Calibration and Performance Analysis of Detector Systems in the K1.8 Beamline at J-PARC

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Overview

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- K1.8 Beamline
- Beam Counter Calibration
- Time-of-Flight Validation
- Hyperball-X HPGe Calibration
- Energy Spectrum Analysis
- AFT Calibration
- Coincidence Analysis
- Summary

Physics Motivation

- Antiprotonic atoms provide a unique probe of the antiproton–nucleus interaction.
- Characteristic X-rays emitted during the atomic cascade carry information about the energy levels of the system.
- Precise X-ray spectroscopy requires accurate calibration and performance validation of the detector systems.

Objective

To calibrate and evaluate the performance of detector systems in the K1.8 beamline for high-resolution X-ray spectroscopy.

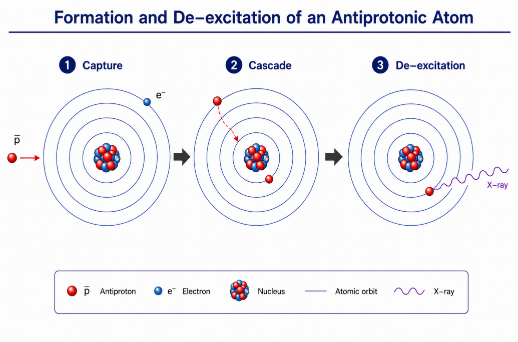


Figure 1. Schematic illustration of the formation and de-excitation of an antiprotonic atom.

The E96 Experiment

- The E96 experiment aims to measure the **atomic cascade X-rays from exotic Ξ^- atoms** using high-resolution X-ray spectroscopy.
- The experiment utilizes the **Hyperball-X HPGe detector array** and the **Active Fiber Target (AFT)** to detect X-rays with improved background suppression.
- Accurate X-ray spectroscopy requires careful calibration and performance evaluation of the detector systems prior to physics measurements.
- In this work, previously recorded antiproton ($\bar{p}$) data were used to evaluate the performance of the Beam Counter System, Hyperball-X HPGe detectors, and the Active Fiber Target.

Experimental Setup: K1.8 Beamline

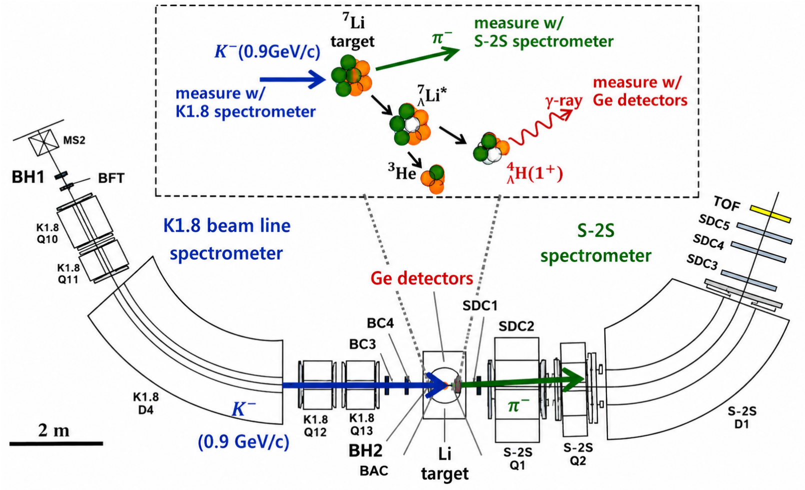


Figure 2. Schematic layout of the K1.8 beamline and detector systems used in the E96 experiment.

- Beam counters provide timing information for charged particles along the K1.8 beamline.
- The timing signals are used for particle identification through Time-of-Flight (TOF) measurements.
- Accurate timing calibration is essential for reliable TOF analysis.

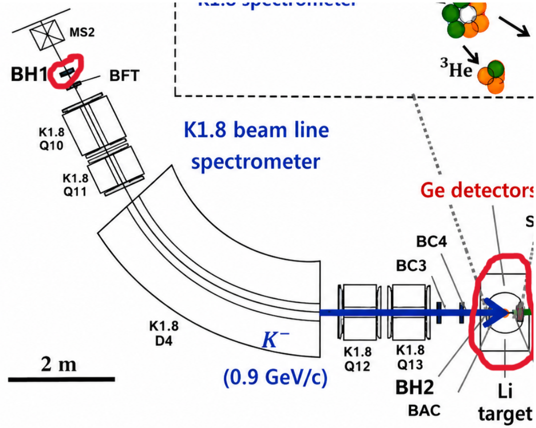


Figure 3. Beam counters used for timing measurements along the K1.8 beamline.

Beam Counter Calibration

- Raw timing signals from the beam counters were recorded using a Time-to-Digital Converter (TDC).
- Each TDC spectrum was fitted with a Gaussian function to determine the timing peak centre.
- The extracted peak centre values were provided as calibration constants for the beam counters.
- The calibrated timing constants were subsequently used to obtain the Time-of-Flight (TOF) spectrum.

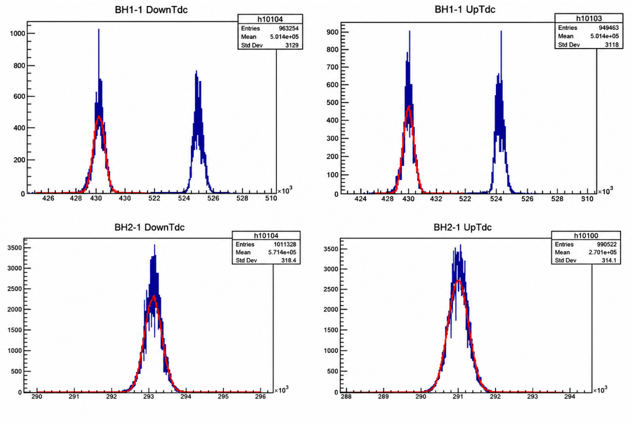


Figure 4. Gaussian fit to a representative TDC spectrum used to extract the timing peak centre.

Time-of-Flight (TOF) Analysis

- Expected particle flight times were calculated using
$$t = \frac{L}{\beta c},$$
for an 11 m flight path.
- The expected proton–pion TOF difference was calculated as
$$\Delta t = t_p - t_\pi = 21.42 \text{ ns}.$$
- The extracted timing peak centres were incorporated into the beamline timing calibration, and the resulting calibration constants were used to reconstruct the TOF spectrum.

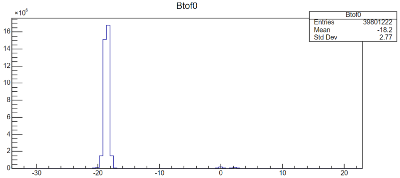


Figure 6. Reconstructed Time-of-Flight spectrum obtained using the extracted timing calibration constants.

Hyperball-X Detector System

Hyperball-X is a high-purity germanium (HPGe) detector array designed for high-resolution X-ray and γ-ray spectroscopy.

- Consists of 16 segmented HPGe detectors surrounding the experimental target.
- Detects characteristic X-rays and γ rays emitted during the de-excitation of antiprotonic atoms.
- Provides excellent energy resolution for precision spectroscopy.

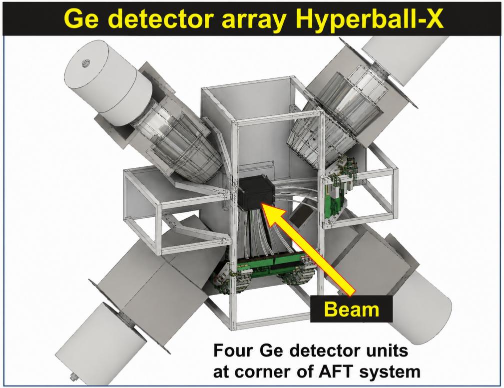


Figure 7. Hyperball-X HPGe detector array used for high-resolution X-ray and γ-ray spectroscopy.

HPGe Energy Calibration

- Characteristic calibration peaks were identified in the ADC spectra.
- Each peak was fitted with a Gaussian function to determine the peak centroid.
- The extracted ADC centroids were matched to the known γ-ray energies of the calibration source.
- A linear calibration was performed to convert ADC channels into energy.

$$E = A \times \mathrm{ADC} + B$$

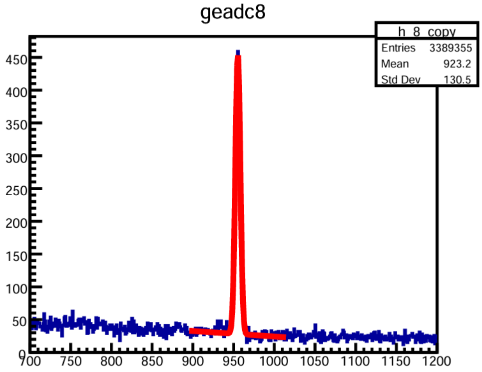
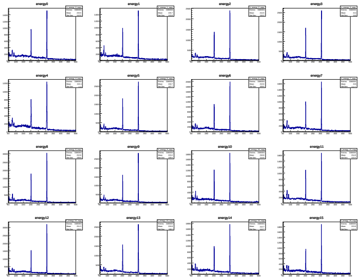


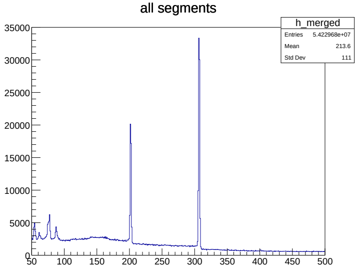
Figure 8. Gaussian fit to a representative calibration peak in the HPGe ADC spectrum.

Calibrated HPGe Energy Spectra

- The energy calibration was applied independently to all 16 HPGe detector segments.
- Individual calibrated spectra exhibit the characteristic X-ray and γ-ray peaks.
- The merged spectrum improves counting statistics for subsequent analysis.



(a) Individual calibrated HPGe spectra.



(b) Merged calibrated energy spectrum.

Figure 9. Calibrated energy spectra obtained from the Hyperball-X HPGe detector array.

Active Fiber Target (AFT)

The Active Fiber Target (AFT) is a scintillating fiber detector that serves as the experimental target while simultaneously detecting charged particles.

- Composed of orthogonally arranged scintillating fiber layers.
- Provides precise tracking of charged particles passing through the target.
- Signals are read out using Multi-Pixel Photon Counters (MPPCs).

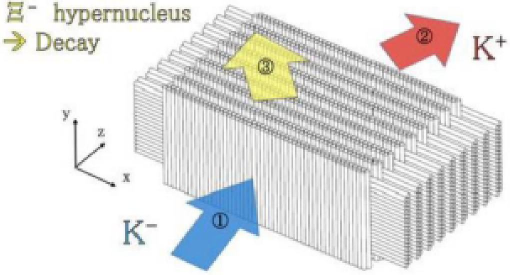
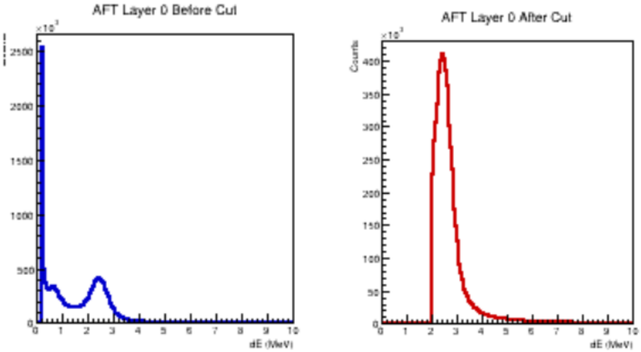


Figure 10. Schematic of Active Fiber Target (AFT) detector.

AFT Event Selection

- Energy-deposition (dE) spectra were obtained for all 36 AFT layers.
- A threshold of $dE > 2.0$ MeV was applied to suppress low-energy noise.
- Representative spectra before and after the threshold are shown.
- The selected AFT events were used to gate the HPGe energy spectrum.



(a) Before threshold **(b)** After threshold

Figure 11. Representative AFT energy-deposition spectrum before and after applying the $dE > 2.0$ MeV threshold.

Effect of AFT Event Selection on the HPGe Spectrum

- The HPGe energy spectrum was first obtained using all recorded events.
- The AFT event selection was then applied as a gate on the HPGe data.
- The gated spectrum exhibits reduced background while retaining correlated events.
- This improves the visibility of the low-energy region for further analysis.

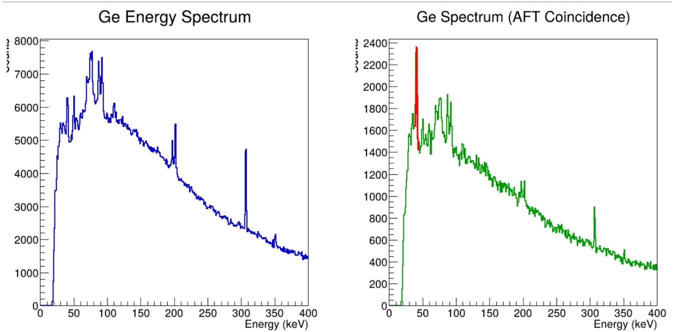


Figure 12. Comparison of the HPGe energy spectrum before (left) and after (right) applying the AFT event selection.

Identification of the 40 keV X-ray Transition

- A Gaussian + step function was fitted to the prominent peak near 40 keV.
- Measured peak energy:

$$\boxed{40.86 \pm 0.07\ \mathrm{keV}}$$

  Previous measurement: $40.539 \pm 0.010\ \mathrm{keV}$
  Calculated value: $40.32\ \mathrm{keV}$

- The measured energy is consistent with the previously reported antiprotonic carbon X-ray transition within the experimental uncertainty.
- The small deviation is attributed to systematic uncertainty, as the peak lies in the extrapolation region of the HPGe energy calibration.

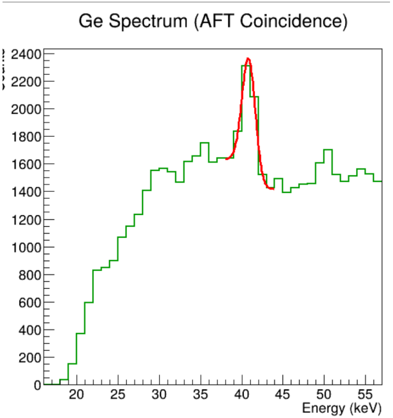


Figure 13. Gaussian + step-function fit to the 40 keV peak in the AFT-gated HPGe spectrum.

Summary

- Beam counter timing spectra were analyzed, and Gaussian fits were performed to determine calibration constants for the K1.8 beamline.
- Independent energy calibrations were carried out for all 16 HPGe detectors of the Hyperball-X system.
- The Active Fiber Target (AFT) was used to select correlated events, resulting in a cleaner HPGe energy spectrum.
- A Gaussian + step function fit to the prominent 40 keV peak yielded an energy of $\mathbf{40.86 \pm 0.07}$ **keV**, consistent with the expected antiprotonic X-ray transition.

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