Electromagnetic Calorimetry in Project X Experiments – The Project X Physics Study

Summary and R&D prospects

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Introduction

The Electromagnetic Calorimetry Working Group investigated a series of muon, kaon and neutron-antineutron oscillation experiments in existing or proposed pre-Project X versions, and in several instances examined whether or not the calorimetric techniques employed in these experiments could be extrapolated to produce viable experiments at Project X in its various stages. This was done, as per our charge, purely from the perspective of the calorimeters involved. In so doing, areas of potentially fruitful R&D in calorimetry were identified. The resulting initiatives have both short term experiment-specific goals, and longer term more generic objectives.

Muon physics

Experiments examined included an improved measurement of *g*-2 of the muon, a search for μ^- to e^- conversion and related searches for μ^- to e^+ conversion and $\mu^+ \rightarrow 3e$ decay, and a search for $\mu^+ \rightarrow e^+\gamma$ decay.

g-2

The BNL *g*-2 experiment uses Pb-scintillating fiber electromagnetic calorimeters, read out with PMTs, to detect decay electrons at twenty four stations around the ring. The Fermilab version of the experiment will upgrade these calorimeters to cope with rates as much as three times higher. $PbWO_4$ scintillating crystals, PbF_2 Cerenkov counters and W/scintillating fiber devices have been considered. Arrays of the latter two have been tested in the Fermilab test beam from 2 to 8 GeV. The PbF_2 crystals are the leading candidate. Readout would be with either Hamamatsu R9800 PMTs or S10362-33-050C sixteen channel SiPMs.

Mu2e

The Mu2e configuration contains an electromagnetic calorimeter designed to furnish confirmation of a 105 MeV conversion electron signal from the tracker, as well as to provide a possible trigger. The calorimeter consists of ~2000 LYSO crystals, read out by large area APDs. The default geometry is four vanes arrayed around the beamline; an alternative disk geometry is also under consideration (see Figure 1). The LYSO has a decay time of 40 ns, requiring a gate interval of about 200 ns. This is sufficient to reject pileup in the current incarnation of the experiment, and perhaps in the early stages of a Project X-capable experiment. It would not suffice for the increases in intensity contemplated at later stages. For this, since energy resolution is of prime importance, a new faster scintillator would have to be employed (see below).

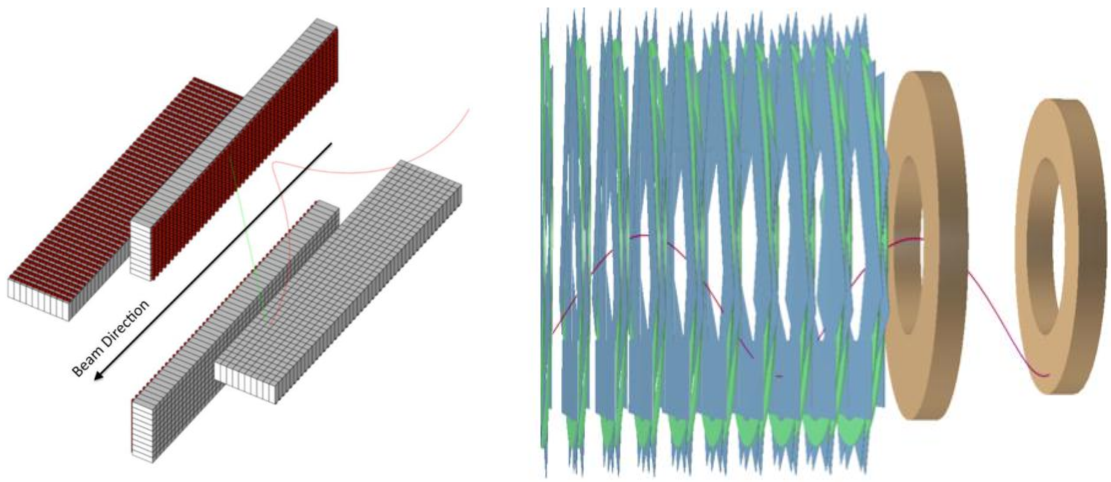

Figure 1. Vane (left) and disk (right) calorimeter configurations in the Mu2e experiment.

$\mu^+ \to e^+ \gamma$

The current MEG experiment at PSI was presented, with an eye to examining the planned upgrade and the possibility of employing a calorimetric technique for a $\mu^+ \to e^+ \gamma$ search at Project X. The current data sets a limit of 2.4×10^{-12} at 90% CL. The liquid xenon calorimeter did not quite reach design specification; upgrades are planned to improve the energy resolution. These involve improving the spatial resolution of the detectors mounted on the entrance face by replacing the existing PMTs with large area (12×12 mm^2) MPPCs, as shown in Figure 2, reducing the reflectivity of the inner walls and improving the time resolution. The expected sensitivity of the experiment would then improve to a few $\times\ 10^{-13}$.

It is unlikely, however, that the MEG technique can be successfully employed at Project X rates, since the accidental rate increases as the square of the stopping muon rate. This has motivated a study of an alternative approach, in which the photon is detected by reconstructing the tracks of an e^+e^- pair produced in a thin converter. This amounts to a tradeoff of detection efficiency for energy resolution and concomitant background rejection. Early simulations indicate that this non-calorimetric technique could reach a single event sensitivity of 2×10^{-16}. The concept uses double pixel layers to measure the position and direction at several points on the helical trajectory of a track in a solenoidal magnetic field, as shown in Figure 3.

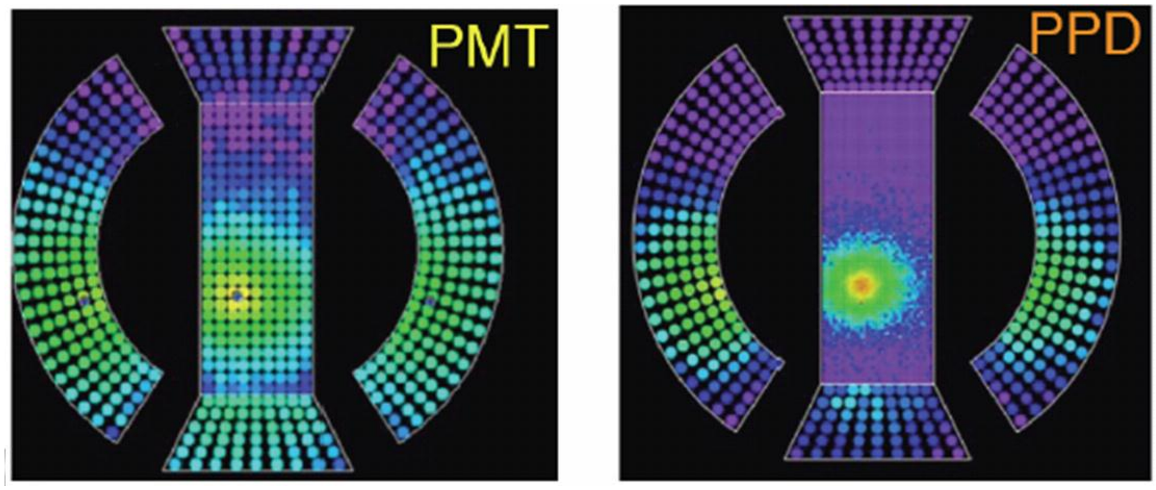

Figure 2. Improvement in shower localization to be achieved by MEG by replacing PMTs on the LXe calorimeter entrance face with MPPC devices and reducing wall reflectivity.

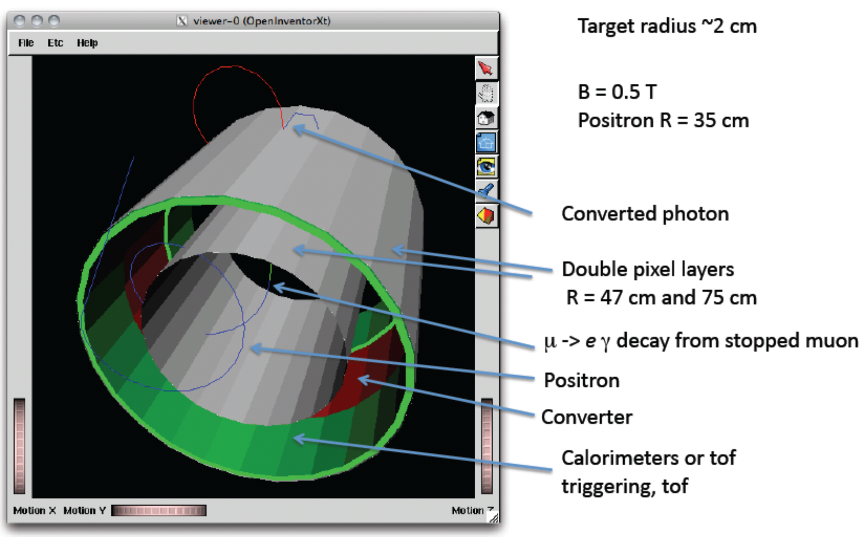

Figure 3. Concept of a $\mu^+ \to e^+ \gamma$ experiment using a photon conversion technique.

The high muon and kaon rates expected at Project X make high quality calorimetry quite difficult. The candidate technologies are based on homogeneous scintillating devices, either noble liquids or crystals. While LXe has a fast decay time of 45 ns, the large radiation length and practical requirement that the light be detected at the periphery of a large volume, limit the achievable time resolution. The current generation of crystal-based high quality, high rate capable, calorimeters employs $PbWO_4$ and LYSO, which have decay times of 30 and 40 ns, respectively. Project X will increase the rates of stopping muon experiments by nearly a factory of fifty, which makes these decay times far too slow to prevent such calorimeters from being overwhelmed by accidentals.

This leads to the question of whether there are other radiation-hard crystals having decay times that are meaningfully faster. BaF_2, has the fastest known scintillation component, with a decay time of 600 ps at 220nm, representing ~15% of the total light output. Unfortunately, 85% of the light, peaking at 300 nm, has a decay time of 650 ns. This crystal was studied in some detail as a candidate technology for the GEM detector at the SSC, but has received little attention in the past two decades. Realizing the promise of a high resolution sub-nanosecond electromagnetic calorimeter requires further development in two areas. The first is the properties of the crystal itself. There is evidence that doping BaF_2 with lanthanum rather than cerium can reduce the slow component while having little effect on the fast component. This parameter space should be further explored. If a more optimum doping is found, other important properties, such as radiation harness, then need to be measured. The second area is the photodetector. There are solar-blind photocathodes for PMTs that can further enhance the fast signal response over the slow, but suitable devices that have the appropriate spectral response, rise time and magnetic field insensitivity do not yet exist. There are, however, several promising avenues that can be explored. One is to extend the current work at Chicago, Argonne, LBNL and Fermilab on fast, large area planar microchannel plate PMTs to use solar-blind photocathodes such as K-CS-Te. The other is to develop SiPM or APD devices with UV spectral sensitivity. There are small devices with enhanced UV sensitivity; these would have to be extrapolated to larger sizes. This two-prong approach should form the basis of an interesting collaborative R&D initiative.

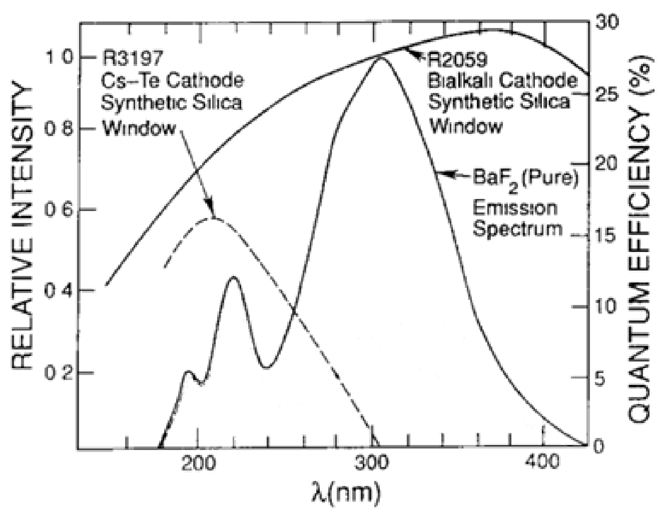

Figure 4. Scintillation light spectrum of BaF_2, showing the fast 220 nm and slow 300 nm components, along with the spectral response of two types of photocathodes.

Work needed on muon experiments

The more than one order-of-magnitude increase in muon stopping rates at Project X will require new approaches to photon detection. There are two main thrusts:

- Explore the reach of $\mu^+ \to e^+ \gamma$ experiments with the technique of detection of the e^+e^- pair from photon conversion.
- Extend high quality scintillating crystal calorimetry to the sub nanosecond realm by developing new dopings for crystals such as BaF_2, and new fast solar-blind readout devices.

Kaon physics

Experiments examined included a $K^+ \to \pi^+ \nu \bar{\nu}$ decay measurement and a search for the decay $K_L^0 \to \pi^0 \nu \bar{\nu}$, along with a review of the KTeV experience.

$K^+ \to \pi^+ \nu\nu$

ORKA (see Fig. 5) is a proposed FNAL experiment to measure the branching ratio of $K^+ \to \pi^+ \nu\nu$, predicted by the standard model to be ~7×10^{-11}. The observed final state in $K^+ \to \pi^+ \nu\nu$ decay is a single charged pion; the main sources of background are the two-body kaon decays $B(K^+ \to \pi^+ \pi^0)$=21% and $B(K^+ \to \mu^+ \nu)$=63%. The rejection of $K^+ \to \pi^+ \pi^0$ is relevant for the requirements on calorimetry. Assuming a signal-to-background of at least 10, the $K_{\pi 2}$ decay background must be suppressed by a factor of ~3×10^{10} or more. $K_{\pi 2}$ rejection is achieved by accurate reconstruction of the kinematics of the charged pion and detection of the photons from π^0 decay. To reduce background from $K_{\mu 2}$ and other muon background, the final state decay chain $\pi^+ \to \mu^+ \to e^+$ is reconstructed in the drift chamber and range stack. The range stack introduces almost one full radiation length of material between the decay point and the calorimeter.

The measurement of $B(K^+ \to \pi^+ \nu\nu)$ in a stopped-kaon experiment requires detection of photons in the energy range (20-225) MeV from π^0 decay. E949 successfully observed $K^+ \to \pi^+ \nu\nu$ with a rejection of ~10^6.

High photon veto efficiency requires conversion and detection of photons. Photon detection can be maximized by a fully active, hermetic calorimeter with sufficient thickness in radiation lengths (X_0). Studies for the KOPIO experiment indicate that 23 X_0 would be sufficient for a stopped-kaon experiment. Inoperative calorimeter elements imply a loss of hermiticity, so redundancy or a high degree of single-channel reliability is required. The stopped-kaon experiment requires a solenoidal magnetic field and the calorimeter must be accommodated by the solenoid. This constraint may imply a compromise between the fully active and thickness requirements. Inactive components of the calorimeter, such as lead layers, effectively lower the minimum photon energy threshold from 20 MeV.

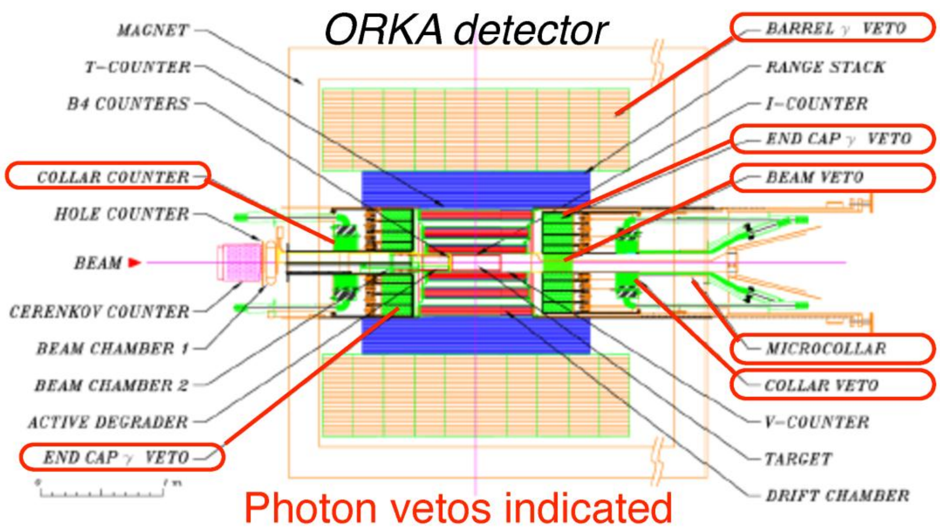

Figure 5. Elevation view of the proposed ORKA detector indicating the locations of photon veto detectors. The beam enters from the left.

High photon veto efficiency must be achieved while minimizing acceptance losses due to vetoing on random or ‘accidental’ detector activity. These acceptance losses can be minimized by minimizing the time interval required for the coincidence of K^+ decay and the putative photon.

A scintillator-based calorimeter would need to have a short decay time, high light yield, and high collection efficiency to satisfy the veto requirement. The ability to reconstruct photons and electrons for other (non-$K^+\rightarrow\pi^+\nu\nu$) measurements in the experiment would place additional requirements on the calorimeter energy, position, and shower timing resolutions. Improvements to the reconstruction ability of the calorimeter may also reduce systematic uncertainties for $K^+\rightarrow\pi^+\nu\nu$; for example, π^0 reconstruction would allow for studies of π^+ detection efficiency using $K^+\rightarrow\pi^+\pi^0$ decays. Studies to quantify the size of these potential improvements would be helpful in choosing among design options.

As proposed, ORKA has two primary calorimetric elements: the endcap and the barrel veto. For the endcap, ORKA could re-use the ∼200 25 cm long CsI crystals from BNL E949 that provide 13.5 X_0 total depth. The expected energy and timing resolutions are $\Delta E/E \sim 11\%$ and $\Delta t \sim 0.7$ ns, respectively. Use of shashlyk detectors, with greater depth, is also a possibility that should be explored.

Several designs are under consideration for the barrel veto. A shashlyk style calorimeter similar to the one designed for KOPIO (see Sect. 0.1.2 below) would satisfy the photon veto requirement. A possible configuration is 155 interleaved layers of 0.8-mm lead and 1.6-mm scintillator read out by ~400 wavelength shifting fibers. This provides 23 X_0 total depth. The expected energy and timing resolutions are (3-4)%/√E and (90-100) ps/√E, respectively. The noise term in the energy resolution is negligible above 50 MeV so was not included in the parameterization for KOPIO, but will likely be relevant for ORKA because the photon energies will be lower. A shashlyk calorimeter has already been prototyped for KOPIO. For ORKA, because it must fit inside the CDF solenoid, the detector must be somewhat more compact without losing veto power. More work on design and prototyping to fulfill this size requirement is needed.

Another option for the calorimeter design is a totally-active ADRIANO calorimeter consisting of 150 interleaved layers of 2mm lead glass and 2 mm fast scintillator. Work to simulate the performance of this style detector in ORKA is ongoing, but the energy resolution is expected to be better than a shashlyk style detector, particularly at low energies. It may also allow reconstruction of angles using timing or light division methods. From the perspective of ORKA, the most important benefit of the totally-active ADRIANO calorimeter would be the potential reduction in photon inefficiency relative to a shashlyk style calorimeter.

NA62 at CERN is a decay-in-flight experiment, currently under construction, to measure $B(K^+\to\pi^+\nu\nu)$. The technique will be complementary to that of ORKA because decay-in-flight and stopped-kaon experiments are sensitive to different parts of phase space.

$K_L^0 \to \pi^0\nu\bar{\nu}$

KOPIO (see Fig. 2) was a proposed BNL experiment to measure the branching ratio of $K_L^0 \to \pi^0\nu\bar{\nu}$. It is expected that a similar experiment will be proposed at FNAL in the Project X era. The standard model value of the $K_L^0 \to \pi^0\nu\bar{\nu}$ branching ratio is ~3x10^{-11}.

$K_L^0 \to \pi^0\pi^0$ is the main background . The two-photon final state of the signal requires accurate reconstruction of single photon energy, position, direction and time. The photon veto requirements are more stringent than $K^+\to\pi^+\nu\nu$ (Section 0.1.1) because background photon energies can extend below 20 MeV due to decay-in-flight of the K_L^0. Also in contrast to a stopped-kaon experiment, the beam represents an extended signal and background source that alters the hermeticity requirements. The minimum performance requirements are:

- Direction resolution: 25 mrad @ 250 MeV
- Energy resolution: 3%/ √E
- Timing resolution: ~100 ps /√E
- Position resolution: 250 μm
- Veto efficiency: $10^{-4}/\gamma$

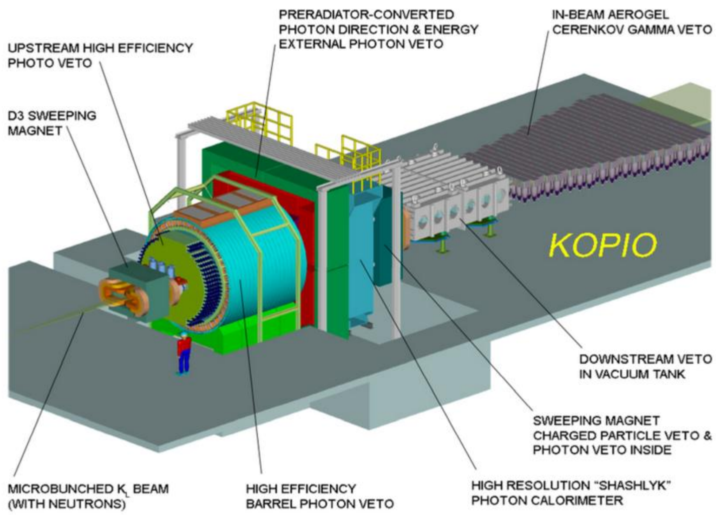

Figure 6. Schematic of the proposed KOPIO detector. The pre-radiator is shown in green and the shashlyk calorimeter is shown in blue.

The measurement of photon energies and directions in KOPIO is made by the combination of a pre-radiator and a shashlyk style calorimeter. The pre-radiator consists of scintillator sheets alternating with cathode strip drift chambers. It contains 2.7 X_0 of material in total; it is important to keep the thickness in the beam direction of the pre-radiator as small as possible in order to limit transverse shower size so that photons from background decay modes may be resolved. The result of this configuration is that most photon interactions are $e+e^-$ pair production in which the angular separation of the $e+e^-$ pair is small enough that the individual particles need not be resolved by the calorimeter. The initial direction of $e+e^-$ pair is the same as that of the photon, so the track reconstructed in the pre-radiator drift chambers is a measurement of the photon angle. Following the pre-radiator is a 19 X_0 shashlyk style calorimeter (lead-scintillator sandwiches read out by wavelength shifting fibers passing through holes in the scintillator and lead), with transverse granularity of ~10 cm. By design, the KOPIO pre-radiator/calorimeter combination satisfies the performance specifications above.

A study comparing the improvement in signal yield relative to background for various improvements in calorimeter performance finds that improvements to angular and energy resolution are most beneficial. Reduction of photon veto inefficiency also provides significant improvement in S/B. Timing resolution is less critical, and position resolution least significant.

Studies from KOPIO show that energy resolution improves as the thickness of the lead plates is reduced, the thickness of the scintillator plates is increased, and as the number of layers increases. These design parameters correspond to increased sampling efficiency and increased photostatistics, which are two of the three primary drivers of the energy resolution. The third is light collection uniformity, which can be improved by increasing the light collection efficiency near the edges of a scintillator tile.

Angular resolution might be improved if the pre-radiator could resolve the opening angle between the e^+e^- pair; this would require use of a high-speed, high-resolution tracker or TPC that does not add large amounts of material to the detector. The ability to reconstruct angles using the calorimeter would also be helpful. These ideas are speculative and have not yet been studied.

KOPIO achieved a modest increase in signal acceptance by using the barrel photon veto (see Fig. 6). Improvements in angle, position, and energy resolution of calorimetry would boost this acceptance.

KOTO is an experiment at J-PARC to search for $K_L^0 \to \pi^0 \pi^0$ decay, building on its predecessor, E391 at KEK. It is currently under construction and expects to begin taking data in 2013. Calorimeter and photon veto performance are critical to this experiment; one of the major upgrades between E391 and KOTO is the use of the KTeV CsI crystals for the KOTO calorimeter. Experience from this experiment will be very useful in the design of a KOPIO-style experiment at Project X.

Work needed on kaon experiments

The calorimeters needed for kaon experiments in the Project X era are reasonably well understood; the shashlyk style calorimeter designed for KOPIO has been prototyped and likely can be modified to meet the design requirements for both ORKA and a KOPIO-style experiment. However, it may be possible to significantly improve the sensitivity of these experiments and/or broaden their physics reach by making improvements to the calorimetry. Much work remains to optimize the calorimeter design and study which improvements to the calorimeter are most likely to pay off in improvements to the measurements. Finally, R&D in 3D calorimetry and low energy photon veto detection would be of general use to the HEP community. Specific studies that are needed include:

- Compact shashlyk design for ORKA: the ORKA calorimeter must fit inside the CDF solenoid. The shashlyk calorimeter designed for KOPIO must be made more compact without sacrificing veto efficiency.
- Benefits to ORKA from improved calorimetry: the size of potential improvements to the measurement of $K^+ \to \pi^+ \nu\nu$ resulting from improvements to calorimeter resolution should be quantified.
- Benefits of ADRIANO calorimeter: the size of potential improvements to the measurement of $K^+ \to \pi^+ \nu\nu$ resulting from improved photon veto efficiency in a totally-active calorimeter should be quantified.

- KOPIO calorimeter optimization: improvements to the energy and angular resolution of the KOPIO calorimeter result in significant improvements to the measurement of $K_L^0 \rightarrow \pi^0 \nu\nu$. The detector should be optimized to improve the energy resolution as much as possible. Some thought should be given to potential ways to improve the angular resolution.
- 3D calorimetry: The ability to "track" photons while maintaining high photon veto efficiency is highly desirable. Development of 3D calorimetry techniques such as time difference methods and light division methods as well as R&D for calorimeters with z segmentation, with a focus on preservation of veto efficiency, would be useful for $K \rightarrow \pi\nu\nu$ experiments.
- Low energy photon veto detectors: This document has primarily focused on scintillation detectors. Generic R&D for low energy photon veto detection is important. New design ideas that improve photon veto efficiency could significantly improve the sensitivity of $K \rightarrow \pi\nu\nu$ experiments.