Mid-Internship Progress Report
KEK–J-PARC Summer Student Program 2026
Hypernuclear Physics and Detector Calibration

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About Me

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Research Interests and Background

- Worked with HPGe detectors for the pre-final year project
- Strong interest in Gamma ray spectroscopy and Nuclear Physics

Overview

Training

- Initial Training at KEK
- Hypernuclear Physics

Research Activities

- ROOT Simulations
- HPGe Detector Calibration
- Calibration Script Development

Current Work

- Counter Calibration
- Time-of-Flight Analysis (Ongoing)

Initial Training at KEK

During the first phase of the internship, I attended lectures covering the fundamental concepts required for the project.

Topics included

- Basics of Nuclear Physics
- Basics of Particle Physics
- Radiation Detectors
- Introduction to CERN ROOT

As part of the training, a simulation exercise was performed to generate a uniform decay distribution in momentum vector space using CERN ROOT.

Uniform Decay Distribution Simulation

- Monte Carlo simulation in CERN ROOT
- Random generation of momentum vectors
- Uniform distribution over solid angle
- Visualization in momentum space

The resulting isotropic momentum distribution demonstrates the uniform generation of momentum vectors in three-dimensional momentum space.

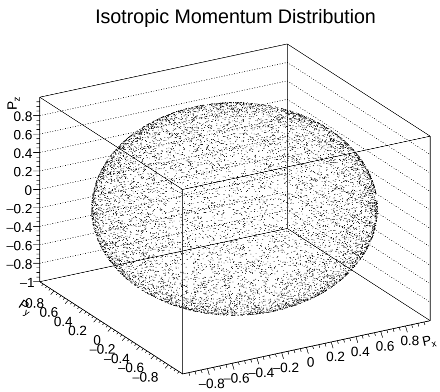


Figure 1: Simulated isotropic momentum distribution generated using CERN ROOT.

Introduction to Hypernuclear Physics

During the internship, I attended lectures by **Dr. Mifuyu Ukai** introducing the physics motivation behind the experiment.

The topics covered included

- Exotic particles
- Hypernuclei
- Hyperon–nucleon interactions
- The K1.8 beamline experiment at J-PARC

These lectures provided the theoretical background required to understand the ongoing experimental work and subsequent data analysis.

Exotic Atom

An exotic atom is formed when an electron is replaced by another negatively charged particle.

Examples

- Muonic atoms
- Pionic atoms
- Kaonic atoms
- Antiprotonic atoms
- Ξ^- atoms

Applications

- Strong interaction
- Nuclear structure

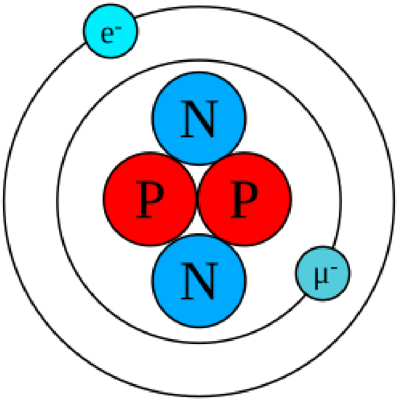


Figure 2: Illustration of an exotic atom.

The K1.8 Beamline Experiment

The K1.8 beamline at J-PARC is designed to produce secondary particle beams for hypernuclear physics experiments.

The beamline enables

- Production of secondary K^- beams
- Momentum analysis using magnetic spectrometers
- Particle identification using dedicated detector systems
- Hypernuclear spectroscopy through the (K^-, K^+) reaction

In the (K^-, K^+) reaction, an incoming K^- beam interacts with a nuclear target to produce a Ξ^- hyperon, which may subsequently be captured by the nucleus to form a Ξ hypernucleus. The small production cross section requires high beam intensity together with efficient particle identification and background suppression.

Experimental Setup of the K1.8 Beamline

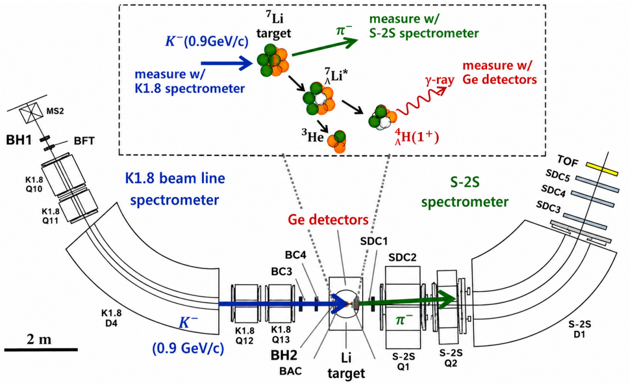


Figure 3: Schematic layout of the K1.8 beamline showing the production and γ-ray spectroscopy of Ξ^- hypernuclei.

Visit to the Hadron Experimental Facility

As part of the internship, I visited the **Hadron Experimental Facility** at J-PARC.

The facility tour, conducted by **Dr. T. Yamamoto**, included an introduction to:

- Beam transport system
- Experimental beamlines
- Detector setup
- Data acquisition system

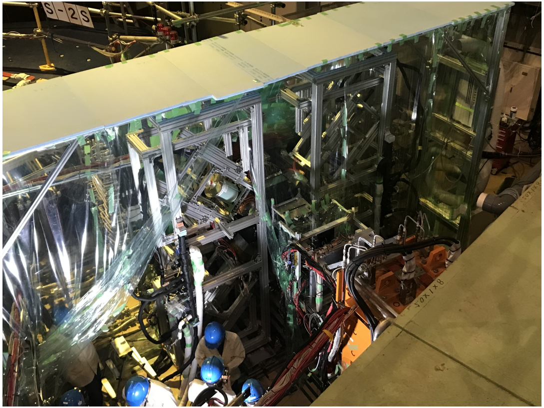


Figure 4: Experimental area of the Hadron Experimental Facility at J-PARC.

Physics Motivation

Measure X-rays emitted from antiprotonic atoms.

An antiproton captured by an atom forms an antiprotonic atom and emits characteristic X-rays as it de-excites. These X-rays provide information on the antiproton–nucleus interaction.

Accurate energy calibration of the Hyperball-X HPGe detector array is therefore essential.

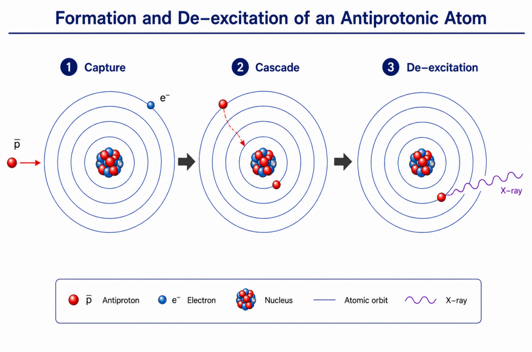


Figure 5: Schematic illustration of X-ray emission during the de-excitation of an antiprotonic atom.

Woods–Saxon Nuclear Density Distribution

One of the first computational tasks was to study the nuclear density distribution of the ^{12}C nucleus using the Woods–Saxon model.

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-c}{z}\right)}$$

where

- ρ_0 : Central nuclear density
- c : Half-density radius
- z : Surface diffuseness parameter

The density distribution was implemented and visualized using CERN ROOT.

Simulated Nuclear Density

Simulation

- Carbon-12 nucleus
- Woods–Saxon model
- Numerical implementation in ROOT
- Density calculated as a function of radius

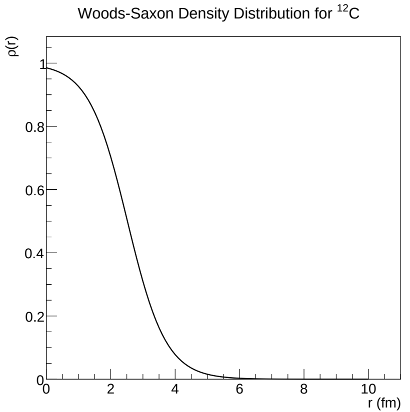


Figure 6: Woods–Saxon nuclear density distribution of the ^{12}C nucleus.

Hydrogen-like Exotic Atoms

The radial wavefunction of a hydrogen-like exotic atom is given by

$$\psi(r) \propto r^{n-1} \exp\left(-\frac{r}{na_0}\right)$$

where

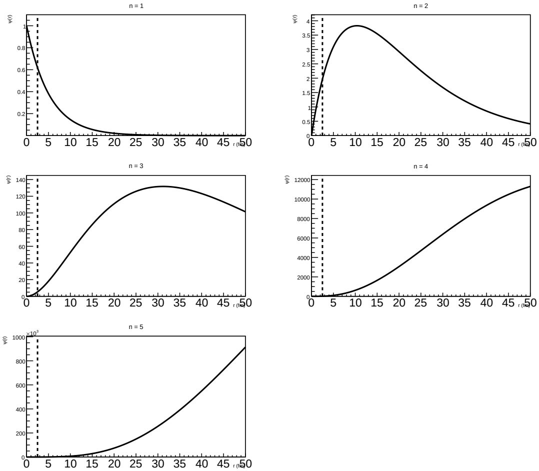
- n : Principal quantum number
- a_0 : Effective Bohr radius
- r : Distance from the nucleus

The wavefunctions were calculated and visualized for several quantum states using CERN ROOT.

Radial Wavefunctions

The simulations show that

- Higher quantum numbers correspond to larger orbital radii.
- The probability distribution shifts away from the nucleus.
- Different exotic particles produce different orbital sizes due to their reduced masses.



Calculated Orbital Radii and Binding Energies

Using the hydrogen-like model, orbital radii and binding energies were calculated for

- Antiprotonic Carbon Atoms
- Ξ^- Carbon Atoms

The calculations demonstrate the influence of reduced mass on atomic structure.

Binding Energy (B_e) for Ξ^- and $\overline{p}$

Ξ^- (Xi minus)				$\overline{p}$ (Antiproton)			
n	r_n (fm)	E_n (eV)	E_n (keV)	n	r_n (fm)	E_n (eV)	E_n (keV)
1	3.81	−1132095.15	−1132.09515	1	5.2	−829338.48	−829.33848
2	15.25	−283023.79	−283.02379	2	20.8	−207334.62	−207.33462
3	34.31	−125788.35	−125.78835	3	46.8	−92148.72	−92.14872
4	61.00	−76755.95	−76.75595	4	83.3	−51833.66	−51.83366
5	95.31	−45283.81	−45.28381	5	130.1	−33173.54	−33.17354
6	137.24	−31447.09	−31.44709	6	187.3	−23037.18	−23.03718

r_n : Radial distance (fm)

E_n (eV): Binding Energy in electron volts

HPGe Energy Calibration

Purpose

Establish the energy calibration procedure for a representative HPGe detector using reference γ-ray sources.

Calibration Procedure

1. Read detector data from ROOT files.
2. Construct ADC histograms.
3. Fit reference photopeaks with Gaussian functions.
4. Determine photopeak centres.
5. Match ADC channels to known γ-ray energies.

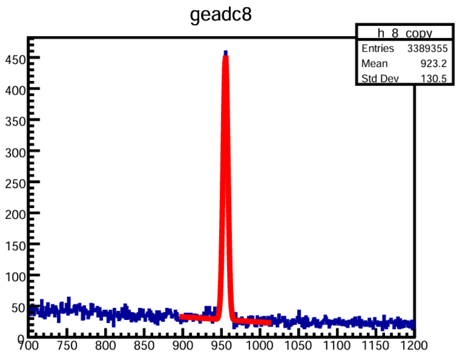


Figure 7: Gaussian fit to a representative γ-ray photopeak for energy calibration.

Calibrated Energy Spectrum

The photopeak centres obtained from the Gaussian fits were matched with reference γ-ray energies to establish the energy calibration relation for a representative detector.

$$E = A \times ADC + B$$

The above calibration relation was then applied to convert the ADC spectrum into a calibrated energy spectrum.

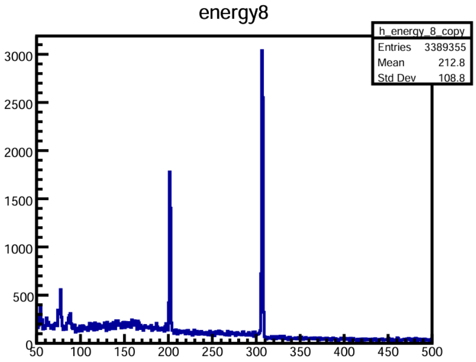


Figure 8: Calibrated γ-ray energy spectrum of a representative HPGe detector.

Development of the Calibration Script

Objective

Automate the energy calibration procedure for multiple detector channels.

Implementation

- Developed a CERN ROOT script with **Mr. Yuning Hong**.
- Automated the calibration workflow for all 16 detector channels.
- Merged the calibrated spectra from all detector segments into a single spectrum for further analysis.

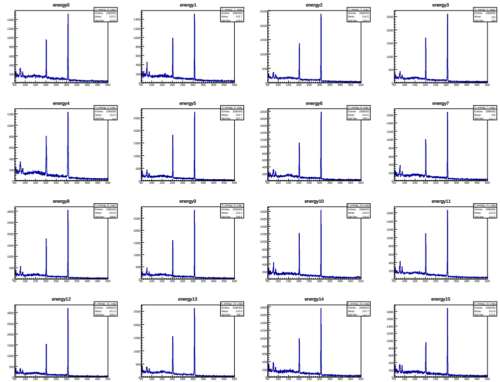


Figure 9: Calibrated energy spectra obtained for all 16 detector channels.

Current Progress: Counter Calibration and Time-of-Flight Analysis

Current Work

- Calibrating scintillation counter signals for the beamline detector system.
- Determining peak centres for each detector segment.
- Extracting calibration parameters for subsequent analysis.
- Preparing calibrated data for Time-of-Flight (TOF) measurements.

Objective

The calibrated counter data will be used to determine particle time-of-flight, enabling particle identification in the experimental analysis.

Counter calibration is currently in progress.

References

- W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, 2nd Edition, Springer (1994).
- R. Brun and F. Rademakers, *ROOT – An Object-Oriented Data Analysis Framework*, Nucl. Instrum. Methods Phys. Res. A **389**, 81–86 (1997).
- Lecture material by Dr. Kyoichiro Ozawa, KEK–J-PARC Summer Student Program (2026).
- Lecture material by Dr. Mifuyu Ukai, KEK–J-PARC Summer Student Program (2026).

Why Study the Antiproton–Nucleus Interaction?

- Antiprotons are ideal probes for studying nuclear matter because they interact through both the electromagnetic and strong interactions.
- After being captured by an atom, an antiproton forms an antiprotonic atom and cascades to lower atomic states.
- Near the nucleus, the strong interaction modifies the lowest atomic energy levels.
- These effects can be observed through precise measurements of the emitted X-rays.

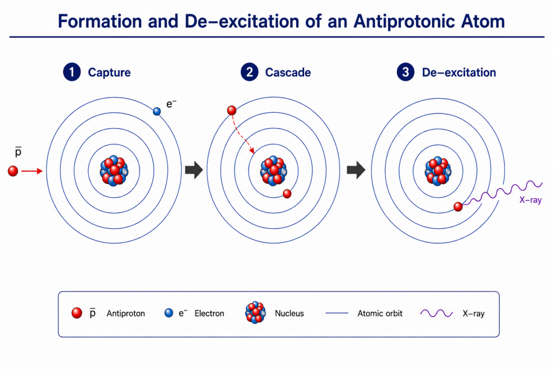


Figure 10: Formation and de-excitation of an antiprotonic atom.

Physics Information from Antiprotonic X-rays

- The emitted X-rays correspond to transitions between atomic energy levels.
- Strong interaction between the antiproton and the nucleus shifts the lowest atomic energy levels.
- The widths of the X-ray transitions are related to the absorption of the antiproton by the nucleus.
- Precise X-ray spectroscopy provides valuable information on the antiproton–nucleus interaction and serves as a benchmark for theoretical calculations.

Hyperball-X HPGe Detector Array

- Hyperball-X is a 16-channel high-purity germanium (HPGe) detector array.
- Designed for high-resolution γ-ray and X-ray spectroscopy.
- Used in hypernuclear and exotic atom experiments at the K1.8 beamline of J-PARC.
- High energy resolution enables precise determination of transition energies.

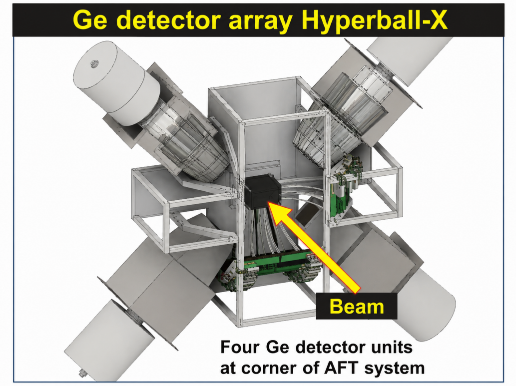


Figure 11: Hyperball-X HPGe detector array used at J-PARC.

Merged Calibrated Spectrum

- Individual calibrated spectra from all 16 HPGe detectors were merged.
- The combined spectrum provides improved counting statistics for analysis.

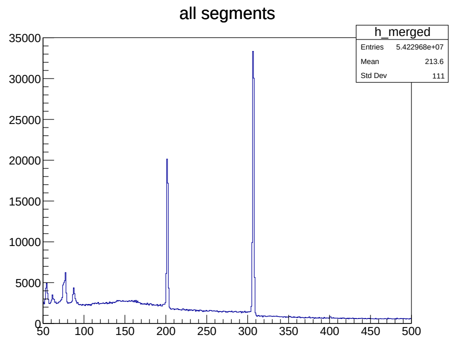


Figure 12: Merged calibrated γ-ray energy spectrum obtained by combining all 16 HPGe detector channels.