIKE-like configurations) and for dedicated measurements of shower development and performance in an aligned crystal calorimeter.

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