Scintillation Detector Calibration and Optimization for Neutral Atom Trap

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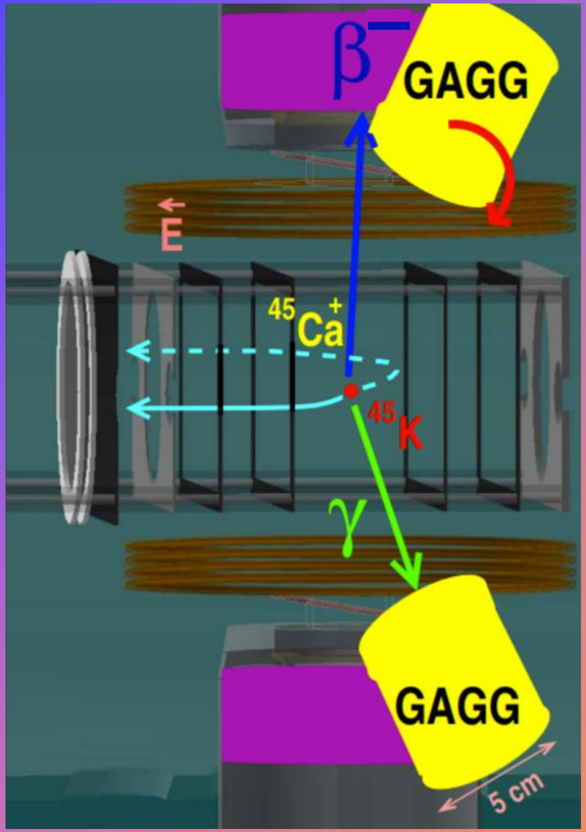


Magneto-optical atom trap with the scintillation detectors.

- **TRI**UMF's **N**eutral **A**tom **T**rap for Beta Decay (TRINAT)
- Physics beyond the Standard Model

- ***Motivation:*** Investigate **time-reversal symmetry breaking** in radiative β decay [1].
- ***Goal:*** Achieve **high precision measurements** of the decay products.
- Calibrate and optimize the **scintillation detectors** used to detect γ and β decays.

[1]: Gardner, Susan, and Daheng He. "Radiative β decay for studies of C P violation." Physical Review D 87.11 (2013): 116012

Time reversal (symmetry) violation (TRV)

- 3 uncorrelated momenta (observables)
- A **scalar triple product** of momenta flips sign with the sign of time

$$p_1 \cdot p_2 \times p_3$$

- A violation of time reversal symmetry would produce **a non-zero value**, but it is prevented by **momentum conservation** for normal beta decay

$$^{37}\text{K} \rightarrow {}^{37}\text{Ar} + \beta^+ + \nu$$

$$\boldsymbol{p_\nu} = -\boldsymbol{p_\beta} - \boldsymbol{p_{recoil}} \Rightarrow \boldsymbol{p_{recoil}} \cdot \boldsymbol{p_\beta} \times \boldsymbol{p_\nu} = \boldsymbol{0}$$

- In **radiative beta decay** of trapped atoms, we look for **a three-momenta state from a four-momentum final state**

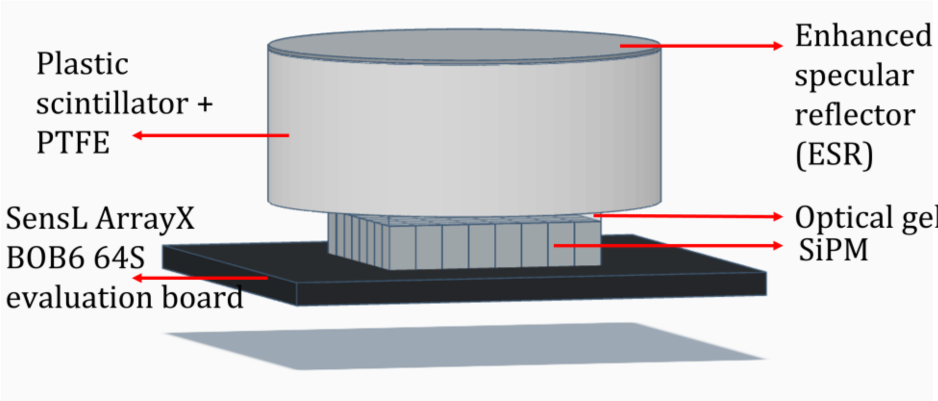
$$^{37}\text{K} \rightarrow {}^{37}\text{Ar} + \beta^+ + \nu + \gamma$$

$$\boldsymbol{p_\beta} \cdot \boldsymbol{p_\nu} \times \boldsymbol{p_\gamma}$$

Detector Assemblies

Organic scintillation detector

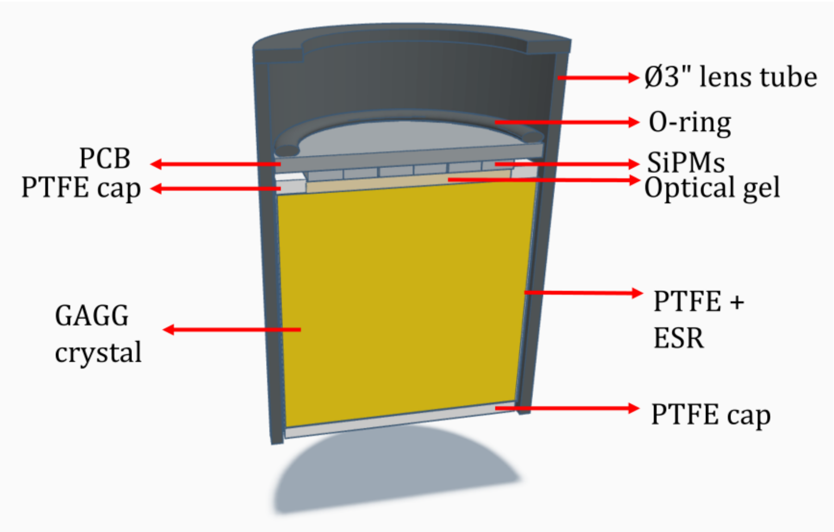
- Plastic scintillator with 90 mm Ø and 35 mm thickness
- **Silicon Photomultiplier** (SiPM) readout



The initial plastic scintillation detector assembly

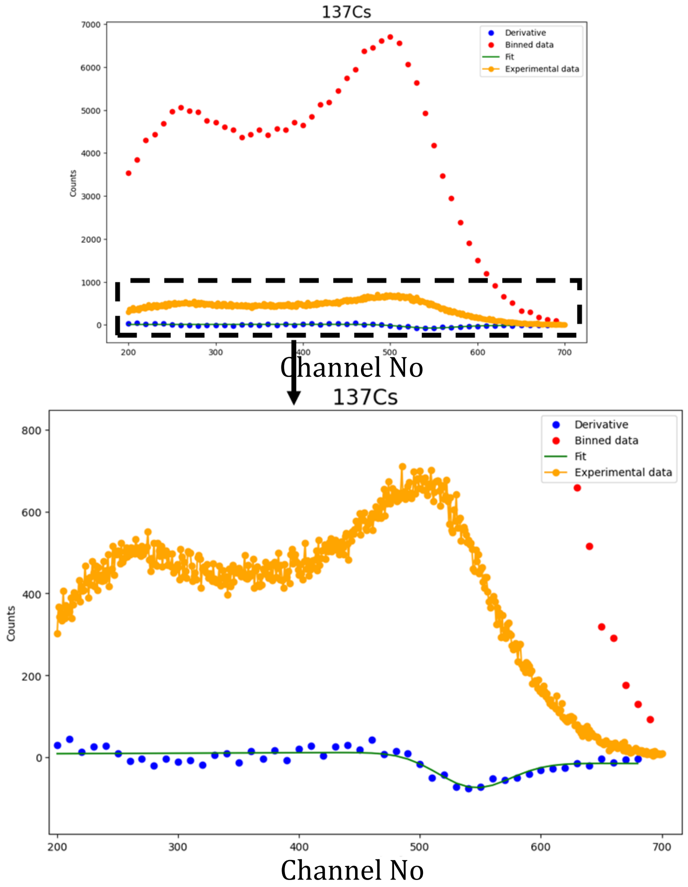
Inorganic scintillation detector

- **G**adolinium **A**luminum **G**allium **G**arnet ($Gd_3Al_2Ga_3O_{12}$)
- Two identical GAGG detectors: GAGG1 and GAGG2



Inorganic scintillation detector assembly

Detector Calibrations



The differentiation method used to estimate the location of the Compton edge of 137Cs for the organic scintillation detector.

Organic scintillator:

- Estimating **the location of the Compton edge** of various $\boldsymbol{\gamma}$ sources through **a differentiation method** [2]:

$$R'(E) = X_1(E) + X_2(E)$$

$$X_1(E) = \alpha \cdot erfc\left(\frac{E - E_c}{\sqrt{2}\sigma}\right)$$

$$X_2(E) = \beta \cdot exp\left(-\frac{(E - E_c)^2}{2\sigma^2}\right)$$

$$\alpha \equiv \frac{1}{2}(2aE + b)$$

$$\beta \equiv -\frac{1}{\sqrt{2\pi}\sigma}\left[a\left({E_c}^2 + 2\sigma^2\right) + bE_c + c\right]$$

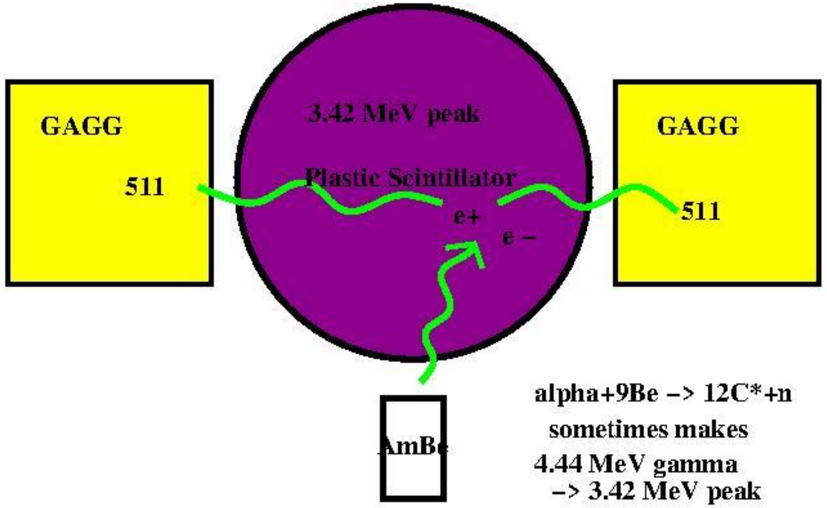
$R'(E)$: differentiated detector response function

E_c: Compton energy

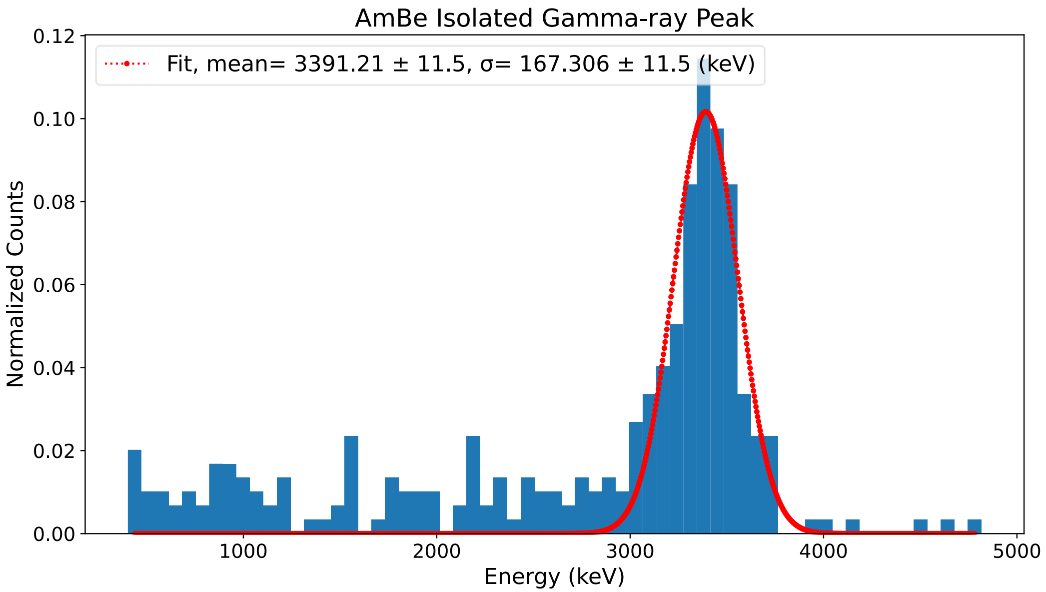
[2]: Safari, M. J., F. Abbasi Davani, and H. Afarideh. "Differentiation method for localization of Compton edge in organic scintillation detectors." arXiv preprint arXiv:1610.09185 (2016).

Higher energy calibrations for plastic detector

- $^{241}\text{Am}^{9}\text{Be}\,(\alpha n) \rightarrow {}^{12}\text{C} + n + \boldsymbol{\gamma}$ (4.44 MeV)
- Looked for **triple $\boldsymbol{\gamma}$ timing coincidences** between the plastic and the two GAGG detectors to isolate the **double escape peak**
    - $\mathbf{4.44 - 1.022 = 3.42\ MeV}$
- Currently studying the origin of the left-hand side tail.

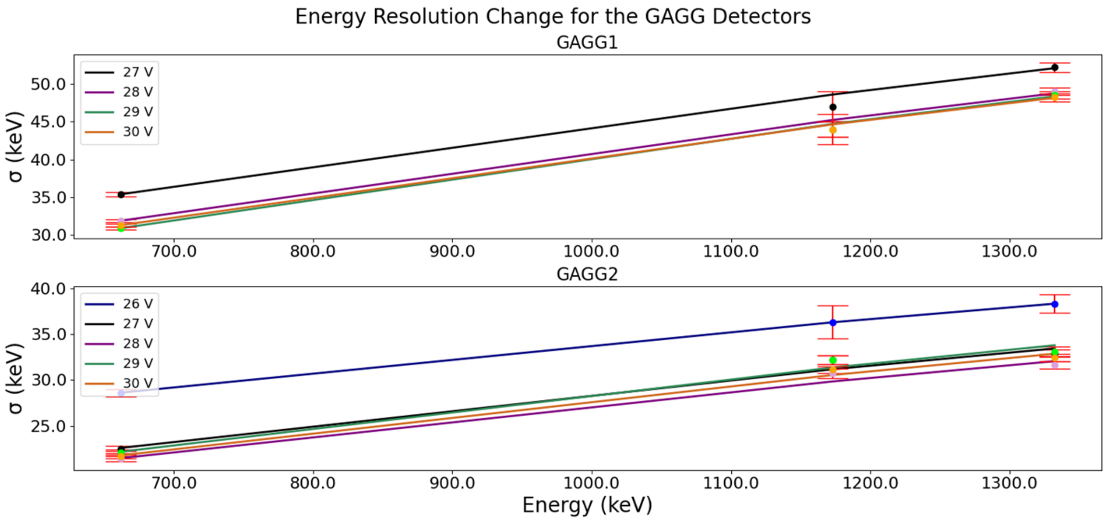


Schematic for the AmBe experiment showing the GAGG detectors located at the sides of the plastic detector.



The double escape peak at 3.42 MeV from the AmBe source, isolated after energy and timing cuts.

Detector Optimizations



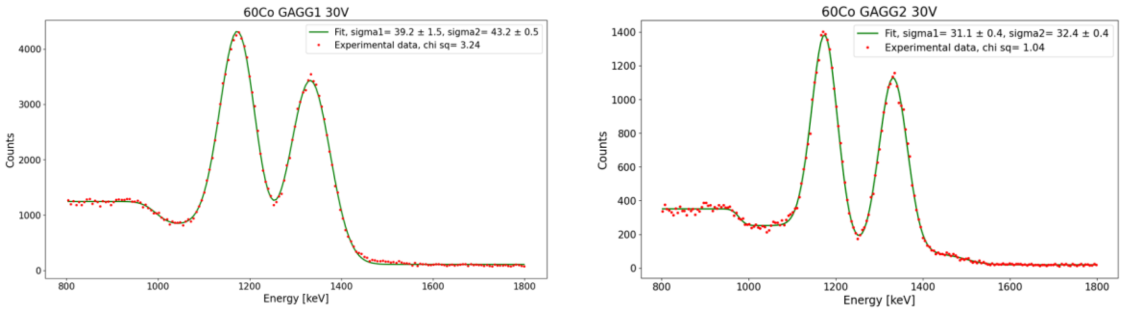
Energy resolution change for the GAGG detectors with the increasing bias voltage.

- **SiPM bias voltage** optimization:
  - **28V - 30V** optimal
- **Reflector material** change to optimize light sealing
  - Nitrocellulose with higher reflection coefficient than PTFE [3]
  - 3-layer PTFE: **(8.4 ± 0.4)%**
  - Nitrocellulose: **(9.3 ± 0.5)%**
- **SiPM replacement** due to high bias current values from GAGG1
  - Energy resolution change: **(8.4 ± 0.4) % → (9.1 ± 0.5) %**
  - **SiPM bias current** might **not be related** to the energy resolution or **dark current**

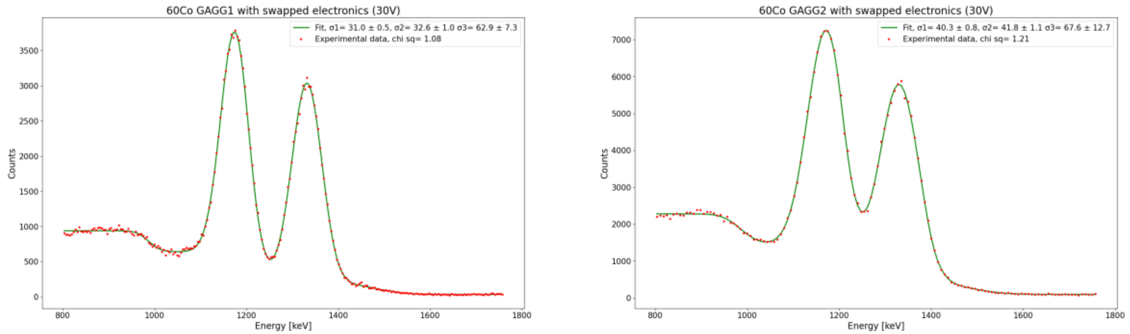
[3]: Janecek, M. "Reflectivity Spectra for Commonly Used Reflectors." IEEE Transactions on Nuclear Science, vol. 59, no. 3, 2012, pp. 490–97.

Detector Optimizations Cont’d

Before the crystal swap



After the crystal swap

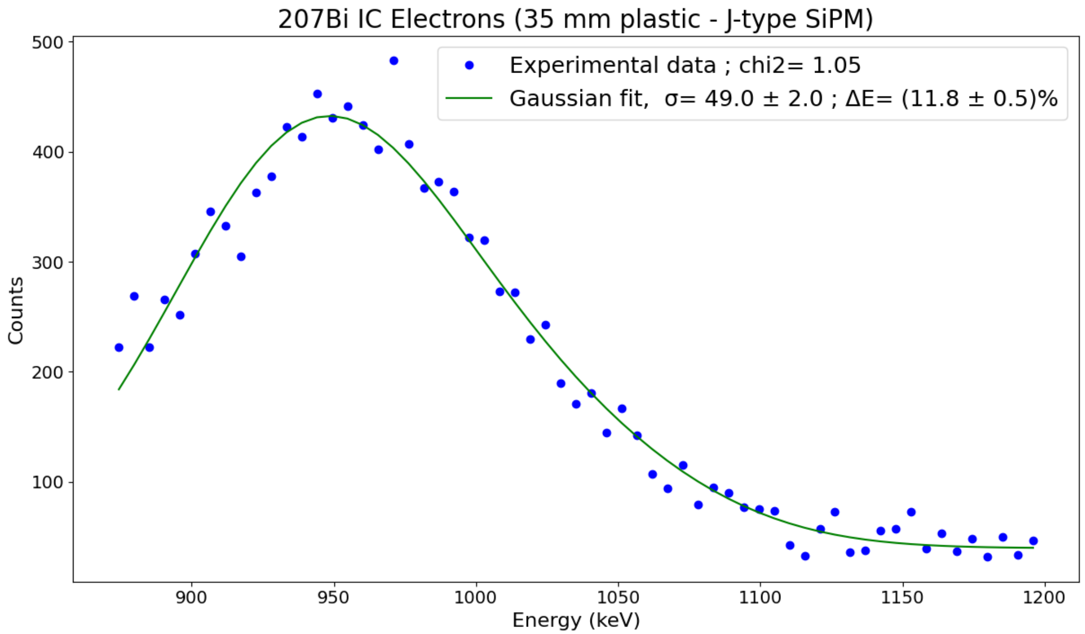


^{60}Co γ spectra for the GAGG detectors biased at 30V, before and after the crystal swap.

- A **difference in energy resolutions** between the **two GAGG** detectors
- **Swapped the GAGG crystals** of the detectors → Swapped the average energy resolutions at 662 and 1333 keV :
  - GAGG1: **(6.9 ± 0.5) %**
  - GAGG2: **(8.5 ± 0.5) %**
- The **intrinsic crystal properties** highly affect the energy resolution of the scintillation detectors.

Energy resolution of the plastic detector

- **Energy resolution determination** for a plastic detector
  - Isolating the **internal conversion (IC) electron peak**
  - K-L-M shells of ^{207}Bi at around **1 MeV**
  - Initial test: **(11.8 ± 0.5) %**

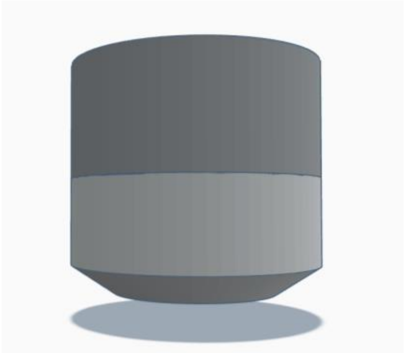


Gaussian distribution fitted to the energy peak of the IC electrons from the K, L, and M shells of ^{207}Bi.

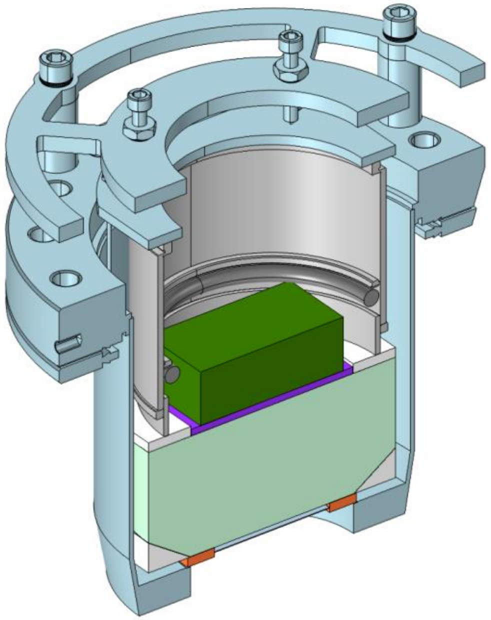
Plastic detector improvements

- New scintillator with 88 mm Ø and 58 mm Ø at the bottom
  - 30 mm thickness
  - 40-mm-thick light guide
- Energy resolution changes (at 1 MeV):
  - **With** the light guide + C-type SiPM: **(21.0 ± 0.7) %**
  - **Without** the light guide + C-type: **(11.2 ± 0.3) %**
  - With the new **housing design** + 0.5 gain:
    - J-type SiPM: **(9.3 ± 0.3) %**
    - C-type SiPM: **(10.2 ± 0.4) %**

- **Light guide** → higher light loss, worse resolution
- **Better detector design** achieved with the housing design
- **J-type SiPM** with **more light collection** than C-type



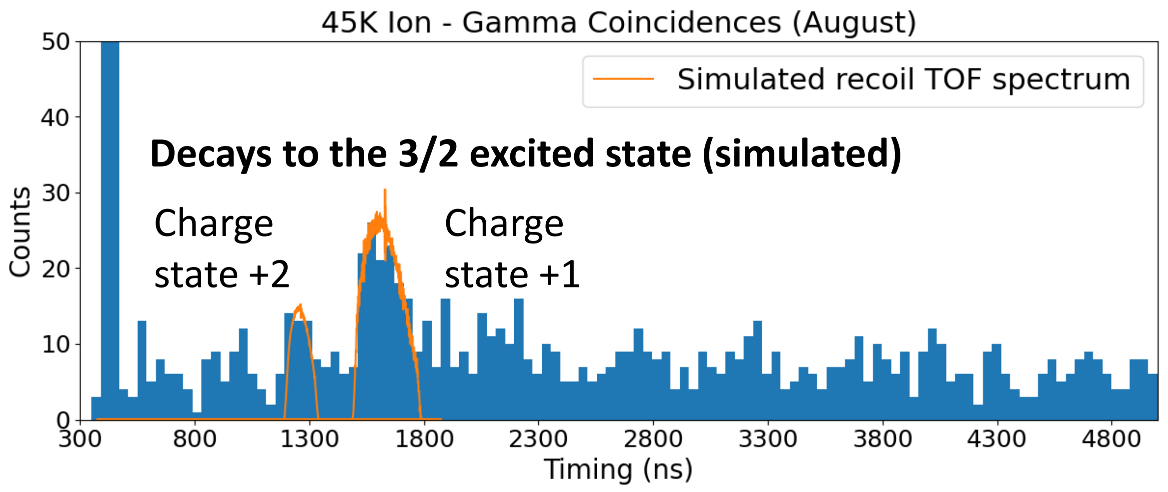
Plastic scintillator attached to a light guide.



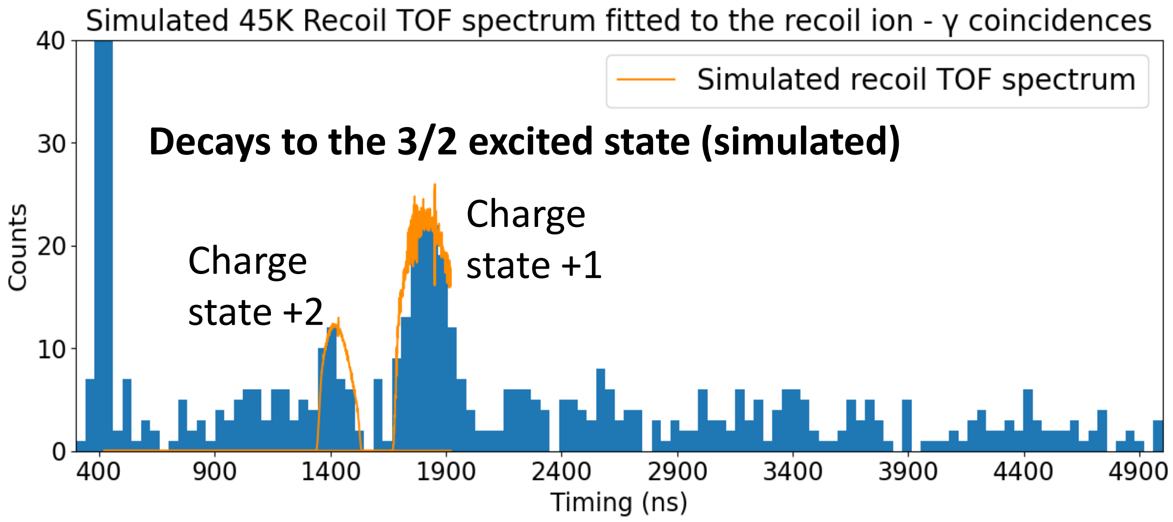
The housing design for the plastic scintillation detector for installation around the atom trap. Courtesy of Alexandre Gorelov.

^{45}K test runs with radioactive beam

- Any **coincident particle pairs** can test the **apparatus symmetry**.
- **August run:**
  - **^{45}K recoil ion – γ** pair was **not clean enough** to test the apparatus symmetry for **TRV**
  - **Background** was too large even after an energy cut around the main ^{45}K γ photopeak at 1706 keV
- **December run:**
  - **Better trap light polarization** achieved
  - Much **lower electron backgrounds** from the microchannel plates
  - **Better signal-to-noise ratio**



^{45}K recoil- γ spectrum from the August run.



^{45}K recoil- γ spectrum from the December run.

Summary

- **Differentiation method** adopted to **calibrate** the organic scintillation detectors
- **Double escape peak** at **3.42 MeV** from AmBe **isolated** through triple $\boldsymbol{\gamma}$ **timing coincidences**
- **Optimized bias voltage** for SiPMs at **28-30V**
- **PTFE** as the **better reflector** for scintillator wrapping than **nitrocellulose**
- Average **energy resolutions** of **(6.9 ± 0.5) %** and **(8.5 ± 0.5) %** achieved for **GAGG1** and **GAGG2** at 662 and 1333 keV
- Up to **(9.3 ± 0.3) % energy resolution** achieved at 1 MeV for the **plastic detector** through a **housing design** and **J-type SiPM**
- Obtained **better signal-to-noise ratio** through trap optimizations **for recoil ion-** $\boldsymbol{\gamma}$ **coincidence** spectrum for the ^{45}**K** test runs

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