First operation of undoped CsI directly coupled with SiPMs at 77 Kelvin

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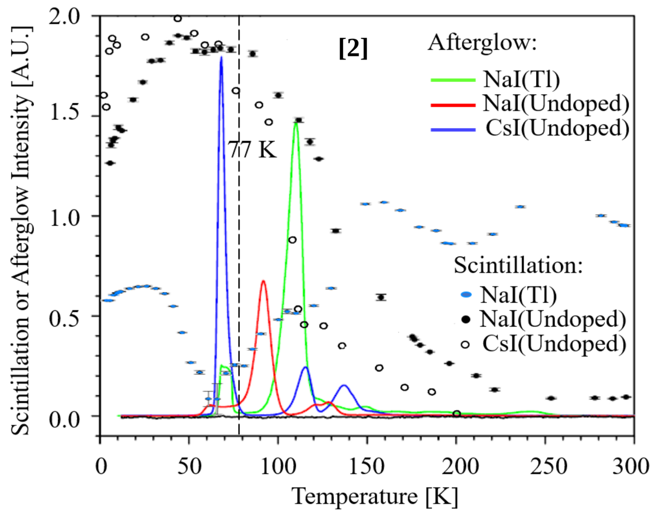
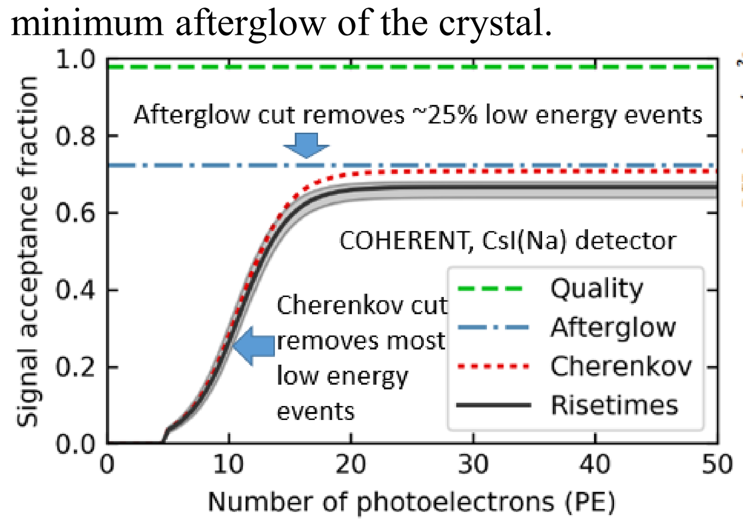
Motivation

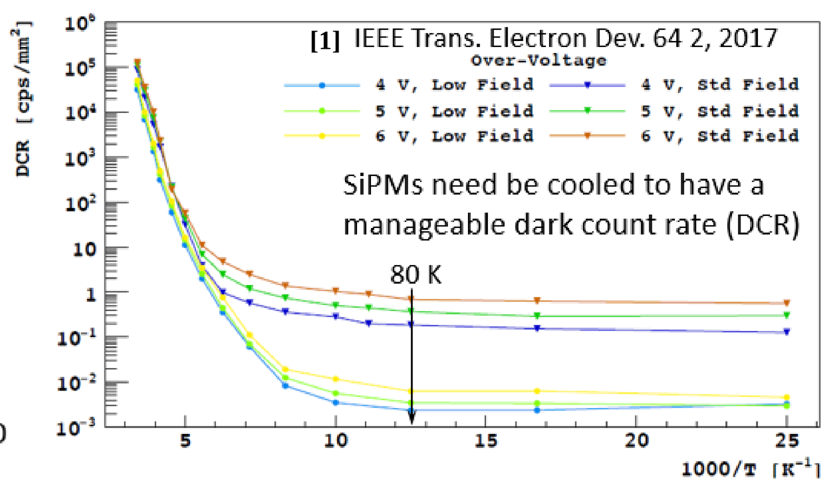
Inorganic scintillating detectors are widely used in the detection of **dark matter** and **neutrinos** due to their relatively high light yields and easy light readout with PMTs at room temperature. Possible improvements of two large limiting factors in decreasing the energy threshold of such a detector are provided:

Replacing PMTs by **SiPMs** to remove Cherenkov radiation caused by charged particles passing through the quartz window of a PMT.

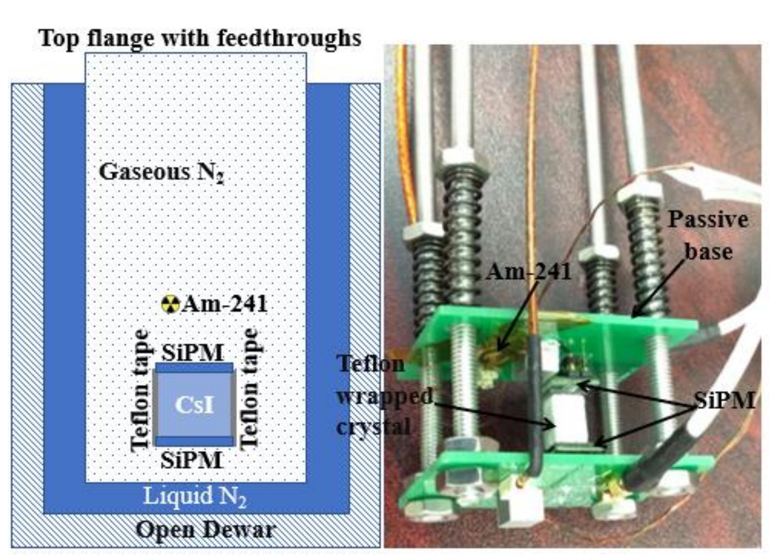
Replacing CsI(Na) at room temperature with **undoped crystals at cryogenic temperatures** to reach the minimum afterglow of the crystal.

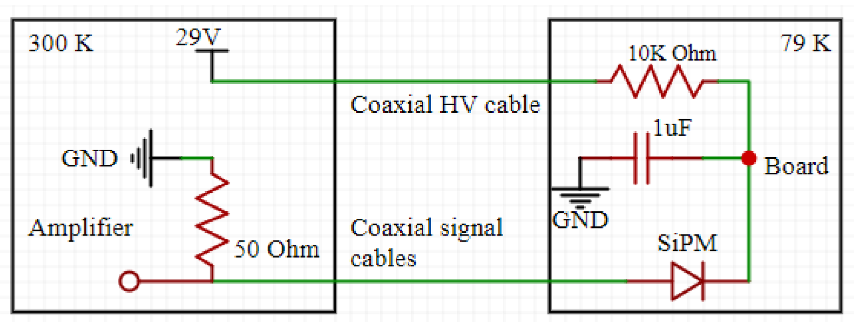






Experimental setup



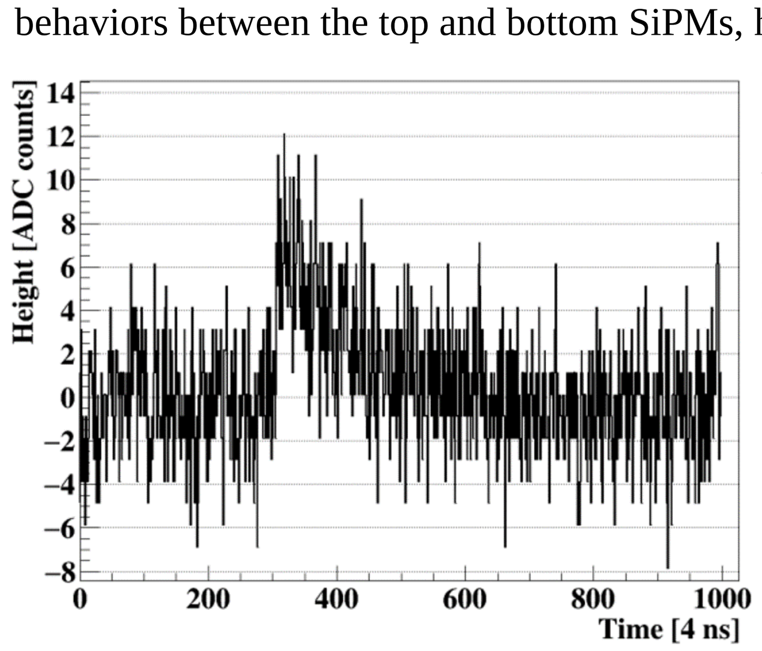


- A cryogenic vacuum chamber has been used to operate an undoped CsI scintillating detector at **liquid nitrogen temperature**.
- An ^{241}Am source was attached on the top passive base for energy calibration.

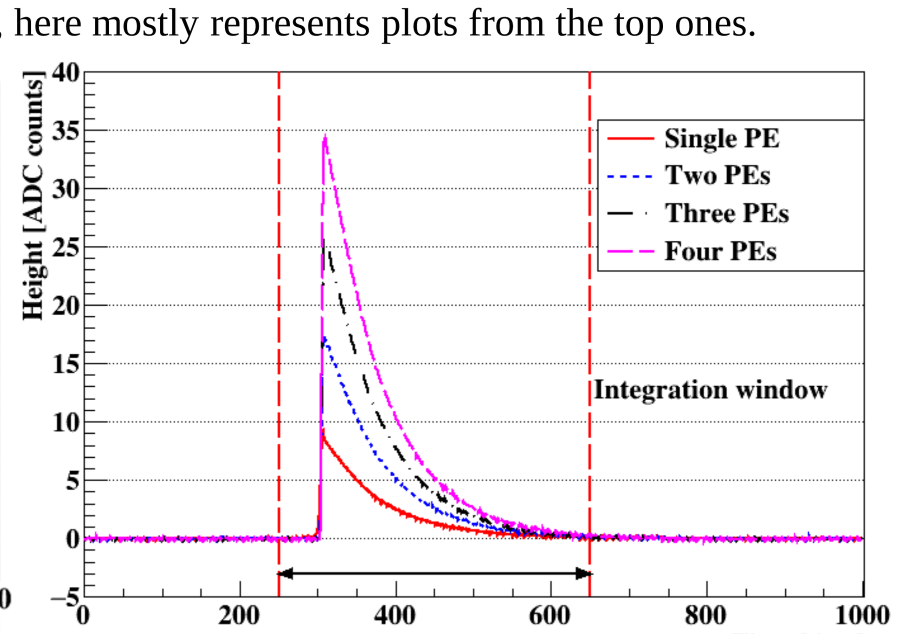
- AMCRYS 6 × 6 × 10 mm3 **undoped CsI** crystal.
- Two 6 × 6 mm2 SensL MicroFJ-SMTPA-60035 **SiPMs** (pixel size: 35 × 35 μm2, total number of pixels: 18980).
- 20 times amplification by a Phillips Scientific Quad Bipolar Amplifier Model 771.
- Bias voltages at 79 K: 29V, breakdown voltages at room temperature: 24.2 - 24.7 V.
- The capacitor was used to sustain large current during the avalanche of a SiPM. It also forms a noise filter together with the 10 K ohm quenching resistor.

Single photoelectron (PE) response

Single PE responses of individual channels were measured right after the energy calibration measurement using waveform data triggered by dark counts from the SiPMs. Due to the similar behaviors between the top and bottom SiPMs, here mostly represents plots from the top ones.



A random single PE waveform from the top SiPM.



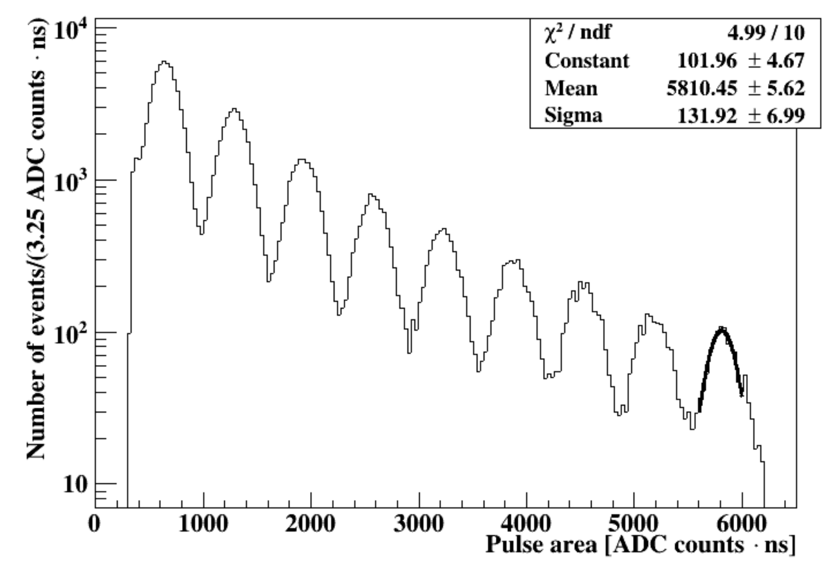
Average waveforms of different PEs from the top SiPM.

Single photoelectrons response (continued)

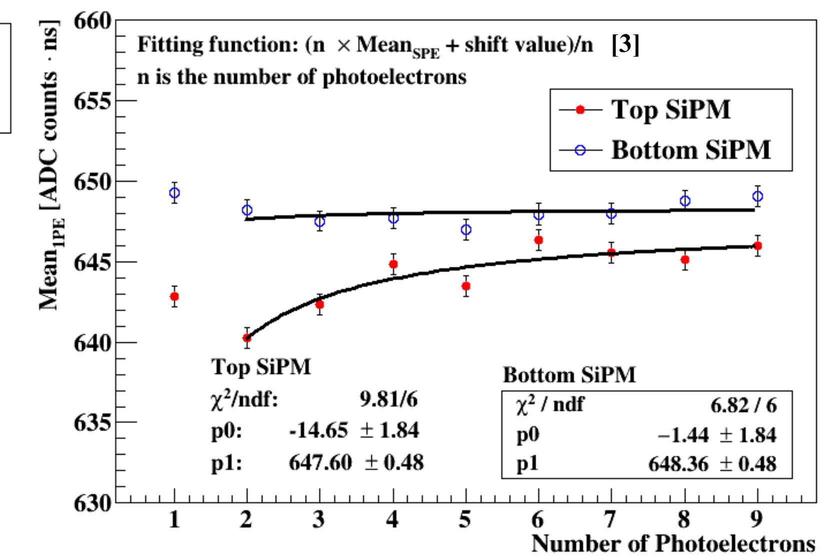
Electron noise was observed in the random single PE waveform. A common way to remove the effect of electronic noise is to calculate the average waveform corresponding to the same PEs, where no obvious noise is seen.

The mean of single PE, $mean_{1PE}$, is defined as the **Gaussian mean** in the single PE response divided by the number of PEs, n.

More single PE measurements were done triggered by dark counts and LED for comparison with this set of data. The largest discrepancy was regarded as the uncertainty of $mean_{SPE}$.



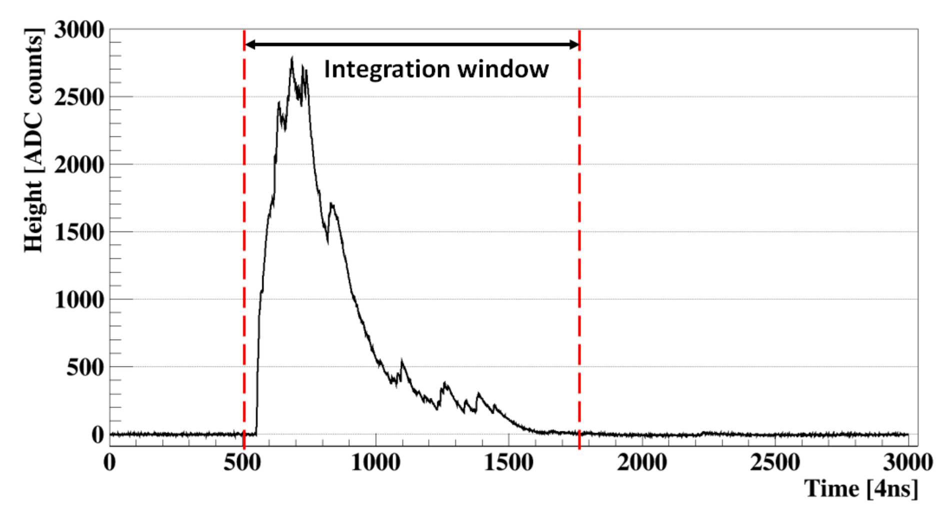
Single PE response of the top SiPM in logarithm scale.



$Mean_{1PE}$ distributions obtained from top and bottom SiPMs.

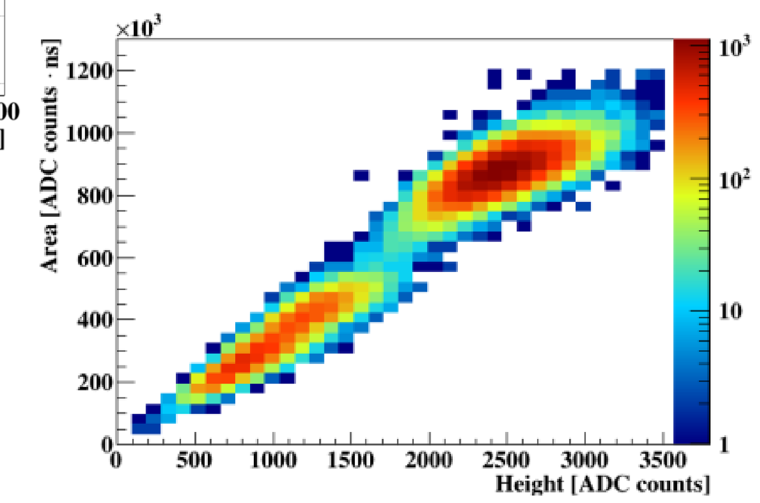
Energy calibration

Energy calibration was performed using an ^{241}Am.

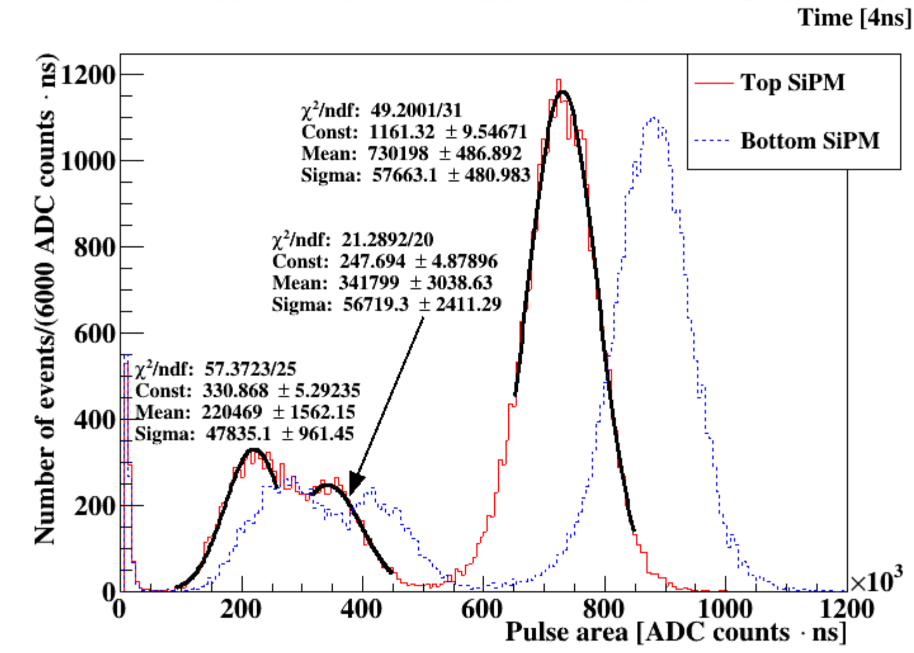


A randomly selected light pulse within the 59.5~keV peak from the top SiPM. The ones from the bottom SiPM are very similar.

Coincident trigger threshold: 80 ADC counts.



Pulse area versus pulse height for events collected with the ^{241}Am source from the bottom SiPM (observed higher PEs). A good linearity of the SiPM up to 59.5 keV was kept and the pulse height was controlled within the digitizer's dynamic range.



Energy spectrum of ^{241}Am as the distribution of pulse areas in units of ADC counts · ns.

Fitting results of ^{241}Am peaks in energy spectra for the top (top table) and the bottom (bottom table) SiPMs are shown in the table.

The slightly worse FWHM makes our detector difficult to resolve *X*-ray peak close to each other. However, it might not be a concern for low energy dark matter detection as the nuclear recoil spectrum has a shape close to an exponential decay near the threshold. The broadening of such a distribution does not necessarily reduce the number of observed events.

Type of radiation	Energy $[keV_{ee}]$	$Mean_{top}$ [ADC · ns]	Sigma [ADC · ns]	FWHM [%]
$X-ray$	17.5	220469	47835.1	51.1
$\gamma-ray$	26.3	341799	56719.3	39.1
$\gamma-ray$	59.5	730198	57663.1	18.6

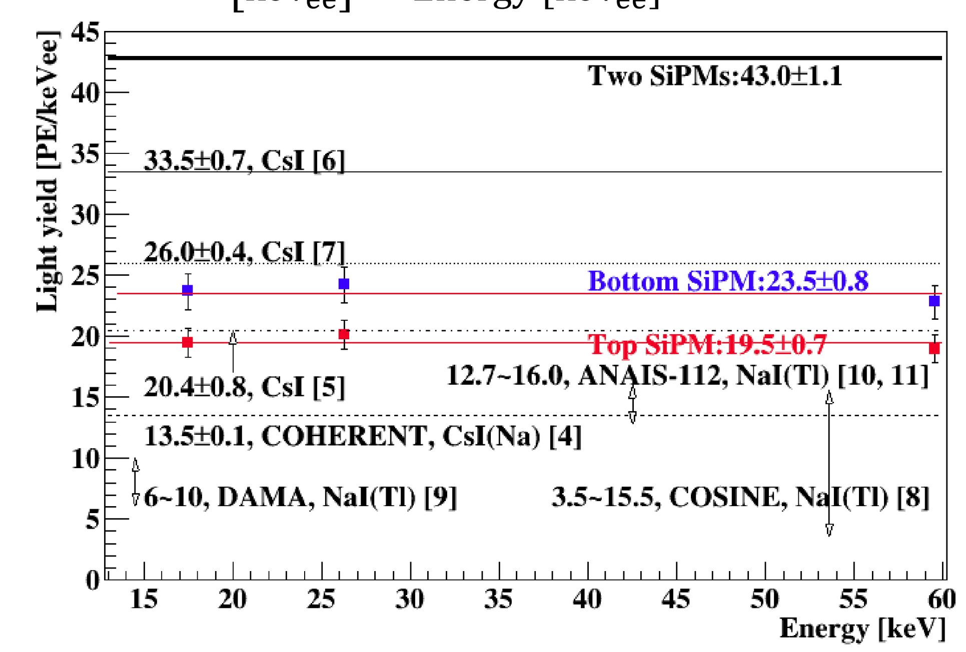
Type of radiation	Energy $[keV_{ee}]$	$Mean_{bottom}$ [ADC · ns]	Sigma [ADC · ns]	FWHM [%]
$X-ray$	17.5	268360	56462.2	49.5
$\gamma-ray$	26.3	413138	64188.3	36.6
$\gamma-ray$	59.5	879406	61193.7	16.4

Light yield

The fitted means of the 17.5 keV, 26.3 keV and 59.5 keV peaks in the ^{241}Am spectrum in the unit of ADC counts·ns were converted to the number of PE using the formula:

$(\text{number of PE}) = (\text{Mean} - \text{Shift value})\frac{[\text{ADC counts}\cdot\text{ns}]}{\text{mean}_{SPE}}$, the light yields were then calculated by:

$\text{Light yield}\left[\frac{\text{PE}}{\text{keV}_{ee}}\right] = \frac{(\text{number of PE})}{\text{Energy }[\text{keV}_{ee}]}$.



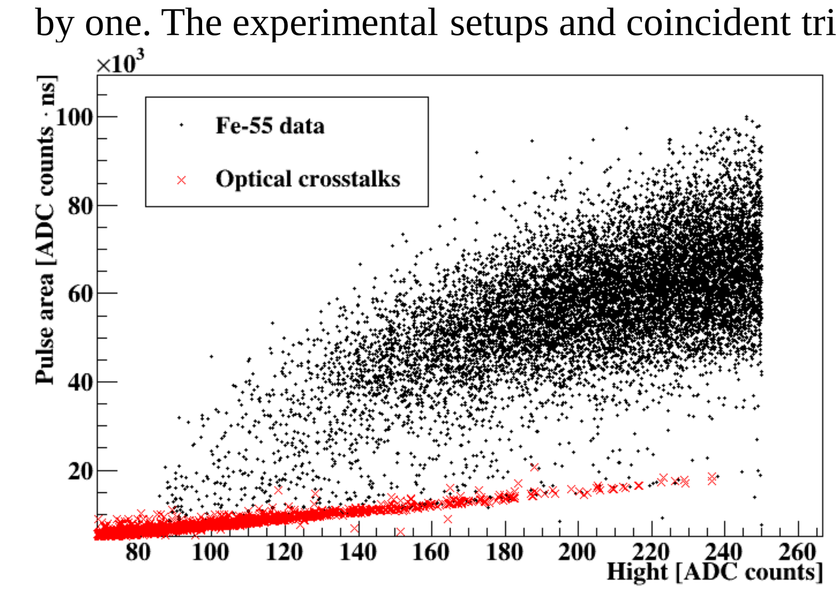
Light yields measured for scintillators made of iodide compounds from various experiments.

All were measured with PMTs except for the one in this work.

The total light yield is **43.0 ± 1.1 PE/keV$_{ee}$**. Assuming coincident trigger of two photons in two different SiPMs and a constant nuclear quenching factor of 5%, the energy threshold of such a detector can be as low as **0.9 keV** for **nuclear recoils**.

Optical cross-talks between SiPMs

A small increase of event rate close to the threshold (~15000 ADC counts · ns) were observed from both SiPMs. However, no *X*-ray peaks around that region from the ^{241}Am source. Certain instrumental noise might be the cause of this small bump, for example, **optical cross-talks**. To verify this possibility, data were taken in coincident trigger mode with different modifications applied one by one. The experimental setups and coincident trigger rates are summarized in the table:



Experimental setups	Trigger rates [Hz]
CsI + ^{241}Am	750 ± 50
Transparent plastic cube + ^{241}Am	70 ± 20
Transparent plastic cube	50 ± 10
Opaque solid plastic bar	2 ± 2

These confirm that the events close to the threshold are indeed due to external optical cross-talks between the two SiPMs.

Area versus height of pulses in ^{55}Fe (black dots) and optical cross-talks (red crosses) from the top SiPM. Since pulses due to optical cross-talks are sharp and narrow, the **area-to-height ratio** is much smaller than that of physical events. Such a ratio can be a good parameter to remove events due to optical cross-talks.

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