Elemental Analysis Using Muonic Characteristic X-rays Detected by an XRPIX

2025.12.01 MON

SOIPIX2025 @ Shiinoki Cultural Complex, Ishikawa Prefecture

Ayaki Takeda (Univ. of Miyazaki)

takeda @astro.miyazaki-u.ac.jp

Hikaru Mitani, Yuto Saito, Koki Sugimoto, Soushi Kudo

Izumi Umegaki (KEK)

Outline

We present the detection results of muonic characteristic X-rays obtained in our previous experiments using the SOIPIX detector “XRPIX”.

✓ **Elemental Analysis Using Muonic Characteristic X-rays**

➡ Using the event-driven detector “XRPIX”, which we have been developing for astronomical X-ray observations

➡ In this experiment, the event-driven mode was not used; instead, the detector was employed for its superior spectroscopic performance.

✓ **Detection of muonic characteristic X-rays**

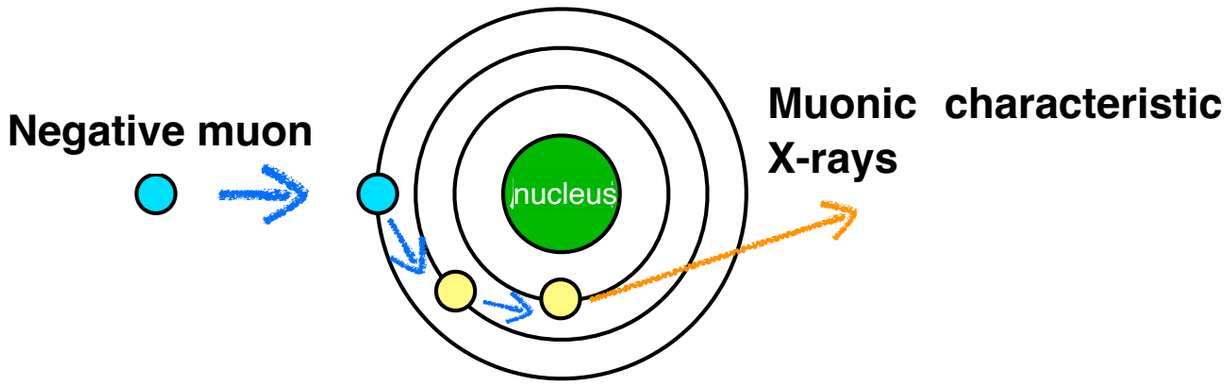
➡ Results obtained using a muon beam

- Imaging (planar spatial distribution)
- Imaging (depth spatial distribution)

✓ **Summary**

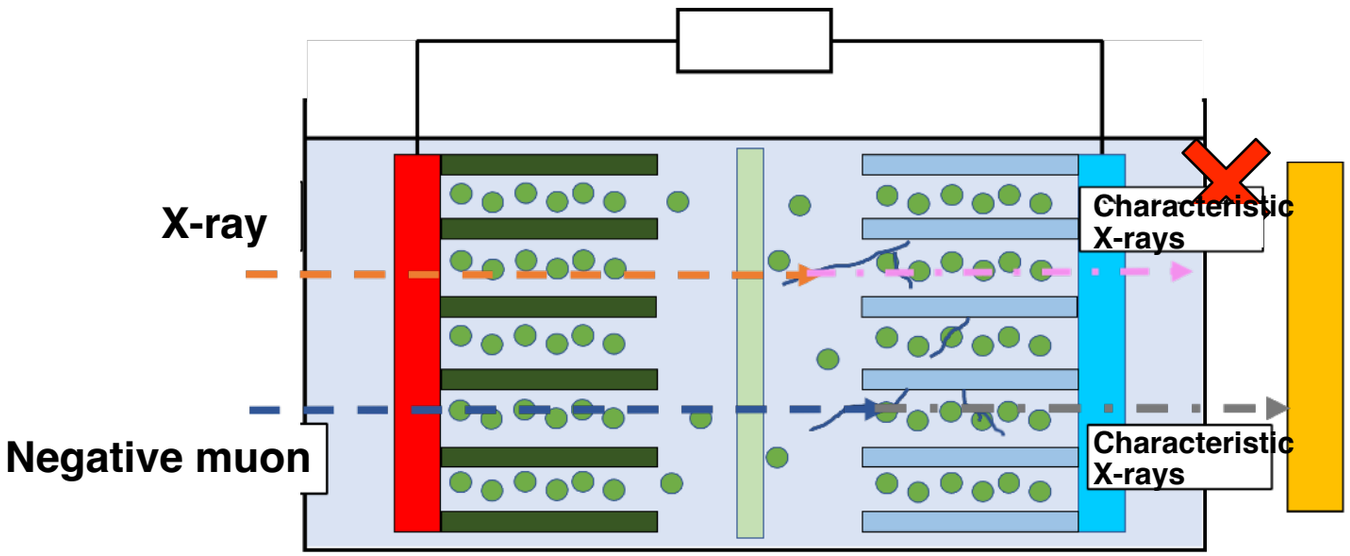
Muonic Characteristic X-rays

Recently, imaging of lithium using characteristic X-rays induced by negative muons has been gaining attention. Because a muon is about 200 times heavier than an electron, the resulting muonic characteristic X-rays have much higher energies than ordinary electron-induced characteristic X-rays.



Analytical method	Li	C	N
Muonic characteristic X-rays	18.7 keV	75 keV	109 keV
Electron-induced characteristic X-rays	< 0.1 keV	0.28 keV	0.39 keV

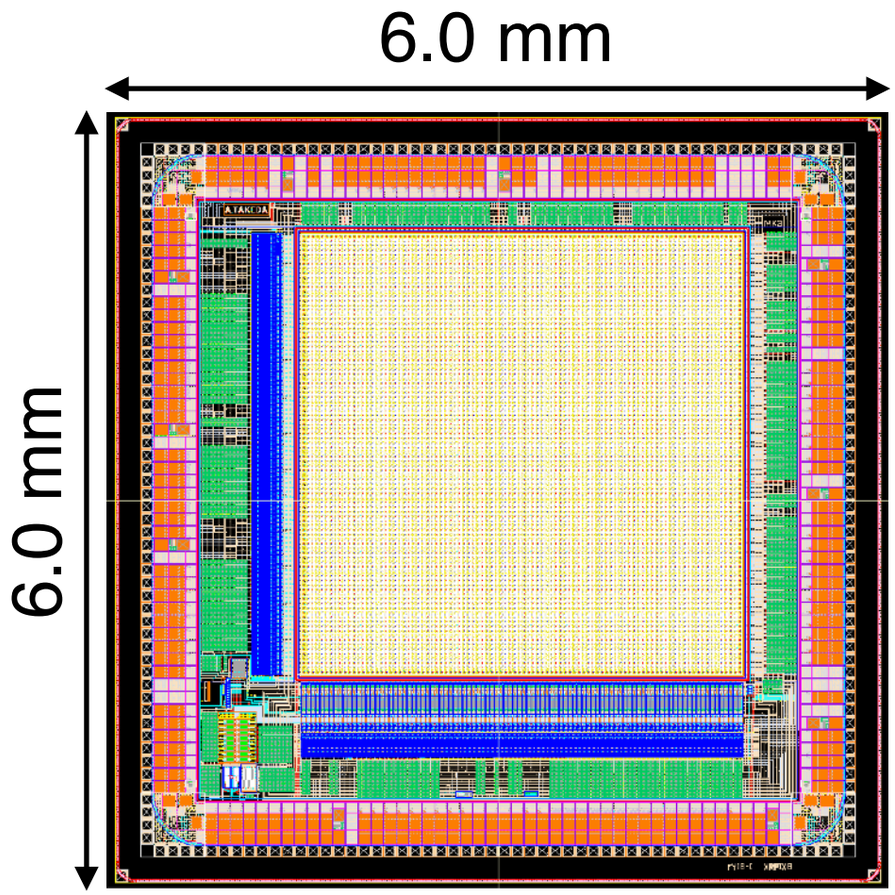
This technique is expected to play an important role in the nondestructive inspection of lithium-ion batteries.



We have been conducting a proof-of-principle study to evaluate the performance achievable with our detector, which began in FY 2022.

XRPIX8

Although the sensor area is small, this detector series can be fully depleted at room temperature and achieves the best spectroscopic performance among all previous generations. For detecting muonic characteristic X-rays, we used the XRPIX8, prioritizing spectroscopic performance over the large-area detectors used for imaging.



Detector Specifications

Chip size: 6.0 mm × 6.0 mm

Effective area: 3.4 mm × 3.4 mm

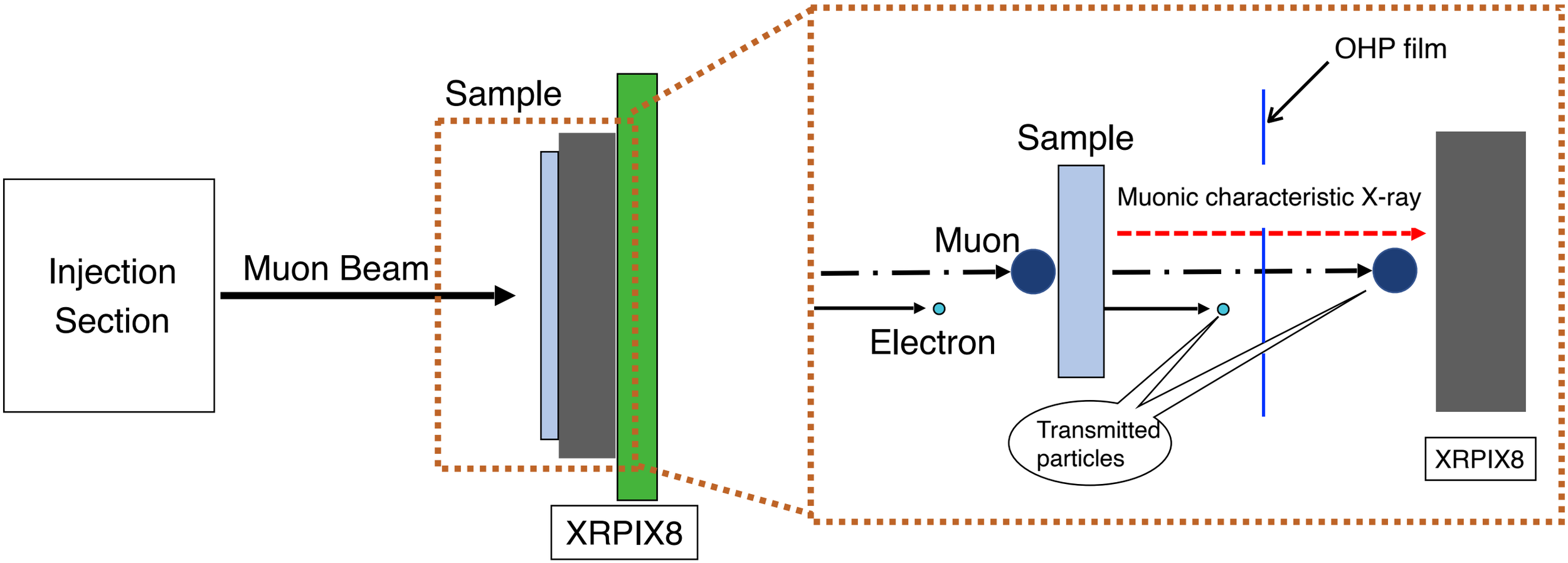
Pixel size: 36 μm × 36 μm

Number of pixels: 94 (H) × 94 (V)

Sensor thickness: 300 μm

Experimental Setup

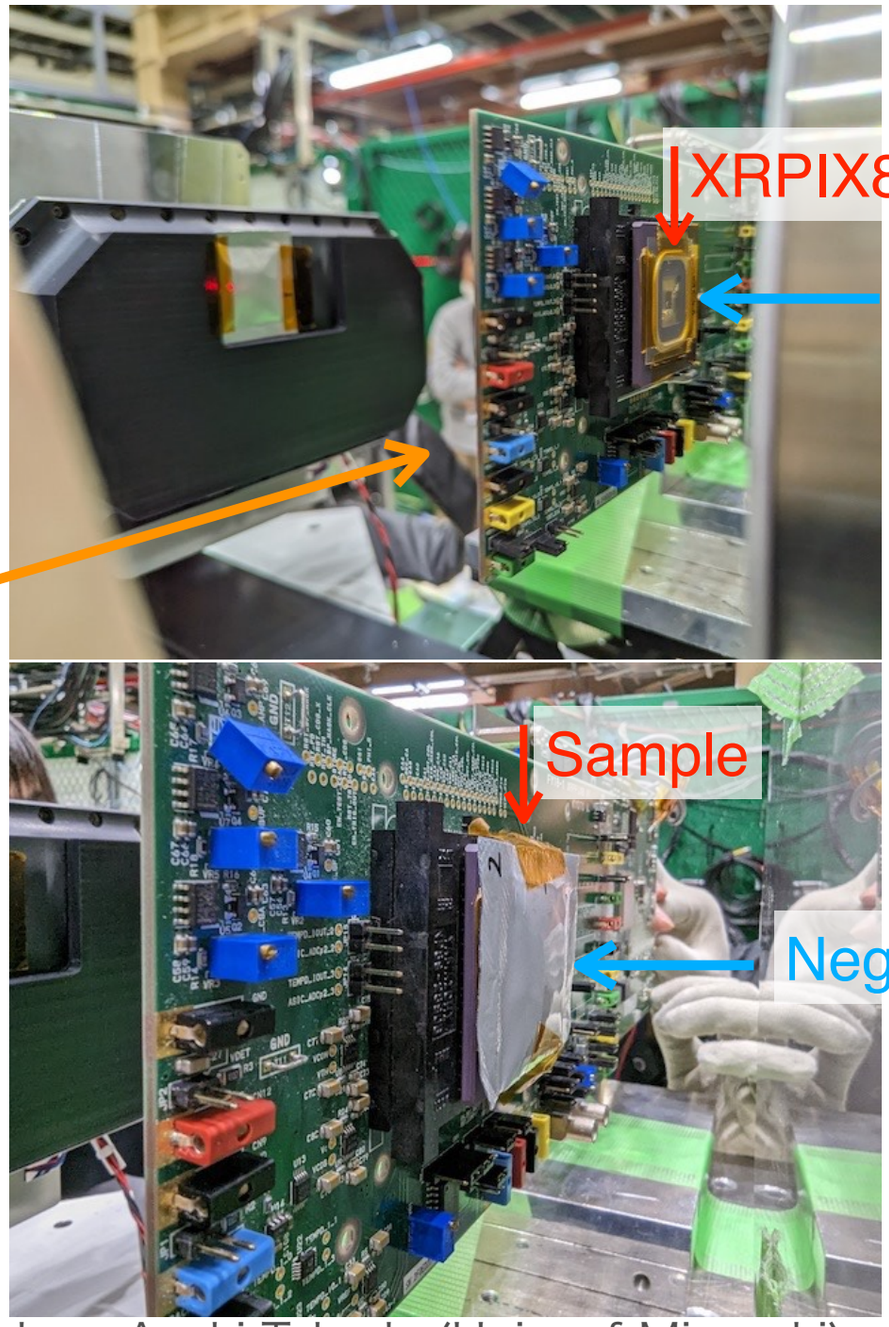
To obtain muonic characteristic X-rays, we conducted the experiment using the small-area XRPIX8 detector, which provides high spectroscopic performance.

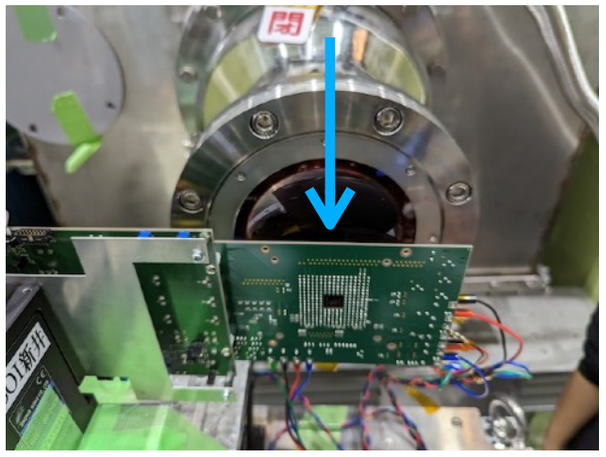


A lithium sample sealed in an aluminum pouch was placed, and the muonic characteristic X-rays emitted from it were detected.

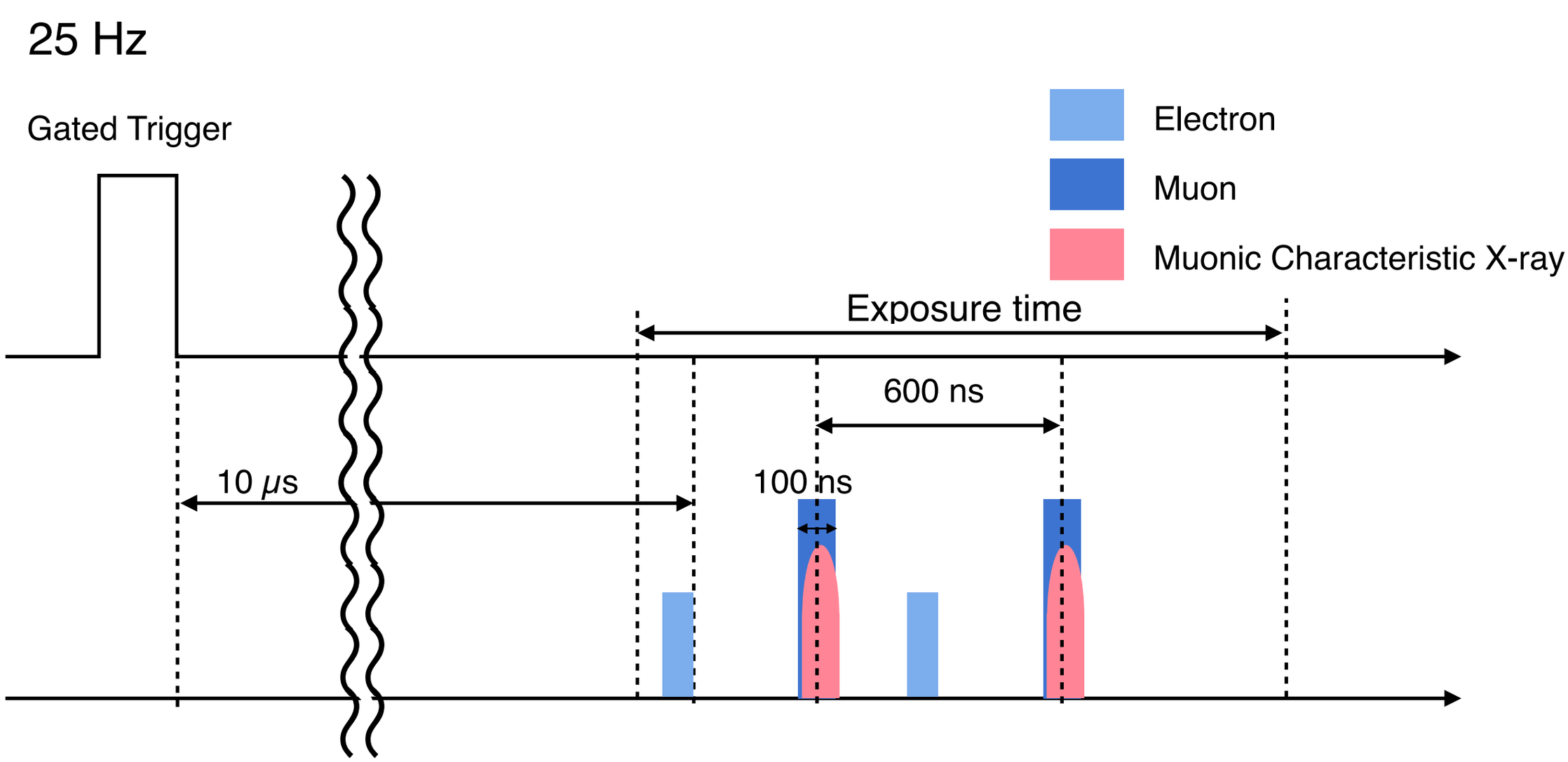
Negative muon irradiation experiment @ J-PARC

The irradiation experiment was carried out using the muon beam at MLF/D2. Because the detector can operate at room temperature, a simple experimental setup was sufficient.



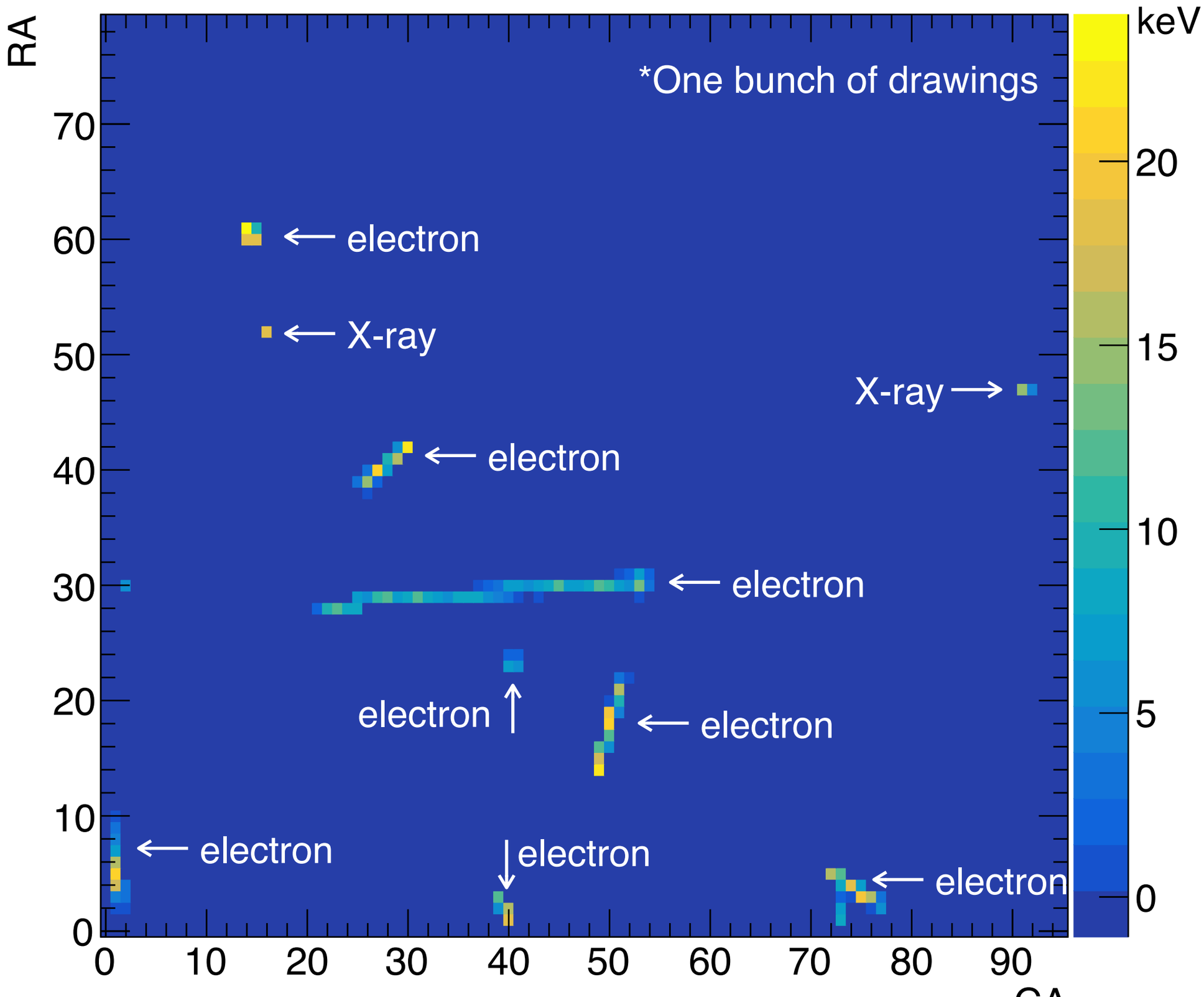


Arrival Timing of Muonic Characteristic X-rays

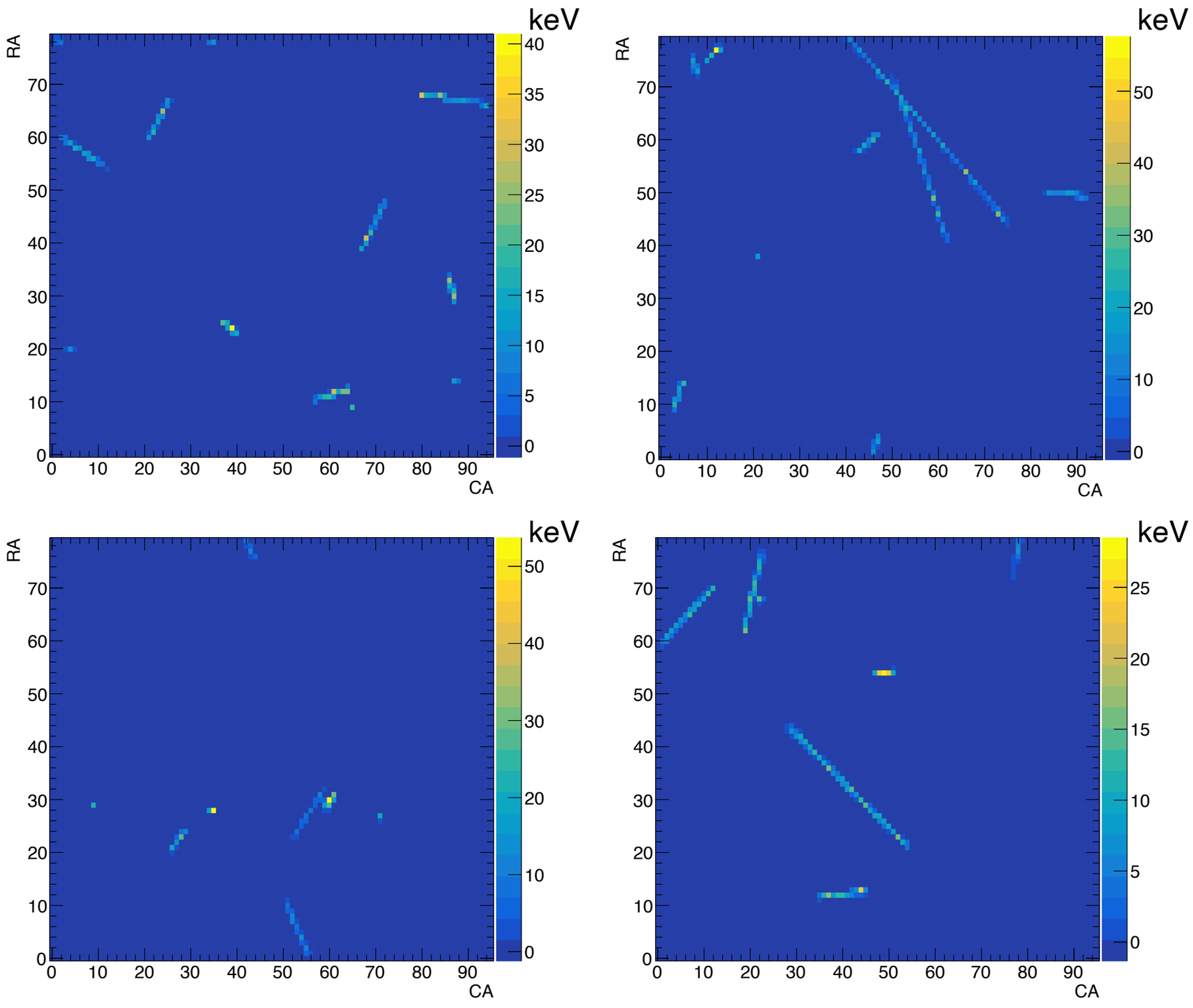


Muons arrive in 25-Hz pulsed beams.

Examples of observed events

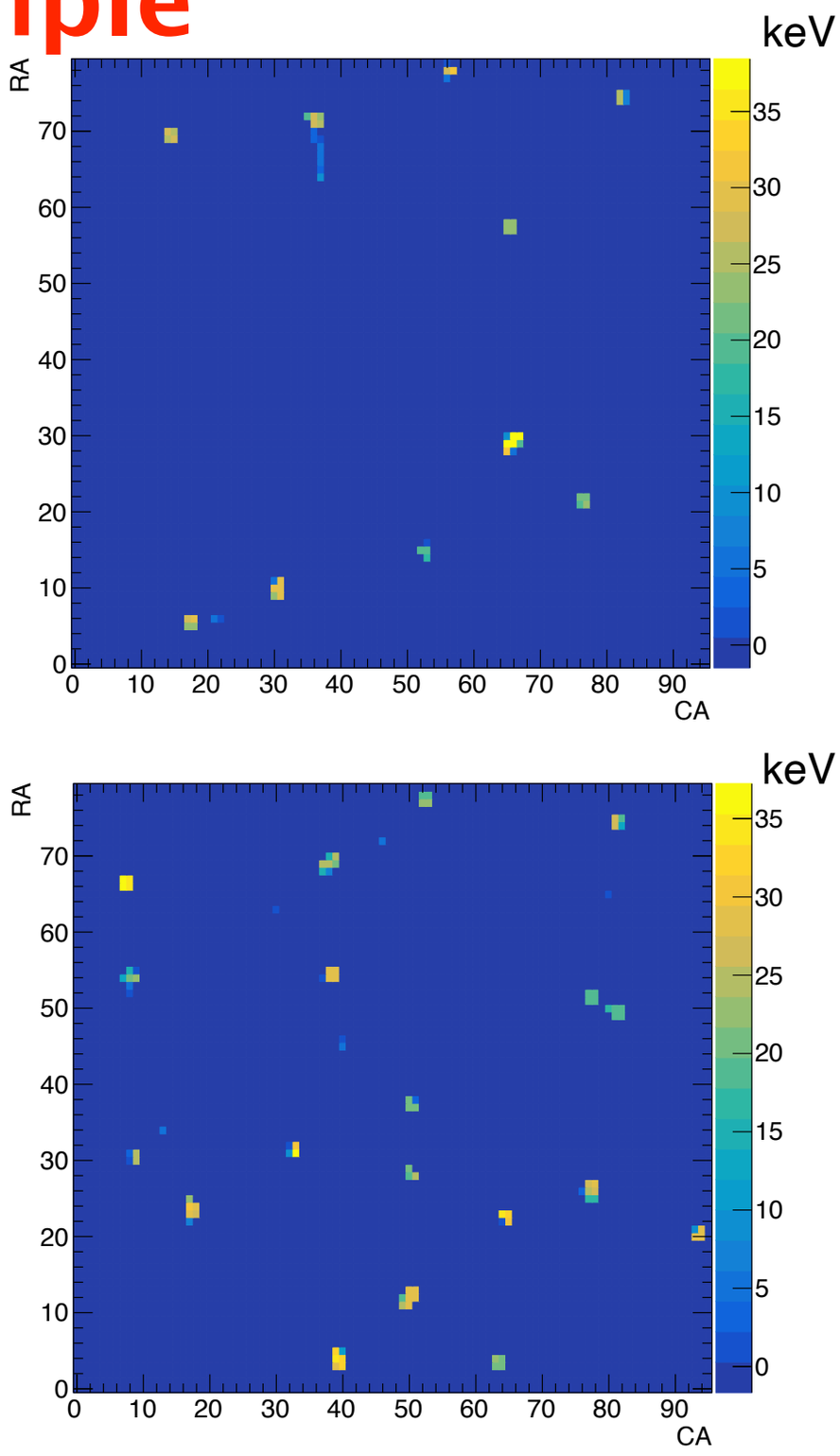


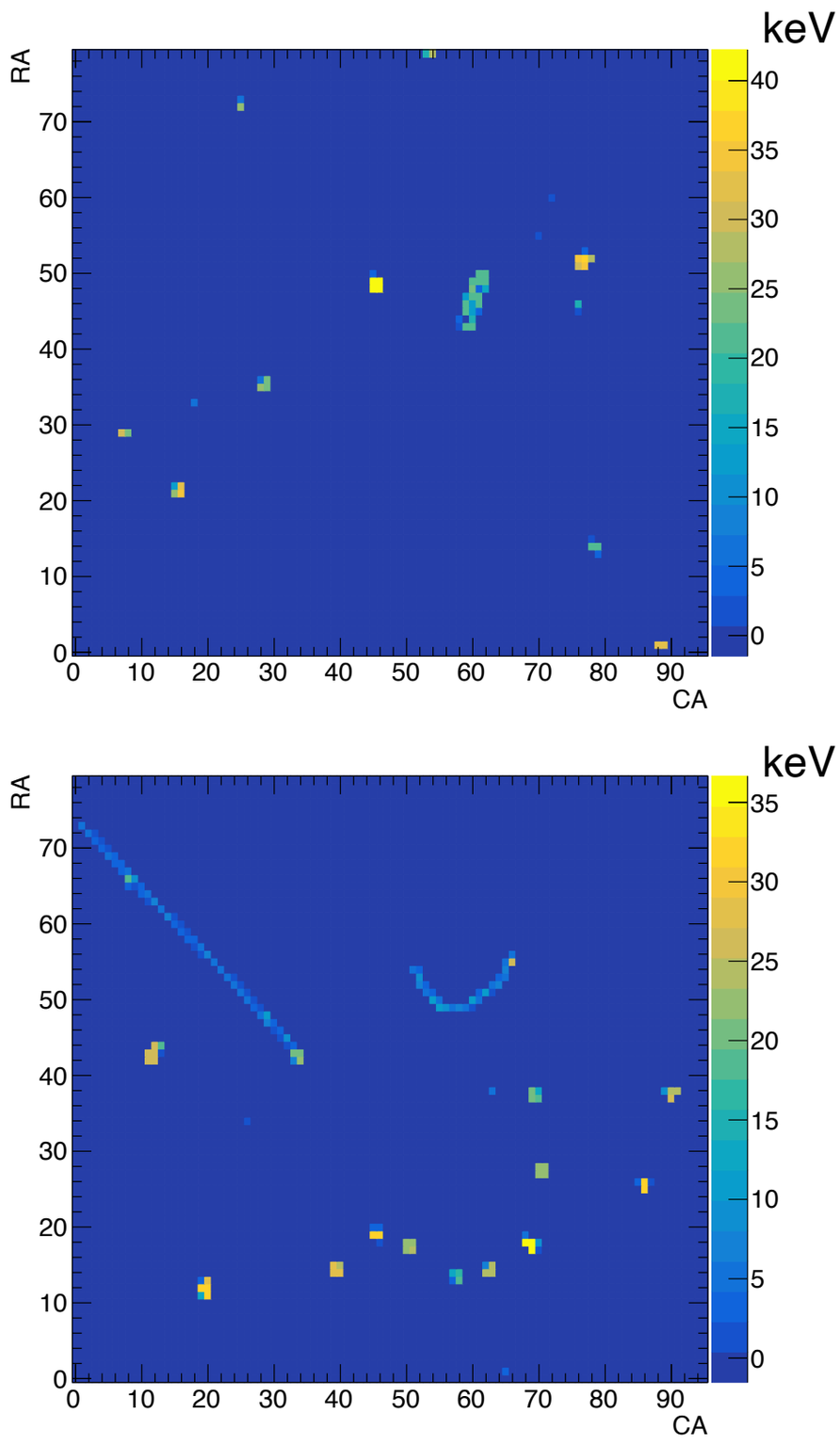
Examples of observed events



Examples of observed events

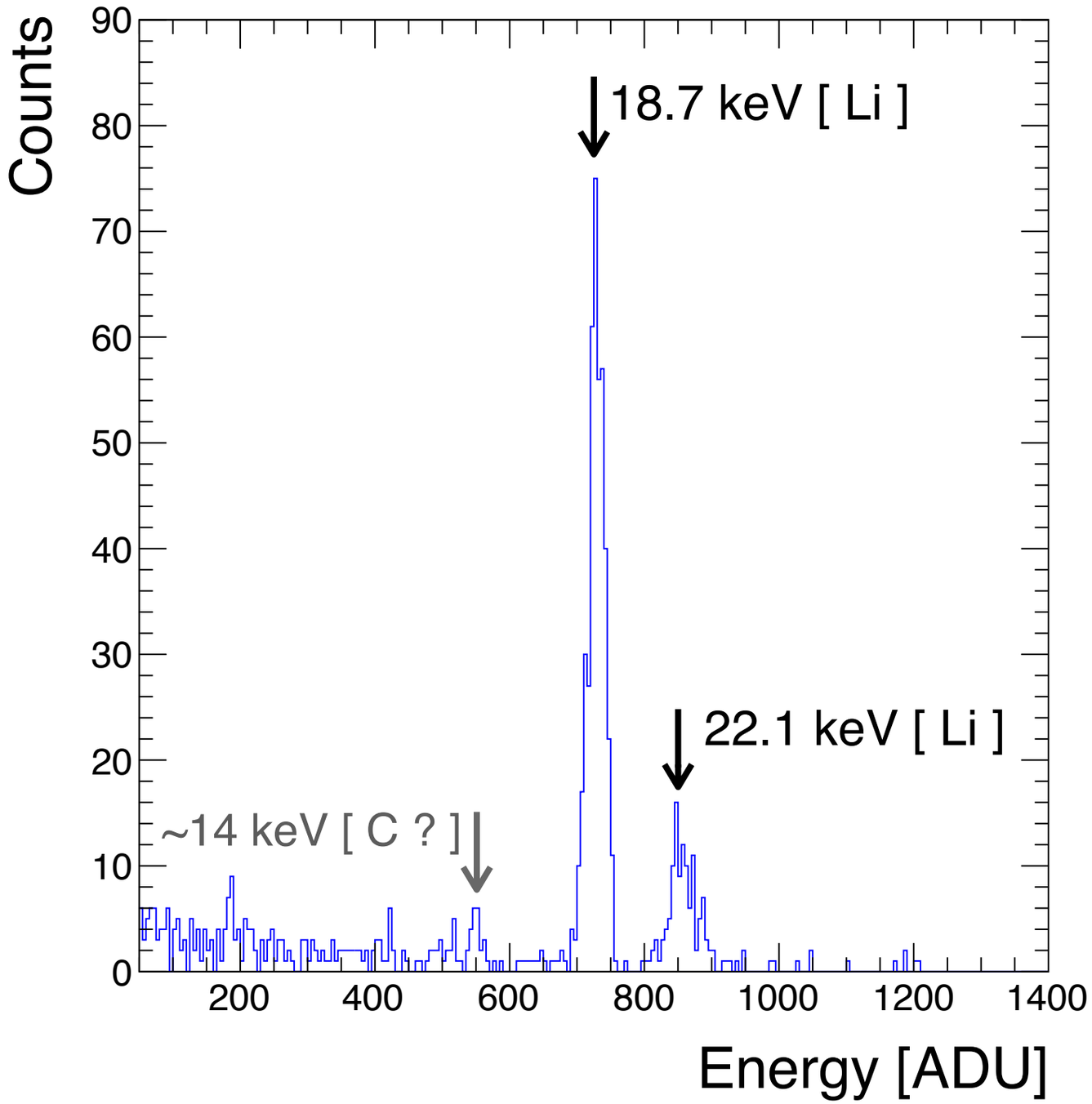
No sample





Detection of muonic characteristic X-rays

X-ray spectrum from the Li sample. The energy was converted using calibration parameters obtained in the laboratory.



Acquisition conditions

Temperature: room temperature

Sensor bias: -200 V (fully depleted)

Sample: Li

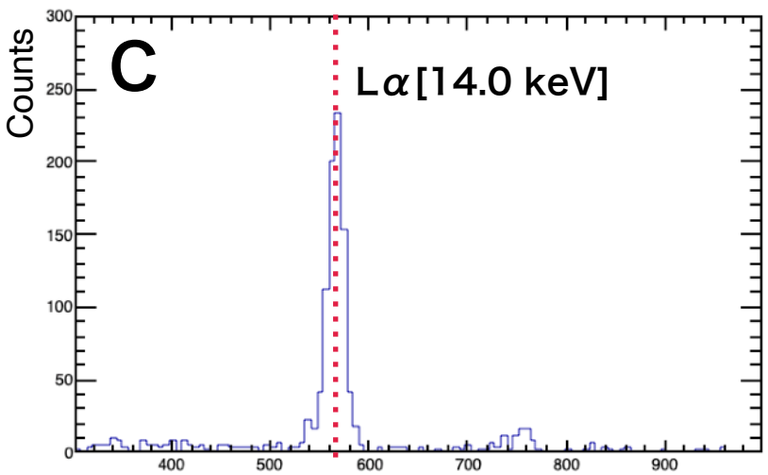
Number of frames: 10k

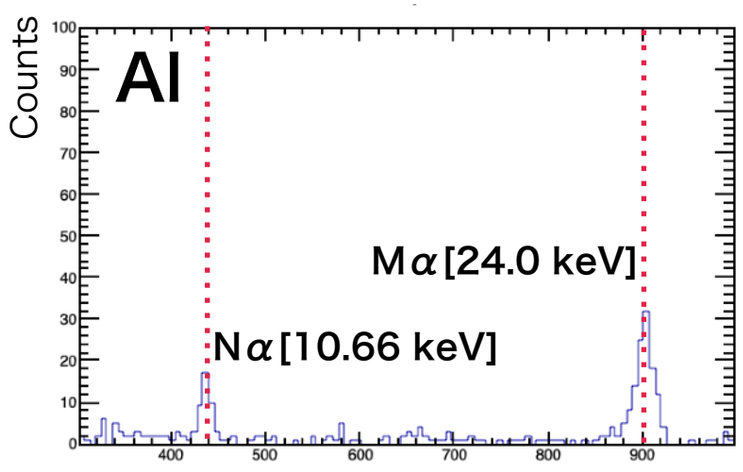
Beam type: single pulse

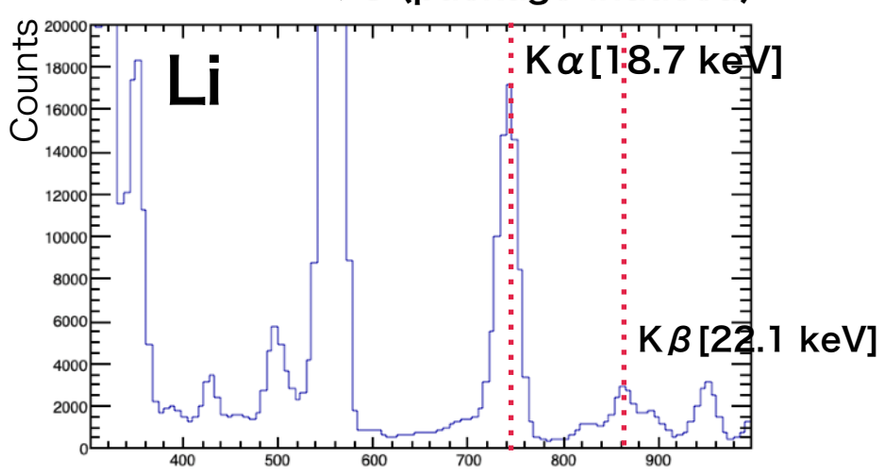
A peak consistent with muonic characteristic X-rays from Li was observed.

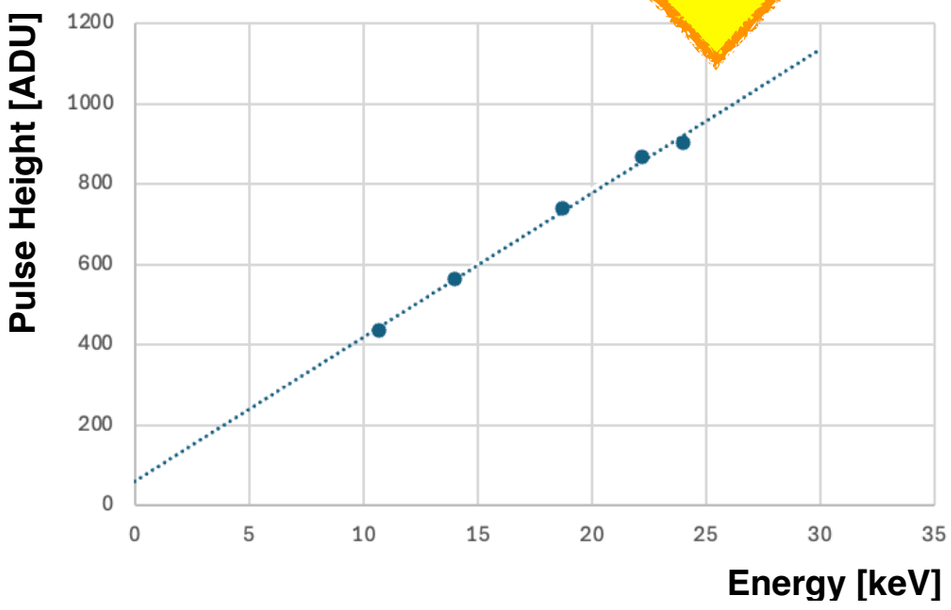
Energy Calibration

For energy calibration, we acquired muonic characteristic X-ray energy spectra from elemental samples of C, Al, and Li.

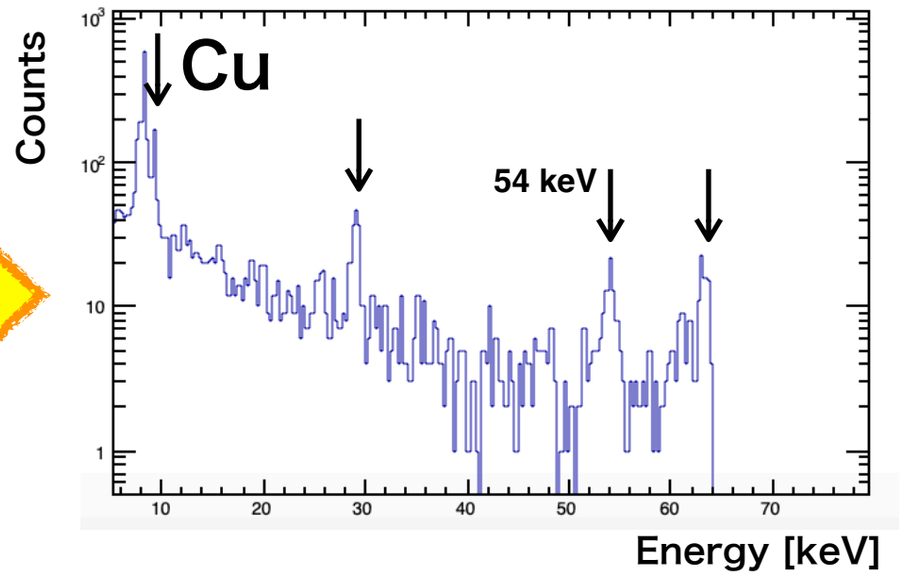








From the energy spectrum, a gain of 31.4 μV/e^- was obtained, which is close to the value measured in the laboratory.

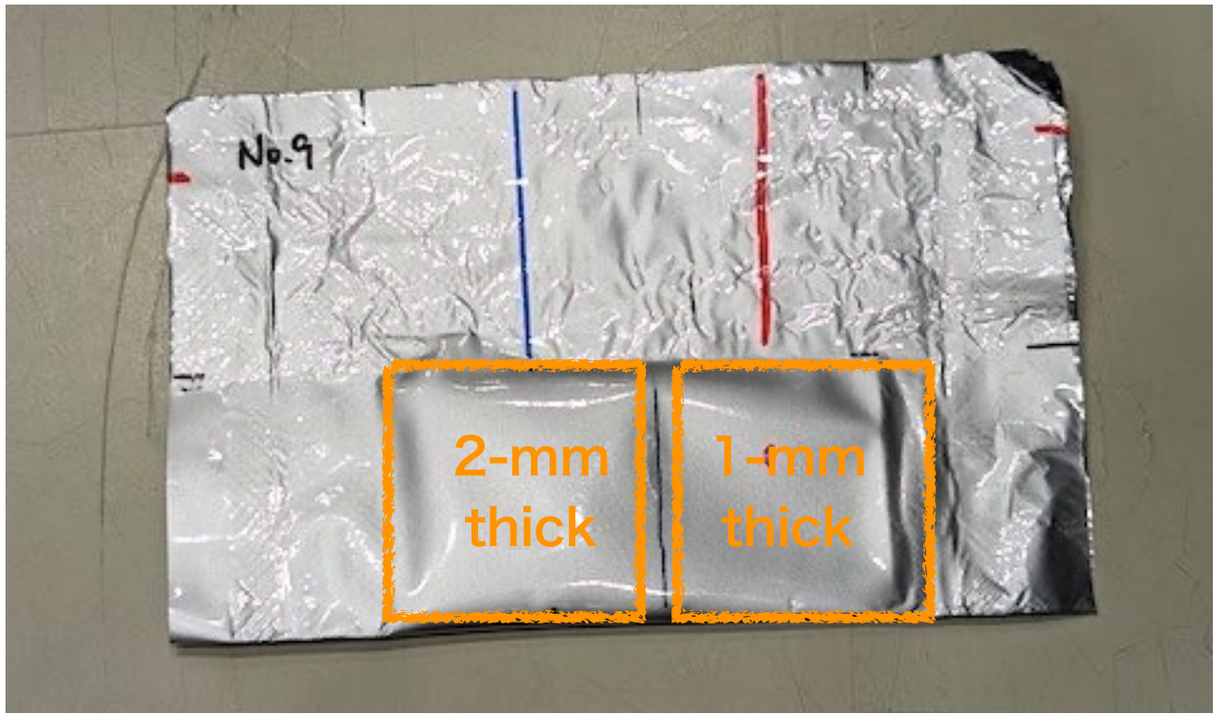


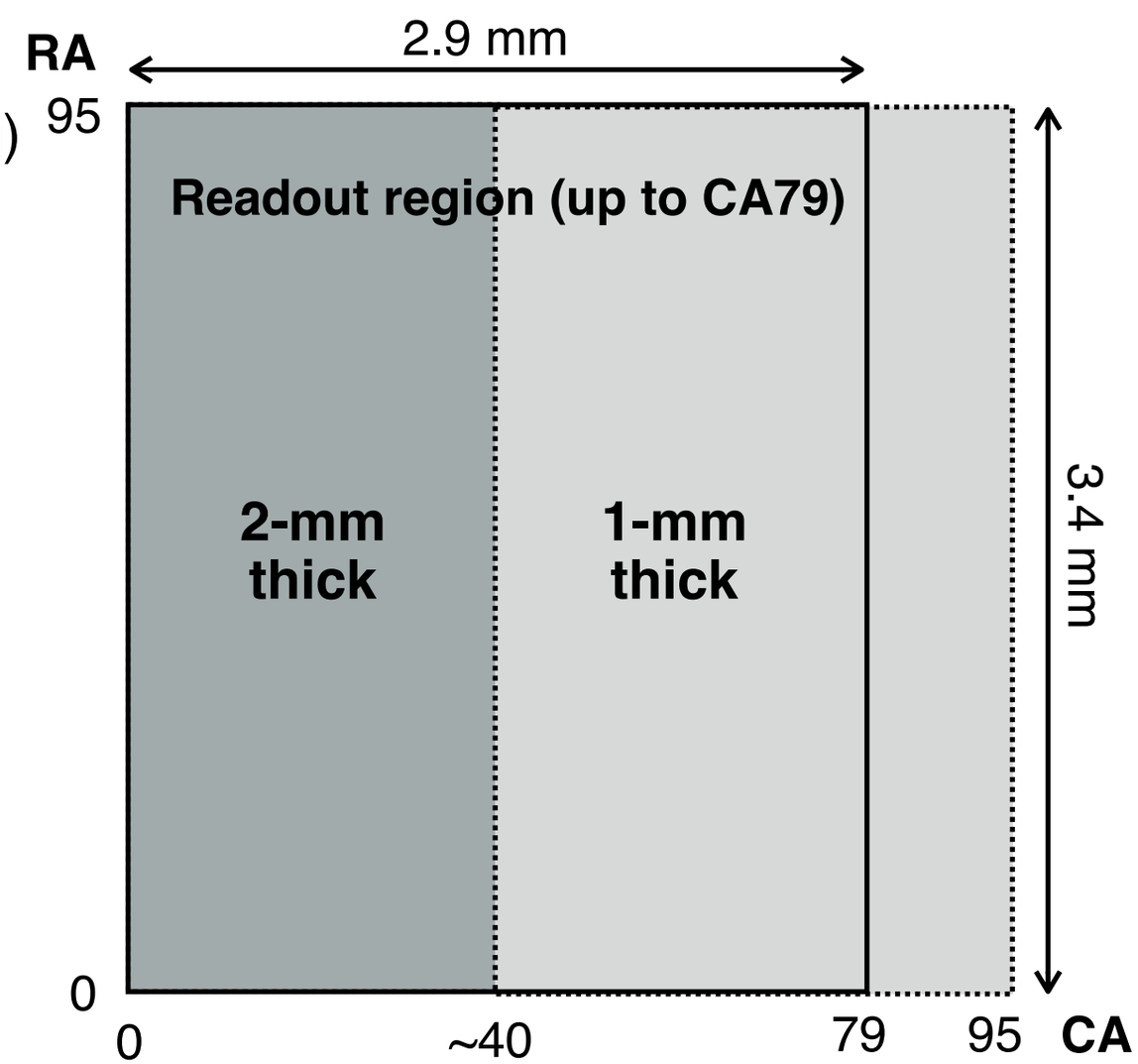
Cu muonic characteristic X-rays also confirmed?

Imaging (planar spatial distribution)

The sample was positioned so that its boundary aligned with the center of the XRPIX8 chip. The sample placement is shown in the figure, and the Column Address (CA) direction was read out up to address 79.

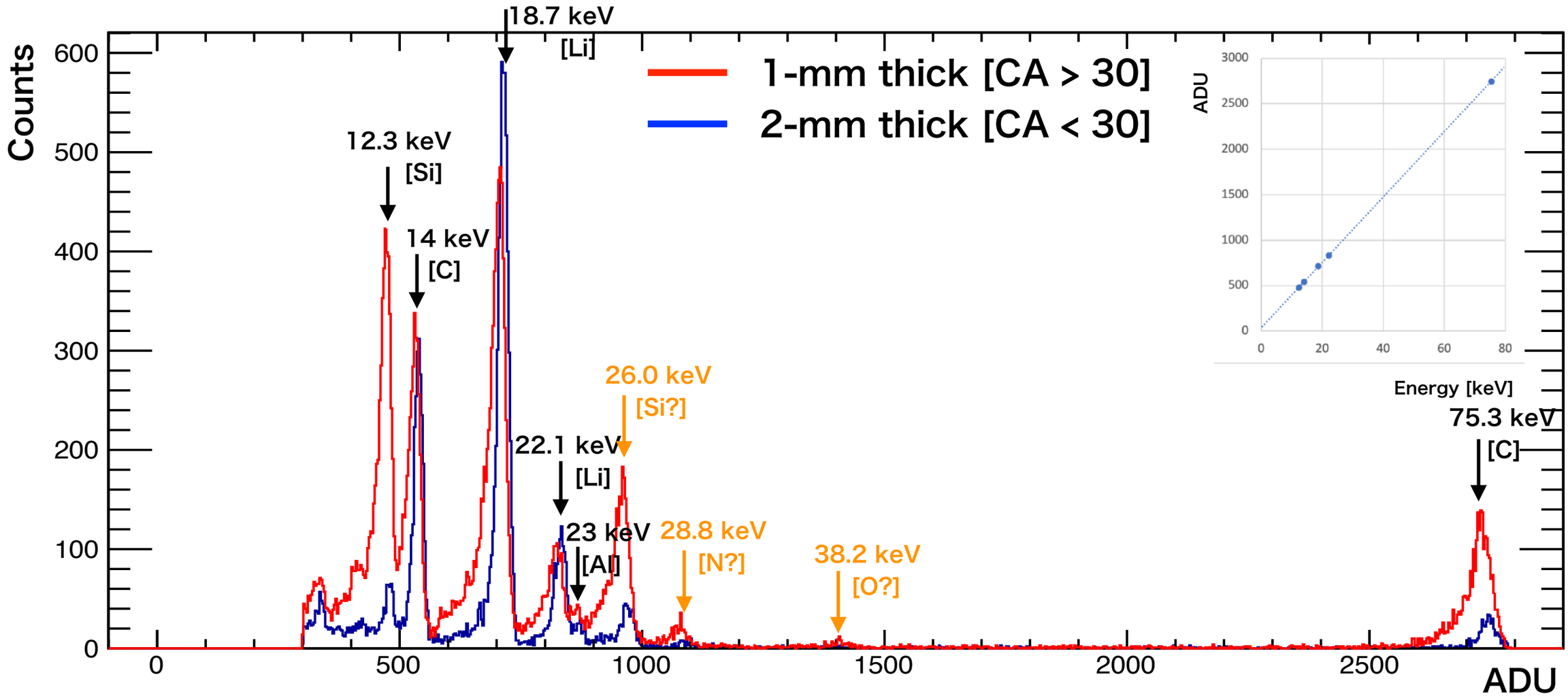
- ✓ Samples containing Li layers of 2 mm and 1 mm thickness
- ✓ Sample positioned so that the boundary aligns with the center of XRPIX8
- ✓ Sensor bias: –200 V (fully depleted)
- ✓ Operated at ambient room temperature (no cooling)





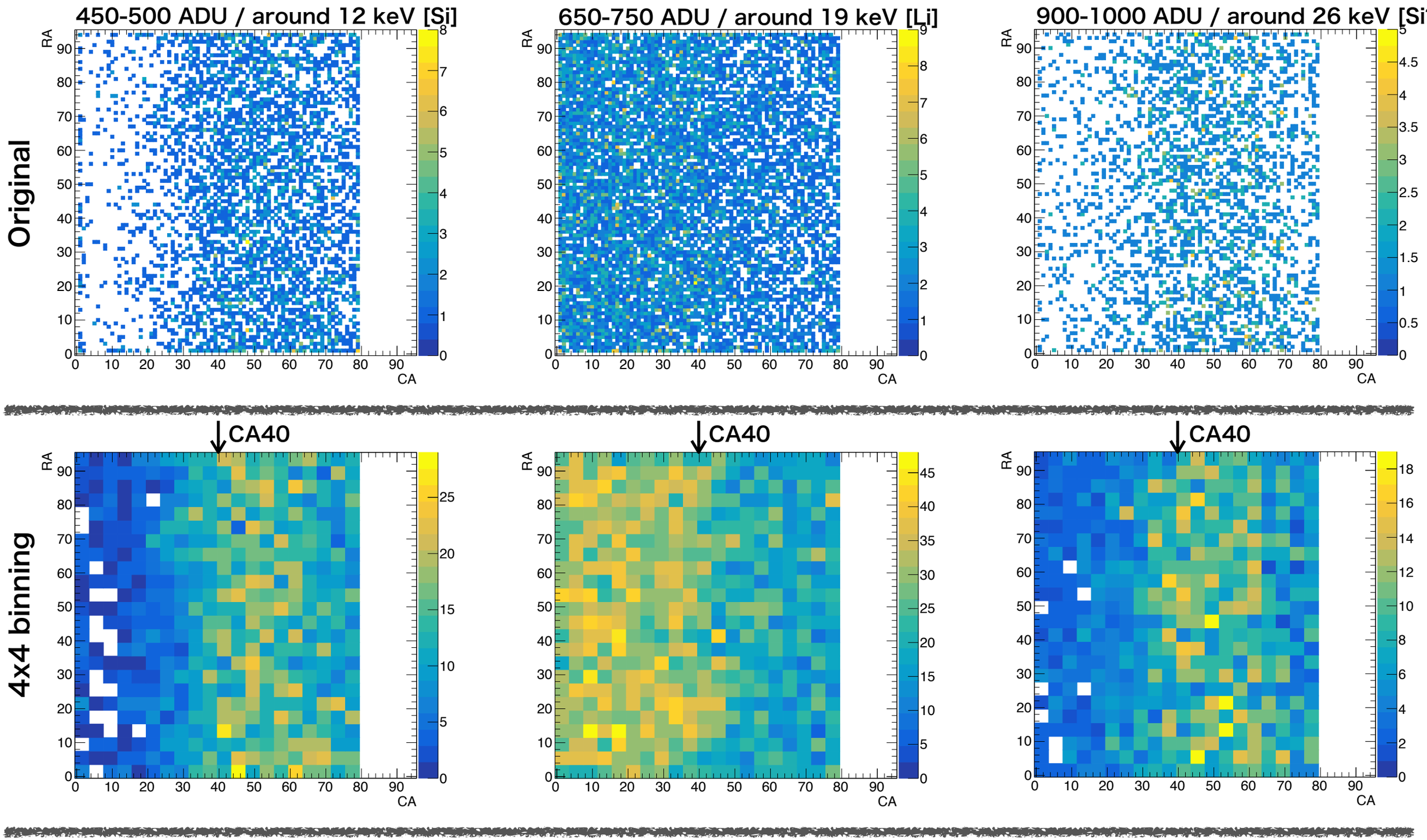
X-ray Spectra | Region split at CA30

- ✓ Only single-pixel events selected for the spectra
- ✓ Loose region definition → some mixing expected
- ✓ Pixel ratio (2 mm : 1 mm) = 3 : 5 (30 CA : 50 CA)
- ✓ Black labels: calibrated with known energies
- ✓ Orange labels: energies from calibration line (ID required)



Imaging (planar spatial distribution)

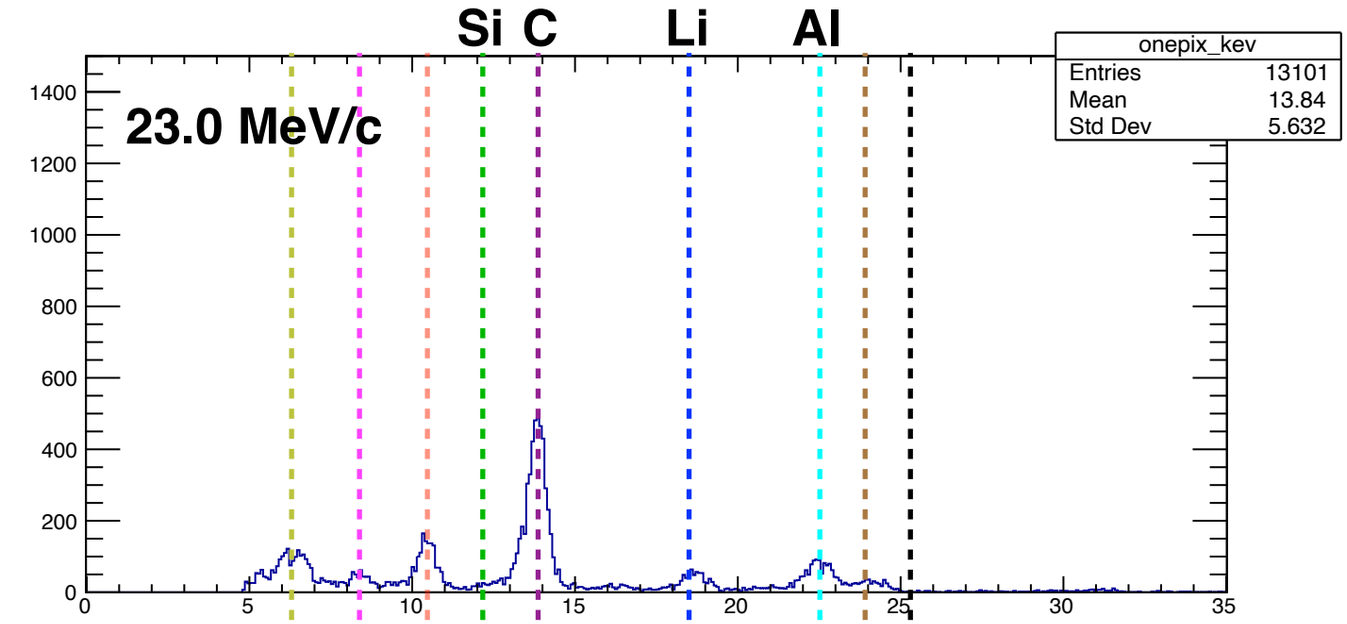
The upper panels show the original maps, and the lower panels show the maps binned into 4×4 pixels. A boundary can be seen around CA40.

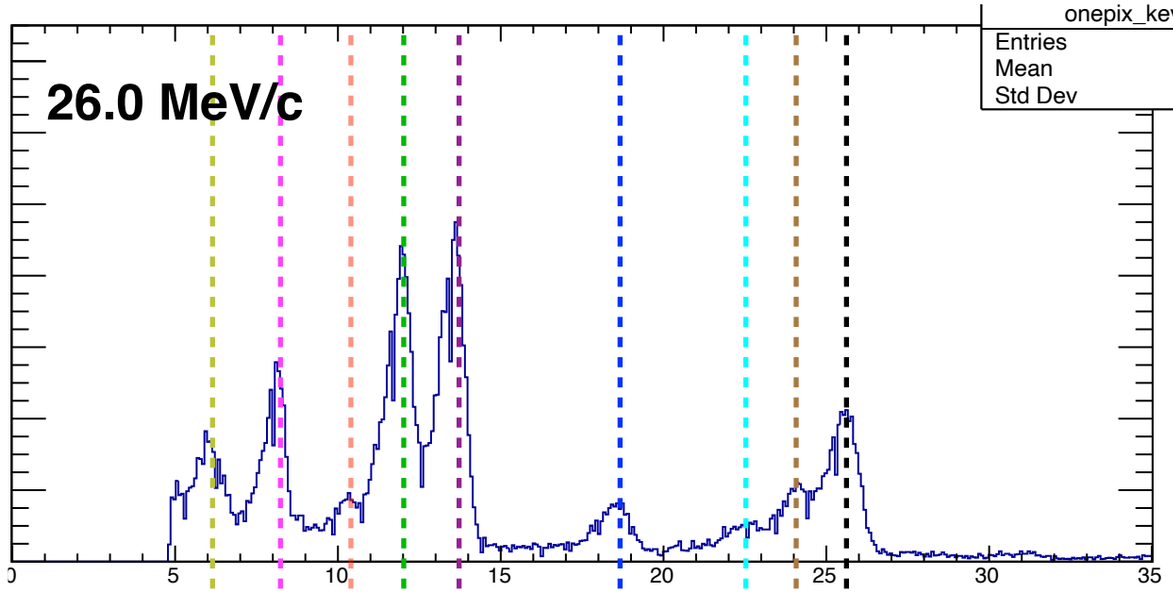


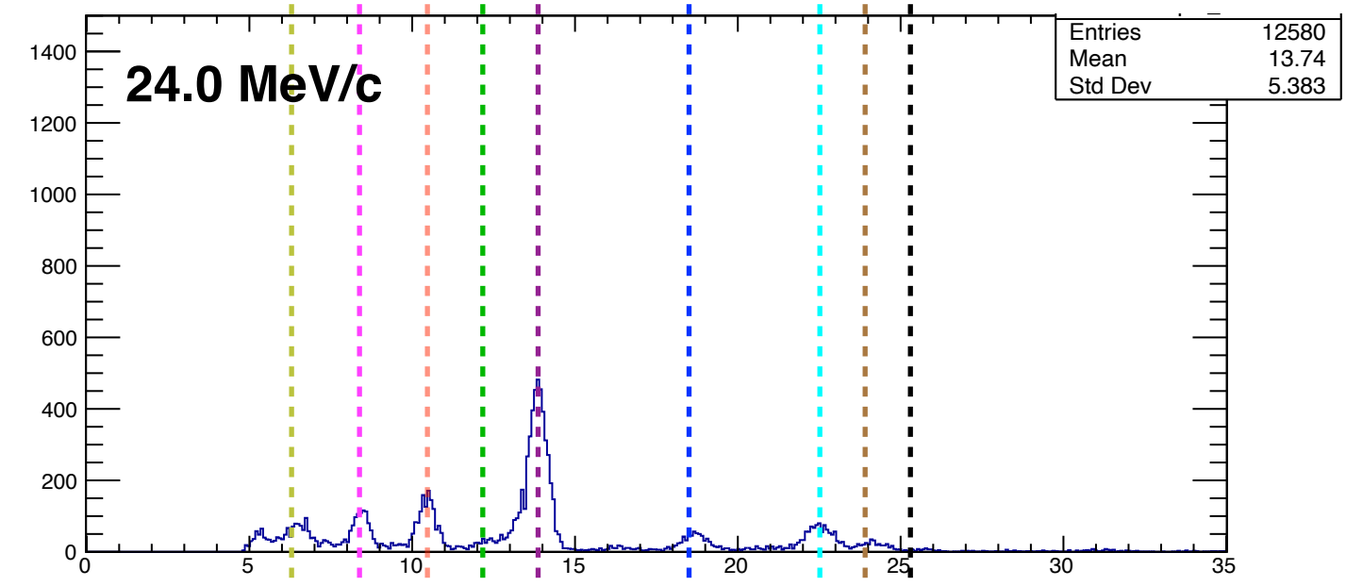
Imaging (depth spatial distribution)

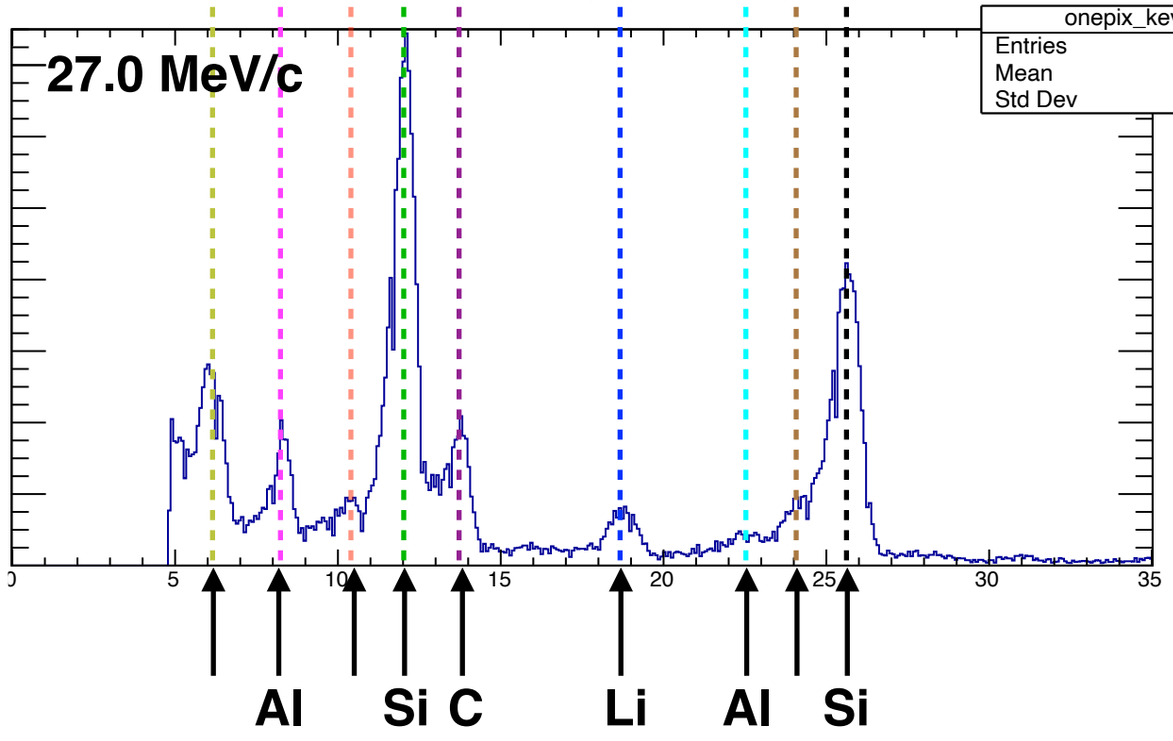
To examine the depth distribution, data were taken at different muon-beam momenta.

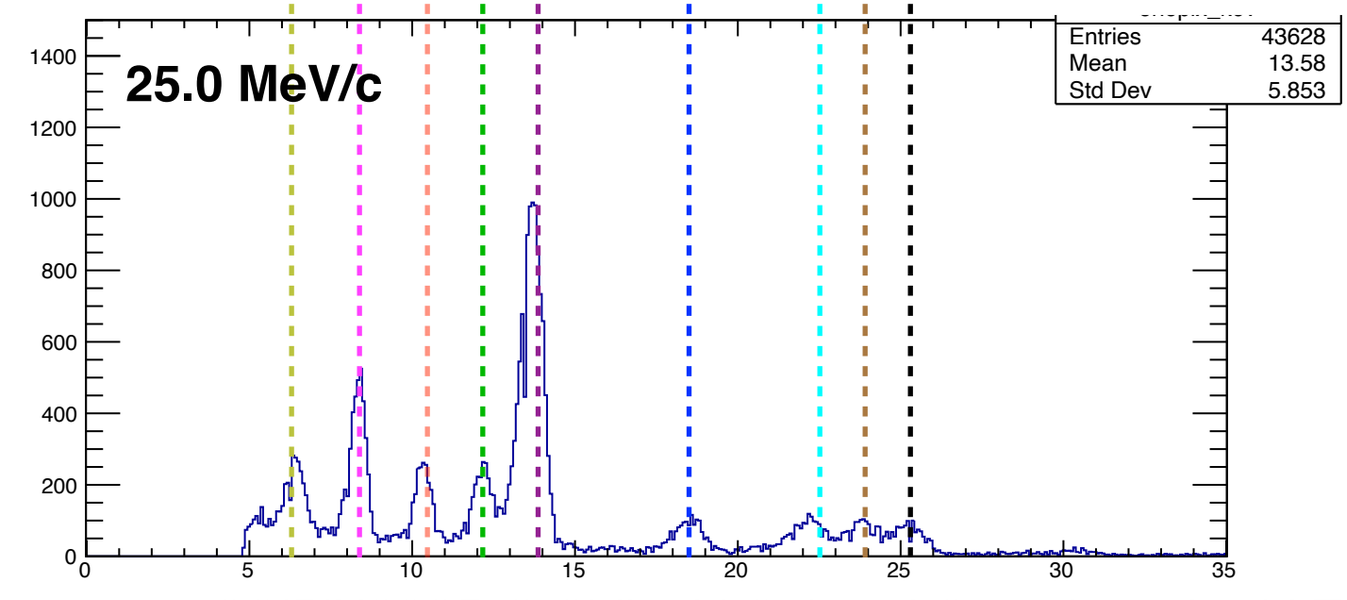
- ✓ Irradiation sample: dry sample (50k frames each)
- ✓ Muon-beam momentum: 23.0–27.0 MeV/c (momentum scan)
- ✓ Sensor bias: –200 V (full depletion)
- ✓ Temperature: ambient room temperature (spot cooler used)











Increasing the momentum from 23.0 to 26.0 MeV/c provided deeper information, and spectral differences were confirmed. We gained confidence that both planar and depth distributions can be derived.

Summary

- ✓ We have been developing the application of SOIPIX detectors to muonic characteristic X-ray imaging.
- ✓ Muonic characteristic X-rays from Li samples have been successfully detected, and differences in energy peaks, planar distributions, and depth distributions for each element have been obtained.
- ✓ We will continue the development of large-area sensors with high spectroscopic performance and pursue the realization of high-performance imaging sensors for soft X-ray applications.