

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Beyond the Barrier

Transfer-Induced Fission with Radioactive Ion Beams at
the ISOLDE Solenoidal Spectrometer

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Gothenburg, Sweden 2026

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THE ISOLDE SOLENOIDAL SPECTROMETER
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Cover: Charge distribution of fission fragments detected in the silicon $\Delta E - E$ telescope. Each peak corresponds to a different element, identified by its nuclear charge Z .

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Abstract

The height of the fission barrier is a nuclear property that governs how readily a nucleus splits: it determines spontaneous-fission half-lives and fission probabilities, hence how likely fission is compared to other decay modes. In the astrophysical *r*-process, responsible for the synthesis of the heaviest elements found in Nature, successive neutron captures and β^- decays drive nuclei towards ever larger masses and charges until they become fissile. Fission then splits them into two lighter nuclei, which might resume capturing neutrons and participate in the *r*-process again.

The fission barrier of *r*-process nuclei determines at which mass and nuclear charge fission starts to limit nucleosynthesis. Relevant nuclei are, however, inaccessible to conventional fission measurements, which require the fissioning species as a target. Extending fission studies towards the neutron-rich region therefore needs a different experimental strategy. This thesis presents a novel approach to determine fission barriers in inverse kinematics.

Heavy radioactive ion beams provided by the ISOLDE facility at CERN impinge on a deuterated plastic target; the (d, p) reaction populates states in the fissioning nucleus above the barrier, and the barrier height is extracted from the fission probability measured as a function of excitation energy. Performing the measurement inside a solenoidal spectrometer optimises the excitation-energy resolution, mitigating the kinematic compression and kinematic shift that limit other inverse-kinematics measurements. Protons, fission fragments and γ radiation are detected in coincidence by detectors mounted inside the 2 T field of a former MRI magnet. Commissioned with a ^{22}Ne beam, the approach was then applied to a ^{232}U beam. The reported results provide the first measurement of the $^{232}\text{U}(\text{d}, \text{pf})$ reaction, with fission fragments resolved in charge and a possible indication of the ^{233}U barrier in the reconstructed excitation-energy spectrum.

Keywords: Radioactive Beams, Fission, r-process, Heavy Elements, Actinides, Inverse Kinematics, CERN, ISOLDE, ISS.

Statement of contributions

The work presented in this thesis is part of a collaborative project, with contributions from other members of the experimental subatomic physics group at Chalmers and the ISS collaboration. The goal of this thesis project was to develop a method that allows for the measurement of the fission barrier height of short-lived isotopes.

The author had no prior experience with such experiments when joining this work and collaborated closely with another PhD student within the group, making it a valuable learning experience for both.

To gain familiarity with the ISOLDE facility environment, the author participated in several experiments (IS659 and IS690) at the ISOLDE Decay Station (IDS) and the Scattering Experiments Chamber (SEC). To gain expertise with the ISS setup, the author also took part in multiple ISS experiments (IS742, IS686, IS587, IS727, IS677, IS708), contributing to shifts, online and near-line data analysis, and preparation. To date, one of those resulted in a publication [1], while data from the others are still being analyzed. To broaden her experimental expertise, the author participated in fusion-fission experiments at INFN Legnaro using the AGATA–PRISMA setup (experiment 22.23) and at GANIL using the VAMOS spectrometer (experiment E866_22). The data analysis of these experiments is ongoing.

The central contribution of the author to the research described in this thesis was work enabling experiment IS739, performed by the ISS collaboration. She held primary responsibilities across simulations, commissioning, and data analysis, as detailed below.

- **Primary simulation lead (pre- and post-experiment).** Served as the lead person for all simulations throughout the project. Pre-experiment simulations drove the optimization of the detector geometry (positioning, distances, configurations), as well as the choice of detector types. Post-experiment simulations underpin the interpretation of the data and the characterization of detector response. The simulations can be found throughout the thesis, in particular in Chapters 3, 6, 7 and 9. Moreover, more extensive simulations in preparation of the experiment proposal [2] can be found in Chapter 5 of her licentiate thesis [3].
- **Physics case identification via GEF (GEneral description of Fission observables code) modelling.** Performed extensive GEF model calculations to screen candidate nuclei for fission barrier measurements, identifying ^{230}Ac as the optimal first candidate for the proposal, as detailed in Chapter 7. Assessed the required reaction and beam rates, providing the scientific justification for the experiment. The procedure used to derive the beam rate requirements is described in Appendix A. Served as one out of three spokespersons for the experiment IS739.

- **Mechanical installation, commissioning, and DAQ testing.** Worked on the physical installation of the experimental setup inside the solenoidal spectrometer and on the testing and optimization of the digital data acquisition system, described in detail in Chapter 4. Ran in-beam commissioning of the setup and used the collected data to validate the detector response in preparation for IS739, as illustrated in Chapter 6.
- **Lead person for the analysis of all detectors downstream of the target.** Responsible for the calibration and characterization of the downstream detector systems, including the fission fragment detectors and the luminosity monitor detailed in Chapter 8. Developed a complete end-to-end analysis pipeline for extracting fission data. Preliminary results of the analysis are presented in Chapter 9.

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Leaving one's country and family is never easy, but I have been fortunate to meet wonderful people along the way.

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It has not been an easy journey, but I am convinced that sharing the joys and sorrows of this PhD with my fellow PhD student Anna Kawęcka made it easier. Anna, I wish you all the best for your future endeavours, and I am glad I was able to share this experience with you.

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I would like to acknowledge the many students who contributed to this project, with particular appreciation for Alice Svärðström and Björn Johansson for their hard work and help in the preparation and data-taking of experiment IS739. A special thank you goes to Paolo Vinai for our conversations and for the advice he so generously shared along the way.

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Behind an experiment lies the work not of one person but of many. I would like to thank the entire ISS collaboration for making experiment IS739 possible, through their local support and their expertise with solenoidal spectrometers. In particular, thank you to Liam Gaffney and Patrick MacGregor, whose software and on-site support were essential to carrying out the experiment. I am also grateful to Ben Kay for his help with the bonding of the position-sensitive silicon detectors of the luminosity monitor. I would also like to thank the CDA Linux support team at Chalmers, and Dr Helmut Weick for our discussions and his insight on SRIM.

I would like to honour the memory of Mauro Bruno, my supervisor during my studies in Bologna, and to thank him for introducing me to the world of nuclear physics. Without him, I would most likely never have taken this path.

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Living abroad is strange. It is as if you were living two lives. Every time you return to your country you expect time to have stood still, and instead you realise how many things have changed. But if there is one thing that has not changed, it is the support I have received from my family. My parents have always let me go where my dreams took me, even when it meant watching me leave, and their love has reached me across every kilometre between us. I am far away, but my roots run very deep, and everything I have achieved carries something of them. Mamma e Papà, I hope I can make you proud. I love you, always.

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Maria Vittoria
Göteborg, August 2026

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“Felix qui potuit rerum cognoscere causas.”

Blessed is the one who has learned the causes of things.

– Lucretius, *De rerum natura*, II, 490

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List of Acronyms

μTCA	Micro Telecommunications Computing Architecture
ADC	Analogue-to-Digital Converter
AGATA	Advanced Gamma Tracking Array
AGB	Asymptotic Giant Branch
ALADIN	A Large Dipole Magnet
ANL	Argonne National Laboratory
ASIC	Application-Specific Integrated Circuit
CAD	Computer-Aided Design
CALIFA	Calorimeter for the In-Flight detection of γ -rays and light charged pArticles
CERN	European Organization for Nuclear Research
CFD	Constant Fraction Discriminator
CM	Center-of-Mass frame
CMS	Compact Muon Solenoid
CN	Compound Nucleus
CNO	Carbon-Oxygen-Nitrogen
CS	Compact Symmetric channel
CSA	Charge-Sensitive Amplifier
CST	Clock-Sync-Trigger
DAC	Digital-to-Analogue Converter
DAQ	Data Acquisition
DFT	Density Functional Theory
DPP	Digital Pulse Processing
DSSDs	Double-Sided Silicon Detectors
DSSSDs	Double-Sided Silicon-Strip Detectors
DWBA	Distorted-Wave Born Approximation
EBIS	Electron Beam Ion Source

EBYE event-by-event
ECRIS Electron Cyclotron Resonance Ion Source
ELUM on-axis Luminosity Monitor
FFDM Fission Fragment Mass Distributions
FMC FPGA Mezzanine Card
FPGA Field-Programmable Gate Array
FRIB Facility for Rare Isotope Beams
FWHM Full Width Half Maximum
GANIL Grand Accélérateur National d'Ions Lourds
GCM Generator Coordinate Method
GEF General description of Fission observables
GLAD GSI Large Acceptance Dipole
GPS General Purpose Separator
GSI GSI Helmholtzzentrum für Schwerionenforschung
HELIOS Helical Orbit Spectrometer
HFB Hartree–Fock–Bogoliubov
HIE High Intensity and Energy
HRS High-Resolution Separator
IDS ISOLDE Decay Station
IGISOL Ion Guide Isotope Separator On-Line
IHS Interdigital H-type Structure
INFN Istituto Nazionale di Fisica Nucleare
ISOL Isotope Separation On-Line
ISOLDE Isotope Separator On-Line DEvice
ISS ISOLDE Solenoidal Spectrometer
IYR Isomeric Yield Ratio
JYFLTRAP Jyväskylä Penning trap
LAB Laboratory frame
LDM Liquid Drop Model
LIGO Laser Interferometer Gravitational-Wave Observatory
LINAC Linear Accelerator
LNL Laboratori Nazionali di Legnaro
LUME Luminosity Monitor
MNT Multi–Nucleon Transfer
MRI Magnetic Resonance Imaging

MUX Multiplexer
MVLC Mesytec VME/VXS USB3 Link Controller
MWPCs Multi-Wire Proportional Chambers
NIM Nuclear Instrumentation Module
PCB Printed Circuit Board
PES Potential Energy Surface
PHC Pulse-Height Correction
PRISMA PRISMA magnetic spectrometer
PSB Proton Synchrotron Booster
PSD Pulse-Shape Discrimination
R³B Reactions with Relativistic Radioactive Beams
REX Radioactive beam EXperiment
RF Radio Frequency
RFQ Radio Frequency Quadrupole
RILIS Resonance Ionization Laser Ion Source
S1 Standard I channel
S2 Standard II channel
S3 Standard III channel
SA Super-Asymmetric channel
SCP Single Channel Processing
SEC Scattering Experiments Chamber
SF Spontaneous Fission
SiPM Silicon Photo-Multiplier
SL Super-Long channel
SOFIA Studies of Fission with Aladin
SOLARIS Solenoid Spectrometer Apparatus for Reaction Studies
TAC Time-to-Amplitude Converter
TDC Time-to-Digital Converter
TDGCM Time-Dependent GCM
TDHFB Time-Dependent HFB
TKE Total Kinetic Energy
TMP Turbo-Molecular Pump
TRIDI Trigger and Timing Distribution
UHV Ultra High Vacuum
VAMOS Variable Mode Spectrometer
VME Versa Module Europa
VULOM VME Universal Logic Module
WKB Wentzel-Kramers-Brillouin
ZD Zero Degree

Chapter 1

Physics motivation

LOOKING at the periodic table, it is possible to wonder about the origin of the elements. Hydrogen and helium isotopes were forged during primordial nucleosynthesis in the first moments after the Big Bang, along with a small fraction of lithium and beryllium. The rapid cooling and expansion of the early Universe, however, meant that within just a few minutes temperatures and pressures fell below the threshold required to ignite the fusion of heavier elements, halting nucleosynthesis before it could proceed further. While lithium and beryllium were partially synthesized during Big Bang nucleosynthesis, the bulk of these elements, along with boron, originates from cosmic-ray spallation, in which energetic particles collide with heavier nuclei in the interstellar medium. Heavier elements up to iron are synthesised through stellar nucleosynthesis, i.e. well after stars formed. Beyond iron, charged-particle fusion is no longer energetically favourable, and heavier elements are instead built up predominantly by neutron capture. A large fraction of the nuclei between iron and lead are produced by the slow neutron-capture process (*s-process*), which operates at modest neutron densities in the late evolutionary stages of low- and intermediate-mass stars. The heaviest elements in the periodic table, such as gold, uranium, and other transuranic nuclei, originate in some of the most extreme astrophysical environments, including neutron-star mergers (Figure 1.1), where an intense flux of neutrons drives the rapid neutron-capture process, known as the *r-process*. Several further processes contribute to the observed abundances at a lower level, among them the *p*-process, the νp -process and the intermediate neutron-capture (*i*-)process; these are not discussed further here, while the *s*- and *r*-processes are treated in more detail in Section 1.2.1.

As illustrated schematically in Figures 1.2 and 1.3, the *r*-process proceeds through rapid neutron captures on seed nuclei, driving the nucleosynthesis towards progressively heavier, neutron-rich nuclei far from the valley of stability. Competition between neutron capture and β^- decay governs the path of nu-

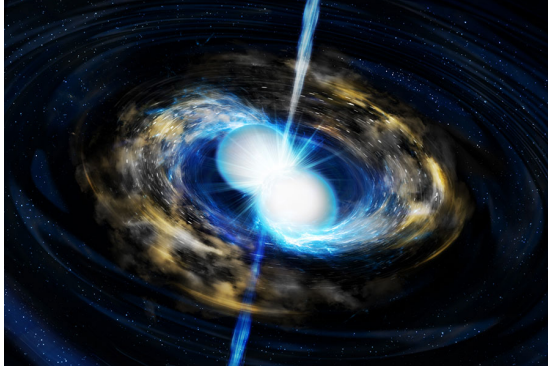


Figure 1.1: Artistic view of a neutron star merger [4]. Tohoku University[©].

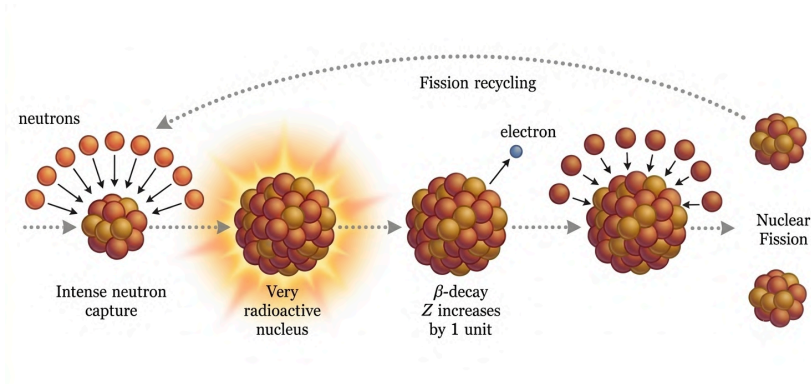


Figure 1.2: Schematic diagram illustrating the rapid neutron-capture process (r-process) and the subsequent recycling of the fission fragments. During the r-process, seed nuclei capture neutrons, moving through the neutron-rich region of the nuclear chart. Once isotopes with short β -decay half-lives are formed, β -decay competes with neutron capture, thereby creating isotopes with increasing proton number. Eventually, as unstable nuclei are produced, they might undergo fission, producing two fission fragments. These fragments can further capture neutrons, contributing to material recycling and continuing the r-process. This process is critical in synthesizing heavy elements beyond iron in explosive astrophysical environments such as neutron star mergers.

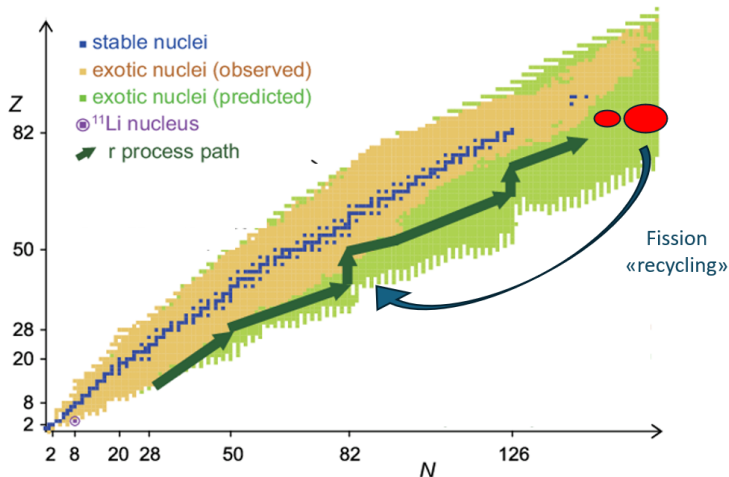


Figure 1.3: Nuclear fission limits the mass of nuclei that are produced in the r-process. The fission fragments will again undergo neutron capture and β -decay, thereby contributing once more to the r-process. Figure adapted from Ref. [5].

cleosynthesis through the nuclear chart, enabling the synthesis of nuclei with increasing mass and charge. Many of the isotopes involved have never been synthesized in the laboratory, and their nuclear properties remain experimentally unconstrained.

As the r-process proceeds toward heavier nuclei, fission becomes an increasingly important de-excitation channel, imposing an upper limit on the mass of nuclei that can be produced. The resulting fission fragments re-enter the r-process as seed nuclei, where they may undergo further neutron captures and decays, a process known as fission recycling and illustrated in Figure 1.3. This process is still not well understood and raises two key questions: Where does the r-process path ultimately terminate? How probable is fission for the neutron-rich nuclei that populate the path?

A key quantity governing this process is the fission barrier height — the excitation energy a nucleus must overcome to fission. Figure 1.4 shows a measurement of this quantity for ^{239}U , obtained at Argonne National Laboratory (ANL) [6]. Constraining fission barriers for neutron-rich nuclei across the r-process path is essential to understanding both the termination point of the process and the extent of fission recycling, yet such data remain largely unavailable. The main goal of this work is to design, develop, and implement an experimental approach for investigating transfer-induced fission of neutron-rich nuclei, contributing to the systematic characterisation of fission properties in

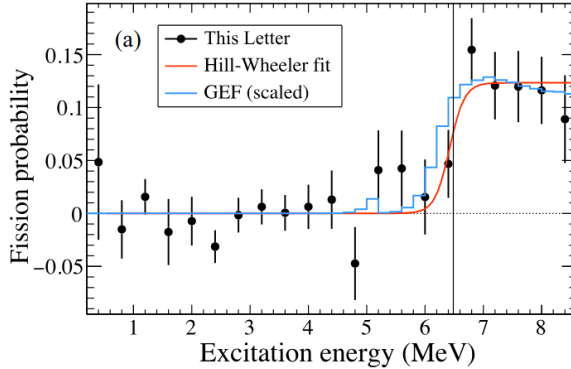


Figure 1.4: Experimental fission probability of ^{239}U measured with the HELIOS solenoidal spectrometer [7] compared with predictions from the semi-empirical GEF model [8] and an empirical Hill–Wheeler fit [9]. The vertical line marks the established fission barrier height. Figure adapted from Ref. [10].

regions of the nuclear chart relevant to the r-process. The following sections expand on the astrophysical and nuclear physics context motivating this work.

1.1 The early Universe

Throughout history, civilizations and cultures have been fascinated by the origin and nature of the Universe. Today, the most widely accepted theory explaining its beginning is the Big Bang theory, which argues that the Universe began expanding from an initially extremely dense and hot state.

In the initial moments following the Big Bang, after a brief period of rapid expansion known as *cosmic inflation*, the Universe existed in a state of matter known as *quark-gluon plasma*. In this extreme state, quarks and gluons, the fundamental particles that later compose nucleons, were not confined to colorless states and could move freely rather than being bound within composite particles. It was only as the Universe cooled after this phase that bound states of quarks, especially neutrons and protons, were formed. This period was characterized by a rapid expansion and cooling of the Universe, which facilitated the combination of quarks and gluons into these particles.

As the Universe continued to cool, neutrons and protons combined to form nuclei of deuterium, an isotope of hydrogen. Some of these deuterium nuclei subsequently fused to form helium. Further nuclear reactions involving protons, neutrons, and various isotopes of helium led to the production of lithium and beryllium. These primordial elements were not evenly spread throughout the Universe. Cooler regions of space exhibited clumpier distributions, with denser

clouds of gas. As these clumps accumulated more mass, gravity began to attract additional matter. Growing denser and more compact, the cores of these clumps became hotter, reaching temperatures conducive to initiating nuclear fusion, and leading to the formation of the earliest stars. Simultaneously, these clumps merged into larger structures called proto-galaxies, which would evolve through further mergers and interactions into the galaxies we observe today.

1.2 Heavy-element nucleosynthesis

Stellar evolution and the deaths of massive stars have since been responsible for the production of most of the elements observed in the Universe today. Currently, around 3000 nuclides have been observed, of which only 288 are stable [11]. According to theoretical estimates, thousands of nuclides may still be undiscovered, many of which are extremely unstable and currently impossible to produce in the laboratory. Figure 1.5 illustrates the periodic table of elements as we know it today, highlighting the numerous processes involved in the creation of the elements found in the Solar System.

Elements heavier than helium are predominantly created through nuclear reactions occurring in stars and stellar explosions, a process collectively known as *stellar nucleosynthesis* [12]. During the formation and evolution of a star, gravitational contraction heats the stellar core until temperatures and pressures become sufficiently high for nuclear fusion to ignite.

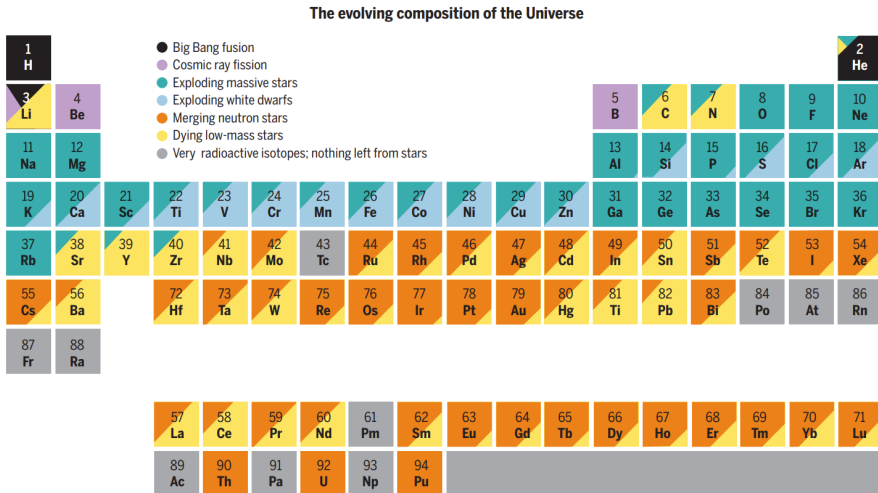


Figure 1.5: Color-coded periodic table illustrating the nucleosynthesis sources of elements found in the Solar System. Figure from Ref. [12].

The process begins with the fusion of hydrogen into helium¹. As hydrogen in the core is exhausted, the core contracts and heats further, allowing helium to fuse into heavier elements such as carbon and oxygen via the triple- α reaction². In massive stars, further fusion stages produce neon, magnesium, and silicon, culminating in the formation of an iron core. Once nuclear burning can no longer provide sufficient pressure support, the core becomes unstable and undergoes gravitational collapse, leading to a core-collapse supernova or the formation of a compact remnant.

To understand why silicon burning that results in the formation of iron and nickel marks the end of fusion reactions in stars, it is useful to consider how the binding energy per nucleon evolves with mass number A . As shown in Figure 1.6, this quantity exhibits a local maximum at ${}^4\text{He}$ and an absolute maximum at ${}^{62}\text{Ni}$, the most stable nucleus known. This has a fundamental consequence: exoenergetic reactions correspond to fusion for nuclei lighter than ${}^{62}\text{Ni}$ and to fission for heavier ones. In practice, however, ${}^{62}\text{Ni}$ is not significantly populated during silicon burning; instead, ${}^{56}\text{Fe}$ represents the effective endpoint of stellar fusion. Each successive fusion stage up to ${}^{56}\text{Fe}$ releases binding energy that counteracts gravitational collapse and sustains the star.

Once a star exhausts its nuclear fuel, it can no longer release sufficient energy to counteract gravitational collapse. In the most massive stars, the core contracts rapidly, density increases dramatically, and the nucleon-nucleon repulsion eventually causes the infalling material to rebound, launching an expanding shock wave. This results in a violent explosion known as a *core-collapse supernova*. These events enrich the interstellar medium with most of the material that constitutes the Solar System today. Nevertheless, the origin of elements heavier than iron and nickel, also present in the Solar System, remains to be addressed.

1.2.1 The s- and r-processes

As early as 1957, the pioneering works of E. M. Burbidge, G. R. Burbidge, Fowler, and Hoyle suggested that the vast majority of elements heavier than iron and nickel are produced via neutron-capture reactions and β^- -decay [14, 15]. Since neutrons carry no electric charge and are unaffected by Coulomb

¹The proton-proton (pp) chains and the Carbon-Oxygen-Nitrogen (CNO) cycles are mechanisms by which stars convert hydrogen into helium. The pp chains are prevalent in lower-mass stars such as the Sun, while the CNO cycles become dominant in hotter, more massive stars. Unlike the pp chains, the CNO cycles are catalytic: carbon, nitrogen, and oxygen isotopes act as catalysts, each consumed in one step and regenerated in another, with the net result being the fusion of four protons into one helium nucleus, two positrons, and two electron neutrinos.

²The triple- α process is a nuclear reaction in which three α particles fuse to form ${}^{12}\text{C}$. Because ${}^8\text{Be}$, formed via $\alpha + \alpha$ fusion, is unbound, the triple- α process requires an additional α capture and is therefore essential for the synthesis of heavier elements. The reaction can be represented as follows: $3 {}^4\text{He} \rightarrow {}^{12}\text{C} + \text{energy}$.

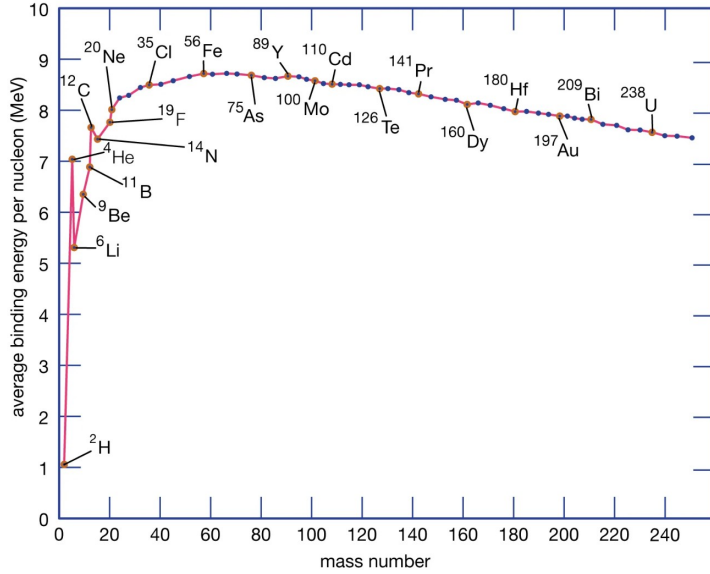


Figure 1.6: Average binding energy per nucleon as a function of the mass number. Figure from Ref. [13].

repulsion, neutron-rich nuclei can form at significantly lower temperatures than those required for charged-particle fusion in stellar cores. However, free neutrons are unstable, with a half-life of approximately 10.2 minutes [16], and, therefore, no reservoir of free neutrons survives on astrophysical timescales, the neutrons required for capture cannot be pre-existing: they must be created or liberated *in situ* by an astrophysical process, at a rate high enough to sustain the capture chain against β^- decay of the neutrons and of the nuclei involved. Such sites capable of producing neutron fluxes must therefore exist. The neutron density they reach determines the nature of the subsequent capture process.

Depending on the intensity of the neutron flux, two distinct processes can be identified: the slow neutron-capture process (*s-process*) and the rapid neutron-capture process (*r-process*).

The *s-process* typically occurs during the late evolutionary stages of Asymptotic Giant Branch (AGB) stars³. Because the neutron flux in these environments is relatively low, the timescale for neutron capture is comparable to that of β^- decay, allowing unstable nuclei to decay before capturing another neutron. Individual captures may be separated by decades, and the overall process unfolds over thousands of years. The synthesised material is eventually dispersed

³AGB stars represent a late stage in the evolution of low- to intermediate-mass stars, with initial masses in the range $0.6\text{--}10 M_{\odot}$.

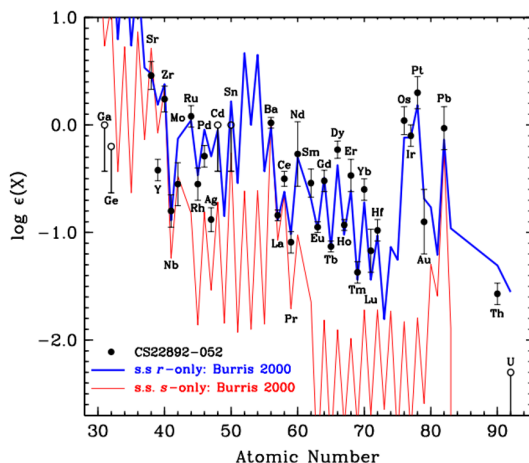


Figure 1.7: Elemental abundances in the metal-poor star CS 22892-052 (black dots) compared with the scaled Solar System r-process (blue) and s-process (red) distributions. Figure from Ref. [17].

into the interstellar medium through slow, dense stellar winds that strip the outer layers of the star, forming a planetary nebula and leaving a white dwarf as the remnant if the progenitor stars lacks the mass to result in a supernova.

The s-process alone, however, is insufficient to account for the observed abundances of heavy elements. Figure 1.7 compares the elemental abundances measured in CS 22892-052, an extremely metal-poor⁴ halo giant with large enhancements of neutron-capture elements, against the abundance distributions predicted by the s- and r-processes. Elements such as gold, platinum, and thorium are clearly underproduced by the s-process alone, pointing to a second, distinct process operating under conditions of far higher neutron flux. In the r-process, the neutron flux has to be so intense that most nuclei capture more than one neutron before they can undergo β^- decay. The entire process unfolds on a timescale of seconds to minutes. As a result, the r-process path shifts far into the neutron-rich region of the nuclear chart, well away from the valley of stability, as illustrated in Figure 1.8. Many nuclei along this path have never been observed in the laboratory, making their properties — masses, decay rates, and reaction cross-sections — largely unconstrained.

Despite the theoretical framework for the r-process having been established over six decades ago, the astrophysical site (or sites) where it could occur remained uncertain for much of that time. Core-collapse supernovae, neutron-star

⁴Metallicity, denoted $[\text{Fe}/\text{H}]$, is the logarithmic iron-to-hydrogen ratio relative to the Sun. Metal-poor stars have $[\text{Fe}/\text{H}] \ll 0$ and are among the oldest objects in the Galaxy.

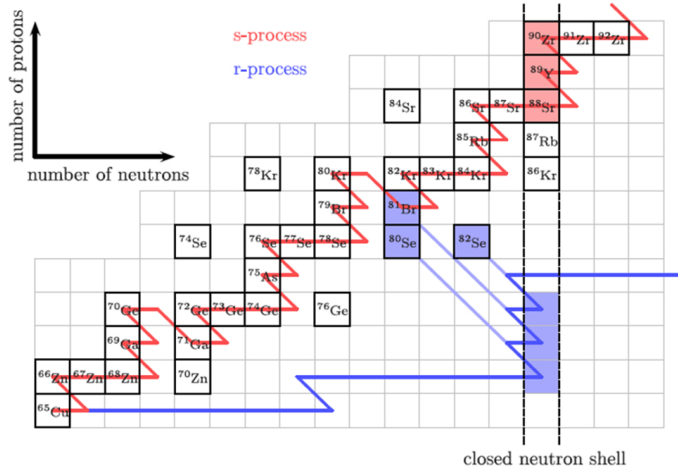


Figure 1.8: Section of the chart of nuclides showing schematic representations of the s-process (red) and r-process (blue) paths. The s-process advances through individual neutron captures followed by β^- decay near the stability line. The r-process proceeds via successive neutron captures deep in the neutron-rich region, with β^- decay becoming dominant once the neutron flux subsides. Figure from Ref. [18].

mergers, and certain binary systems had all been proposed as candidate environments, but definitive observational evidence was lacking [19, 20].

Definitive evidence came in 2017, when the LIGO and Virgo interferometers detected gravitational waves from the neutron-star merger GW170817 [21]. Co-ordinated electromagnetic follow-up observations revealed the associated kilonova⁵ AT2017gfo, in which the spectroscopic signature of strontium ($Z = 38$), an r-process element, was subsequently identified [22]. This observation provided the first direct evidence that neutron-star mergers are sites of r-process nucleosynthesis, and motivates a deeper understanding of the r-process itself, and in particular of the role played by nuclear fission in shaping the final abundance distribution of heavy elements synthesised during the merger.

While compact binary mergers are now considered the dominant contributor to r-process production, a single site cannot reproduce the full solar r-process abundance pattern, and the abundance patterns of the most metal-poor stars indicate that at least one additional site is required. Complementary sources such as magneto-rotational supernovae, collapsars, and neutron star–black hole mergers have been proposed, each expected to contribute to different regions of

⁵A kilonova is a transient event produced by the merger of two neutron stars or a neutron star and a black hole. The extreme conditions of the merger drive rapid neutron capture, synthesising heavy elements that power optical and infrared emission fading over days to weeks. The energy released is typically $\sim 10^3$ times that of a classical nova.

the abundance distribution [23].

1.3 Nuclear fission: an introduction

Nuclear fission is a complex reaction in which a heavy nucleus splits into two fragments of intermediate mass, releasing a substantial amount of energy. The process involves changes in large-scale collective motions of the nucleons, during which the nuclear system evolves from its initial configuration through a highly deformed scission configuration, ultimately separating into two distinct fragments.

This phenomenon was first identified experimentally in the late 1930s, following a sequence of fundamental discoveries in nuclear physics. The detection of the neutron by James Chadwick in 1932 [24] provided a neutral probe capable of penetrating the nucleus without Coulomb repulsion. Building on this, Enrico Fermi recognised the exceptional effectiveness of neutrons in inducing nuclear reactions and pioneered systematic studies of neutron bombardment on heavy elements, including uranium, with the aim of producing transuranic nuclei.

Although neutron irradiation of uranium consistently produced β^- activity, the large number of radioactive products observed or artificially synthesized was incompatible with the prevailing interpretation based on successive neutron capture and decay [25]. This unresolved discrepancy was settled in 1938, when Hahn and Strassmann demonstrated that barium was produced following neutron irradiation of uranium [26], providing direct evidence that the uranium nucleus had split into lighter fragments. The correct physical interpretation was subsequently provided by Lise Meitner and Otto Frisch, who recognised the process as a division of the nucleus into two fragments and introduced the term *fission* [25]. This discovery established fission as a new class of nuclear reactions and paved the way for its theoretical description in terms of collective nuclear dynamics.

1.3.1 The Liquid–Drop Model

One of the first successful models describing the fission process was the Liquid Drop Model (LDM), initially proposed by Lise Meitner and later developed in detail by Niels Bohr and John Archibald Wheeler [27]. Within the LDM, the atomic nucleus is described macroscopically as a drop of an incompressible, uniformly charged nuclear fluid. The stability of the nucleus results from the competition between the surface tension associated with the strong nuclear force, which provides a restoring force against deformation, and the Coulomb repulsion among protons, which tends to drive the system toward fission. The ground state is assumed to be spherical with uniform density, and the nuclear

radius is given by

$$r = r_0 A^{1/3}, \quad (1.1)$$

where A is the mass number and $r_0 = 1.15$ fm is the classical nucleon radius. These assumptions lead directly to the *semi-empirical mass formula* (Weizsäcker, 1935 [28]):

$$B(A, Z) = \underbrace{a_v A}_{\text{volume}} - \underbrace{a_s A^{2/3}}_{\text{surface}} - \underbrace{a_c \frac{Z^2}{A^{1/3}}}_{\text{Coulomb}} - \underbrace{a_a \frac{(A - 2Z)^2}{A}}_{\text{asymmetry}} + \underbrace{\delta(A, Z)}_{\text{pairing}} \quad (1.2)$$

where each term captures a specific physical contribution: the volume term arises from the bulk strong interaction, the surface term accounts for the reduced binding of nucleons at the nuclear surface, the Coulomb term represents proton repulsion, the asymmetry term reflects the energy cost of deviating from equal proton and neutron numbers, and the pairing term accounts for changes in binding energy due to nuclear pairing.

This description can be further generalized to account for more complex or deformed nuclear shapes beyond the simple spherical assumption. The radial position $R(\theta, \varphi)$ of the nuclear surface can be parametrized in terms of spherical harmonics in the (θ, φ) direction:

$$R(\theta, \varphi) = R_0 \left[1 + \sum_{\lambda=0}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta, \varphi) \right] \quad (1.3)$$

where R_0 is the same as in Eq. 1.1.

In the case of axial symmetry, the nuclear shape is expressed in terms of Legendre polynomials P_ℓ , and Eq. 1.3 reduces to:

$$R(\theta) = R_0 \left[1 + \sum_{\ell=0}^{\infty} a_\ell P_\ell(\cos \theta) \right] \quad (1.4)$$

To understand how the nuclear energy evolves with deformation along the path to scission, it is sufficient at this stage to focus on the surface and Coulomb contributions, which explicitly depend on the changing nuclear radius. The volume term, being independent of the nuclear shape, remains constant throughout the fission process. In contrast, surface and Coulomb energies are strongly influenced by deformation: as the nucleus elongates, the surface area increases, resulting in a higher surface energy, while the Coulomb repulsion is progressively reduced due to the increasing average separation between protons, as shown in Figure 1.9.

The surface energy is proportional to the nuclear surface area S :

$$E_S = \sigma S, \quad (1.5)$$

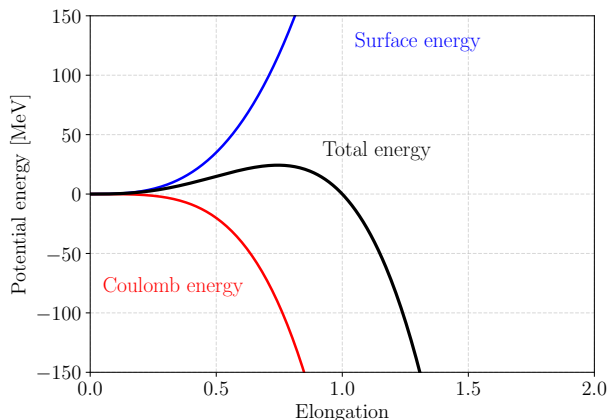


Figure 1.9: Surface and Coulomb energy contributions as a function of nuclear elongation during the fission process. The surface energy increases with deformation, while the Coulomb energy decreases, illustrating the competition between surface tension and electrostatic repulsion governing nuclear fission. The total energy, given by the sum of the two contributions, exhibits a maximum that corresponds to the fission barrier.

where σ is the surface energy coefficient. For a spherical nucleus of radius R_0 , the surface and Coulomb energies are

$$E_S(0) = 4\pi\sigma R_0^2, \quad E_C(0) = \frac{3}{5} \frac{(Ze)^2}{R_0}. \quad (1.6)$$

These energies allow one to define the fissility parameter:

$$x \equiv \frac{E_C(0)}{2E_S(0)} = \frac{3}{40\pi} \frac{e^2}{\sigma R_0^3} \frac{Z^2}{A}, \quad (1.7)$$

where Eq. 1.1 has been used to write $R_0^3 = r_0^3 A$. Inserting $e^2 = 1.44 \text{ MeV fm}$, $r_0 = 1.15 \text{ fm}$ and a surface energy coefficient $\sigma \simeq 1.0 \text{ MeV fm}^{-2}$ gives the familiar numerical form

$$x \simeq \frac{Z^2}{50A}, \quad (1.8)$$

which quantifies the tendency of a nucleus to undergo fission: the larger x , the more unstable the nucleus. The deformation energy relative to the spherical shape is then defined as

$$E_{\text{def}} = E_S + E_C - [E_S(0) + E_C(0)], \quad (1.9)$$

or in dimensionless form as

$$B_{\text{def}} = \frac{E_{\text{def}}}{E_S(0)} = (B_{\text{surf}} - 1) + 2x(B_{\text{Coul}} - 1), \quad (1.10)$$

where B_{surf} and B_{Coul} are the normalized surface and Coulomb energies for the deformed shape. Here, B_{def} corresponds to the difference in binding energy between the deformed nucleus and the spherical nucleus.

A fission barrier arises at small deformations for most known isotopes. This barrier represents the energy that must be overcome for the nucleus to undergo fission. Beyond this point, the potential energy of the nucleus decreases with increasing deformation, rendering fission energetically favorable. The maximum along this deformation path, referred to as the *saddle point*, corresponds to an unstable equilibrium configuration from which any further deformation drives the nucleus toward the *scission point*, where it splits into two fission fragments.

The LDM provides a qualitatively correct picture of fission and accounts for its occurrence as a decay mode of heavy nuclei. However, it fails to reproduce a key experimental observation: fission of actinide nuclei predominantly produces two fragments of different mass. Explaining this asymmetry requires going beyond the purely macroscopic description and incorporating the quantum shell structure of the nucleus. This became possible through the *macroscopic-microscopic* approach, which combines the LDM with nuclear shell corrections.

1.3.2 The Strutinsky Model

To account for quantum effects arising from individual nucleons and their interactions, microscopic shell corrections were incorporated into the description of the fission process employing a method proposed by Strutinsky [29]. Strutinsky postulated that nuclear shell effects are not confined to spherical nuclei but can also be significant in deformed nuclei. Therefore, at a given nuclear deformation, the total energy could be obtained by combining the macroscopic potential energy described by the liquid drop model with the microscopic potential energy arising from shell effects:

$$V_{\text{total}} = V_{\text{macro}}(\text{LDM}) + V_{\text{micro}}(\text{Shells}). \quad (1.11)$$

The microscopic term is evaluated from the single-particle spectrum of a deformed mean-field potential. This is provided by the Nilsson model, which generalises the spherical shell model to an axially deformed harmonic-oscillator potential with spin-orbit and ℓ^2 terms. Deformation breaks the spherical symmetry: each level with total angular momentum j splits into $j + 1/2$ levels, labelled by the projection Ω of the single-particle angular momentum on the symmetry axis. Each level is doubly degenerate in terms of $\pm\Omega$, and the single-particle energies vary with the deformation parameter, some rising and others

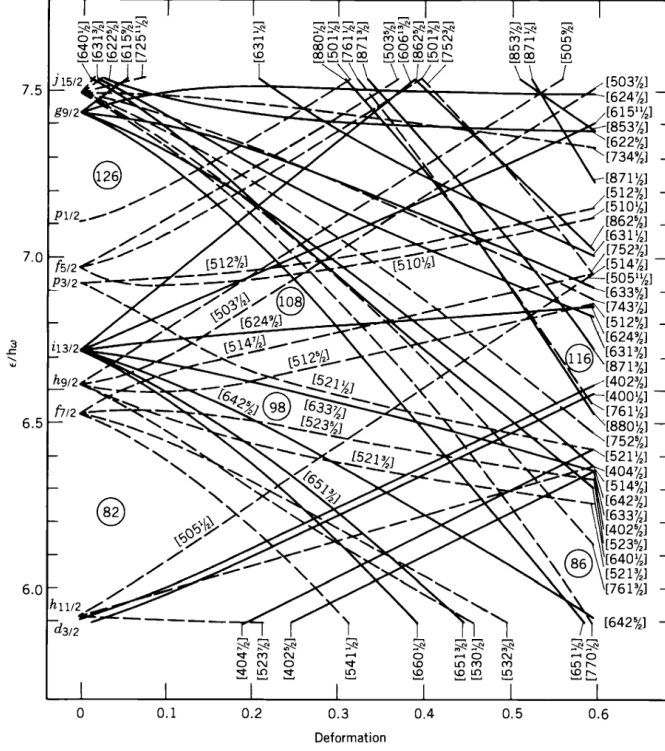


Figure 1.10: Energy levels for neutrons in a prolate-deformed potential. The numbers in brackets label the states; solid lines indicate states with even parity, while dashed lines indicate states with odd parity. Figure from Ref. [30].

falling, as shown in Figure 1.10. The shell correction is then obtained by comparing the sum of the occupied single-particle energies at a given deformation with the same sum evaluated for a smoothed level density, which represents the macroscopic reference already contained in the LDM.

The incorporation of microscopic shell effects into the description of nuclear fission provides a consistent interpretation of several experimental phenomena that cannot be captured by a purely macroscopic approach. Shell-induced modifications of the potential-energy surface can stabilise highly deformed configurations along the fission path. In a number of actinides, this produces a second minimum in the barrier, which allows for the existence of so-called *fission isomers* [29, 31], as illustrated in Figure 1.11, although the depth and even the existence of such a minimum depend on the nucleus. Since the single-particle level structure depends on deformation, the nucleon numbers associated with

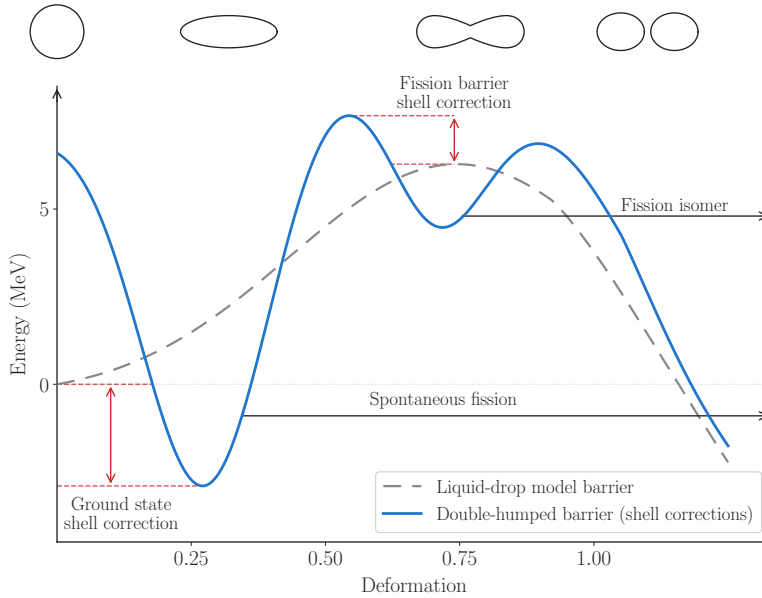


Figure 1.11: Schematic representation of the potential energy of deformation of a fissioning nucleus as a function of deformation. The dashed line shows the single-humped barrier predicted by the Liquid Drop Model, while the solid line represents the double-humped barrier obtained by including Shell Model corrections.

enhanced stability differ from those of spherical shell closures, giving rise to the concept of deformed magic nuclei [32]. These microscopic effects have a direct impact on the mass and charge distributions of the fission fragments, also favoring intermediate energetically preferred configurations along the fission path. As a consequence, shell effects play a key role in explaining the systematic occurrence of asymmetric fission in heavy nuclei [33].

1.3.3 Modern theoretical approaches

The theoretical description of nuclear fission has undergone a profound transformation in recent decades, driven by advances in both many-body nuclear theory and high-performance computing. In this context, it is useful to clarify what is meant by a *microscopic* model. A model is microscopic with respect to a given phenomenon when its degrees of freedom are the constituents of the system on a scale smaller than that of the phenomenon itself; the label is therefore relative to what is being described, not an absolute property of the model. Fission is a rearrangement of a nucleus into two fragments, so a microscopic description of fission is one whose explicit degrees of freedom are the nucleons

and their effective interactions, as in the mean-field methods introduced below. The liquid-drop model, which characterises the nucleus only through bulk quantities such as shape, surface tension and charge distribution, is macroscopic in this sense. Microscopic does not mean parameter-free: the effective interactions entering such models contain coupling constants adjusted to experimental data, so quantitative predictions retain a phenomenological element.

Several theoretical approaches have been developed to describe fission dynamics within such microscopic frameworks, and a central concept underlying many of them is the adiabatic approximation, which assumes that the collective evolution of the nucleus proceeds through a sequence of local ground states, each defined at fixed values of the collective coordinates. Deviations from this picture, referred to as non-adiabatic effects, arise when excited configurations significantly mix with the instantaneous ground state, and their importance depends on the separation of timescales between the collective motion and the intrinsic single-particle dynamics.

The most widely used microscopic method is the nuclear Density Functional Theory (DFT), particularly in its Hartree–Fock–Bogoliubov (HFB) formulation.⁶ This approach enables the computation of the Potential Energy Surface (PES), namely the nuclear energy as a function of selected collective deformation coordinates, whose structure of minima, saddle points and ridges provides key insights into the fission process, allowing one to infer properties such as shape isomers, fission barriers, and fragment distributions [34], as further discussed in Section 1.3.5.

To describe the time evolution of the system, the time-dependent version of DFT, known as Time-Dependent HFB (TDHFB), is used; it conserves energy and provides a good description of one-body observables [35]. In its standard formulation, the system follows a single mean-field trajectory, so quantum fluctuations of the collective degrees of freedom and barrier penetration are generally not accounted for [34]. This is a limitation of the usual implementation rather than of the framework itself, and extensions capable of describing tunnelling have been developed [36, 37]. Collective quantum effects are treated explicitly in beyond-mean-field methods such as the Generator Coordinate Method (GCM) and its time-dependent extension Time-Dependent GCM (TDGCM) [38, 39]. Most fission applications of the TDGCM rely on adiabatic generating states, which restricts the description of energy dissipation from collective to intrinsic degrees of freedom and of non-adiabatic effects near scission, where the collective motion accelerates rapidly, and level crossings become significant [34]. Formulations going beyond this restriction, including collective fluctuations and intrinsic excitations, have nevertheless been developed [40–42].

⁶The Hartree–Fock method is a self-consistent mean-field approach in which each nucleon moves independently in an average potential generated by all other nucleons. The Bogoliubov extension generalizes this framework by incorporating pairing correlations, which are essential for an accurate description of open-shell nuclei.

A crucial role is played by nuclear pairing correlations, which act as a “lubricant” for the fission process: without pairing, the mean-field time evolution is often unable to find a path to scission, and the strength of pairing directly influences the collective inertia and the spontaneous fission half-life [43, 44]. To incorporate dissipative effects, stochastic formalisms such as the Langevin equations are employed, in which the collective dynamics is described as a Brownian motion in a multidimensional deformation space [45]. Hybrid DFT–Langevin approaches, where the PES and the inertia tensor are computed microscopically while the dissipation tensor is treated phenomenologically, have shown good results in reproducing fragment mass and charge distributions [46], although a microscopic justification of the dissipation tensor remains an open challenge [34].

For spontaneous fission, the standard treatment of quantum tunnelling relies on the quasi-classical Wentzel-Kramers-Brillouin (WKB) approximation,⁷ in which the barrier penetration probability is computed along a one-dimensional path in the collective space. Key open challenges include the generalisation to multidimensional tunnelling paths and the development of a unified microscopic theory capable of describing both spontaneous and induced fission on equal footing [34].

Despite significant progress, microscopic fission theory faces important open challenges. Fission barriers of neutron-rich nuclei, directly relevant to r-process nucleosynthesis, remain largely unconstrained experimentally, and theoretical predictions from different models can diverge substantially in this region of the nuclear chart [34]. Providing experimental input to benchmark and constrain these models is therefore a central motivation for the present work.

1.3.4 Fission probability and barrier heights

It is important to highlight the pivotal role of the excitation energy in the behaviour of the fissioning nucleus. As the excitation energy increases, the influence of microscopic shell effects progressively diminishes. At sufficiently high excitation energies, the fine structure induced by shell corrections is gradually washed out, and the nuclear potential energy is increasingly dominated by its macroscopic component. In this regime, the fission process approaches the behaviour predicted by the liquid drop model, and the preference for asymmetric fission associated with shell effects is reduced, leading to an increased probability of symmetric mass splits, as shown in Figure 1.12 where Fission Fragment Mass Distributions (FFDM) from α -induced fission on ^{232}Th have been measured at different excitation energies. This underscores the impor-

⁷The WKB approximation is a semi-classical method for computing the probability of quantum tunnelling through a potential barrier, based on the assumption that the wavelength of the quantum state varies slowly compared to the scale of the potential.

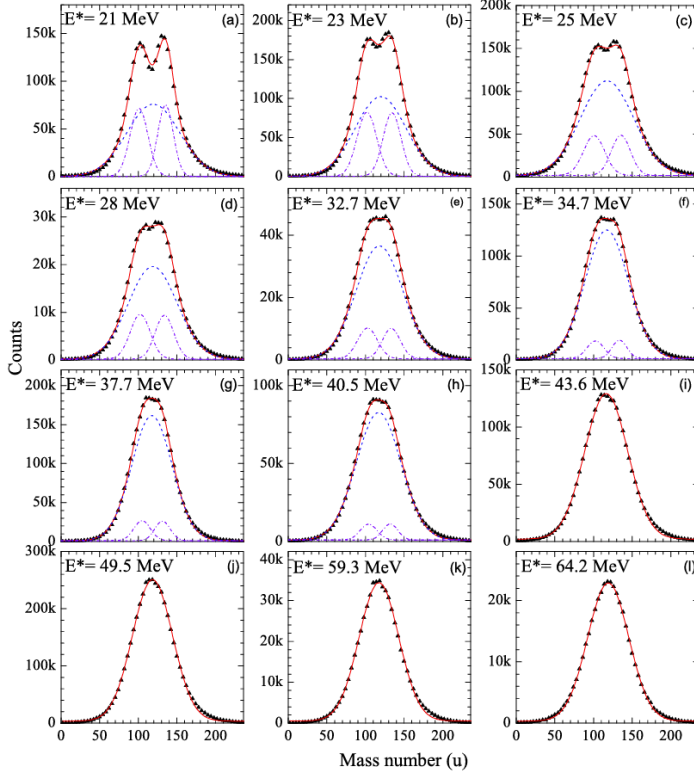


Figure 1.12: Fission fragment mass distributions for α -induced fusion–fission reactions on a ^{232}Th target over a wide excitation-energy range of 21–64 MeV. For excitation energies between $E_x = 21$ and 40.5 MeV, the mass distributions are fitted with three Gaussian components, shown as dashed blue lines for the symmetric contribution and dash-dotted violet lines for the asymmetric contributions. The total fit is indicated by the solid red lines. At higher excitation energies ($E_x \geq 43.6$ MeV), the distributions are best described by a single Gaussian, providing direct evidence that shell effects are washed out at excitation energies of about 40 MeV in ^{236}U . Figure from Ref. [47].

tance of investigating fission over a wide range of excitation energies in order to disentangle macroscopic and microscopic contributions to the fission dynamics.

As already mentioned, the fission process is strongly reduced for most nuclei by the presence of a high fission barrier. Fission can occur through two main mechanisms [48]. The first is Spontaneous Fission (SF), in which the nucleus undergoes fission via quantum tunnelling from its ground state, in a manner analogous to the tunnelling process responsible for α decay. For nuclei relevant to the r-process, spontaneous fission is not expected to play a dominant role, as the typical time scales of the r-process are much shorter than the corresponding spontaneous fission half-lives [23].

The second mechanism is *induced fission*, where an incident particle interacts with a target nucleus, leading to the formation of an excited compound system. This can be achieved through different reaction mechanisms, such as neutron-induced fission, direct reactions, spallation or fragmentation, Coulomb excitation, or fusion. In the case of complete fusion, the projectile merges entirely with the target nucleus, forming a Compound Nucleus (CN). If the excitation energy of the CN exceeds the height of the fission barrier, fission becomes a competitive de-excitation channel, often accompanied by the emission of one or more neutrons. The sequence of events following the formation of the compound nucleus is schematically illustrated in Figure 1.13. In the simplest case, referred to as *first-chance fission*, the compound nucleus proceeds directly to scission without prior neutron emission. If instead the excitation energy is sufficient, the compound nucleus may first emit one or more *pre-scission neutrons* before undergoing fission, a process known as *second-chance fission* (and higher orders thereof [49]), as illustrated in Figure 1.14. Following scission, the two primary fission fragments, still in highly excited states, de-excite by emitting *prompt neutrons* and *prompt γ rays*. These are to be distinguished from *delayed neutrons*, emitted on much longer timescales (milliseconds to minutes) following β^- decay of the neutron-rich fragments.

Typically, stable or long-lived light projectiles such as electrons, protons, neutrons, or light ions are used to induce fission in heavy nuclei. Fission induced by heavy ions results in compound nuclei formed with relatively high excitation energy, since the Coulomb barrier between the colliding nuclei suppresses the formation of low-excitation fissioning systems.

1.3.5 Potential Energy Surface

The fission process can be described in terms of the nuclear Potential Energy Surface (PES), first introduced by Bohr and Wheeler [9]. In this approach, the total energy of the nucleus is expressed as a function of a set of collective deformation parameters. These coordinates typically account for the overall elongation of the system and the mass asymmetry between the emerging fragments, and the formation of a neck connecting them. Although a full description

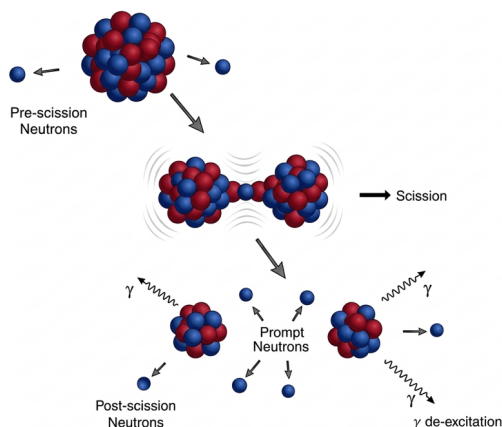
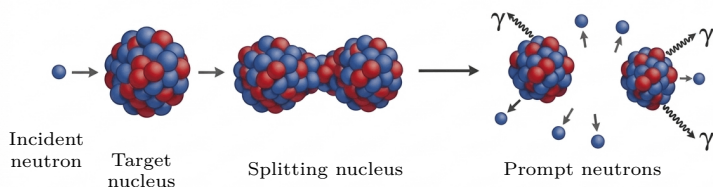


Figure 1.13: Schematic overview of the fission process. Prior to scission, pre-scission neutrons may be emitted as the compound nucleus evolves toward the scission configuration. Following scission, the primary fragments de-excite by emitting prompt neutrons and γ rays.

First-chance fission



Second-chance fission

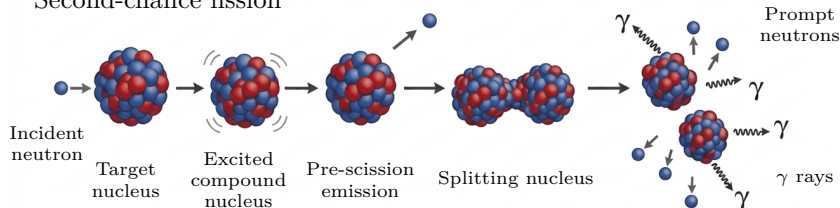


Figure 1.14: Schematic comparison of first-chance (top) and second-chance (bottom) fission. In single-chance fission, the excited compound nucleus proceeds directly to scission. In second-chance fission, the compound nucleus first de-excites via pre-scission neutron emission before undergoing fission, with both fragments subsequently emitting prompt neutrons and γ rays.

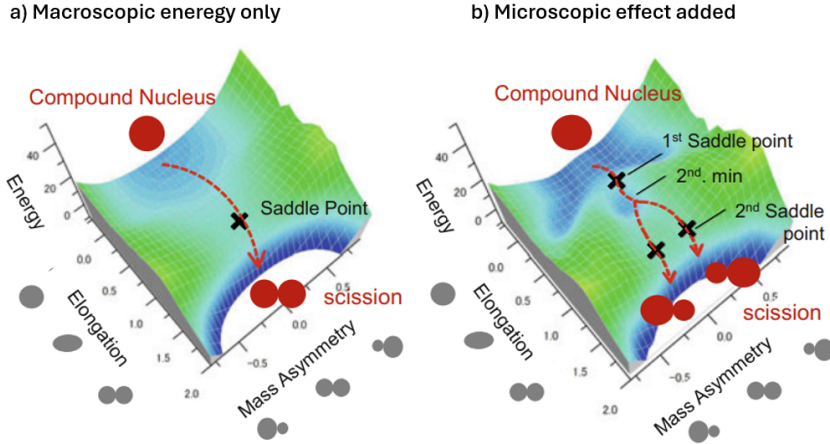


Figure 1.15: Potential-energy surface as a function of elongation and fission-fragment mass asymmetry of the ^{240}U nucleus according to the macroscopic liquid-drop (a) and the macroscopic-microscopic (b) models. At each point of the plane, the energy is minimised with respect to the remaining shape coordinates, so the surfaces shown are two-dimensional projections of a multidimensional potential. The red lines with arrows depict the most likely fission paths. While the LDM approach limits fission to a symmetric pathway along a singular “symmetric” valley, the inclusion of microscopic shell effects gives rise to asymmetric fission valleys. Figure from Ref. [50].

of the fission process may require several shape parameters, only a reduced set of collective coordinates can be displayed at a time for visualization purposes. The potential-energy surface for the ^{240}U nucleus is shown on the left in Figure 1.15.

The structure of the PES determines the main features of the fission dynamics: local minima correspond to equilibrium or metastable configurations, while saddle points and the ridges separating neighbouring valleys define the fission barriers that must be overcome on the way to scission. Fission paths can thus be interpreted as trajectories connecting the ground state to large deformations, with the likelihood of following a given path increasing as the energy along it decreases. Barrier heights and widths play a central role in governing fission probabilities and fragment properties.

Within the macroscopic-microscopic framework, the PES is obtained from the superposition of the smooth LDM contribution and the microscopic shell corrections evaluated at each deformation for the fissioning nucleus. As the system evolves toward scission, however, the shell structure of the nascent fragments becomes increasingly relevant, since the emerging fragments begin to develop

their own independent shell closures. This naturally leads to the appearance of asymmetric fission valleys and, consequently, to asymmetric fission-fragment mass distributions, as can be seen on the right in Figure 1.15 from Ref [50]. The inclusion of microscopic shell effects results in a more complex potential-energy landscape, which can differ significantly among nuclei, since shell effects vary as a function of neutron and proton numbers. This leads to the emergence of multiple “fission valleys”, each characterized by specific properties, including the presence of more than one saddle point and distinct fission-fragment mass distributions.

1.3.6 Fission channels

Following the description of the PES, it is useful to introduce the concept of fission channels, which provide a convenient framework for classifying the different scission configurations accessible to the system [51]. In this picture, distinct fission channels correspond to different trajectories on the PES that lead to different scission points through specific valleys and saddle points, each characterized by a particular combination of elongation, mass asymmetry, and neck properties [51].

Within the multimodal random neck rupture model [51], the fission process is decomposed into distinct fission channels, each associated with a specific pre-scission shape and neck configuration. The position of each fragment mass peak is determined by the characteristic scission geometry of the channel, while the random neck rupture mechanism, arising from hydrodynamic instabilities of the neck, governs the width of the resulting mass distribution. The main fission channels identified within this framework are the following:

- **Standard I channel (S1):** This channel is associated with asymmetric fission leading to a heavy fragment with mass number $A \approx 132$, close to the doubly magic configuration $Z = 50$, $N = 82$ (^{132}Sn). The enhanced stability provided by shell effects favors scission configurations with moderate elongation and a well-developed neck. The resulting mass distribution is asymmetric and relatively narrow.
- **Standard II channel (S2):** The Standard II channel also corresponds to asymmetric fission, but with a heavier fragment typically around $A \approx 140$, stabilized by a deformed neutron shell closure at $N \approx 86\text{--}88$ in the heavy fragment. Compared to Standard I, this channel is associated with more elongated scission shapes and tends to dominate in most actinide nuclei.
- **Standard III channel (S3):** A third, weaker component of the standard family, more asymmetric and with a longer pre-scission shape than standard II [51]. Consistent with this larger elongation, it exhibits a lower Total Kinetic Energy (TKE) and broader mass and TKE distributions

than standard II. It has been identified in the heavier fissioning systems, through decompositions of mass–TKE distributions in the plutonium isotopes, $^{241}\text{Am}(n,f)$ and in spontaneous fission of ^{252}Cf .

- **Super–Long channel (SL):** The super-long channel is characterized by highly elongated scission configurations and a thin neck, leading predominantly to symmetric mass splits. In this case, shell effects play a reduced role, and the fission dynamics are largely governed by macroscopic liquid-drop properties. The SL mode also exhibits a relatively low TKE, which can be attributed to the significant deformation of both fragments at the scission configuration: the energy available from the fission process is partially stored as internal excitation energy of the fragments rather than being released as kinetic energy, resulting in a higher prompt-neutron multiplicity. This channel becomes increasingly important at higher excitation energies.
- **Compact symmetric (CS) channel:** A recently identified symmetric fission mode, observed in neutron-deficient thorium isotopes with the SOFIA setup [52], corresponds to a compact scission configuration, in contrast to the traditional super-long mode. In this channel, both fragments are produced with significantly lower deformation, leading to higher Coulomb repulsion and thus higher total kinetic energy, accompanied by a reduced prompt-neutron multiplicity. The emergence of this channel is associated with a distinct valley in the potential energy surface that becomes increasingly favored as the neutron number decreases, eventually dominating the symmetric fission yield in light thorium isotopes.
- **Super–Asymmetric channel (SA):** The super-asymmetric channel corresponds to extreme mass splits far from symmetry, typically involving one very light and one very heavy fragment. This channel is less probable and is associated with specific scission configurations that can be stabilized by shell effects in both fragments. Its contribution depends sensitively on the nuclear system and excitation energy.

In the case of actinide nuclei, low-energy fission is often dominated by asymmetric fission yield, with the production of light fragments of mass $A \approx 100$ and a heavy fragment of mass $A \approx 140$.

1.3.7 Angular momentum generation in nuclear fission

In nuclear fission processes, the resulting fragments emerge with a non-negligible intrinsic angular momentum, typically of a few units of $\hbar$ [53], even when the initial parent nucleus had zero or near-zero spin. This behavior, evident from the γ -ray spectra emitted during fragment de-excitation [54, 55], provides key

information on the dynamics of fission and on the spin distribution in the final nuclear populations. The origin of this angular momentum has been the subject of theoretical and experimental investigations for decades, with models attributing it to the excitation of collective vibrational modes prior to rupture (*pre-scission*) [56, 57], as well as to processes occurring at or immediately after scission (*post-scission*), such as Coulomb forces acting on deformed fragments with coupled orientations [58–60].

Following scission, the de-excitation of each fragment proceeds via a statistical cascade. A large fraction of the excitation energy is initially removed through the evaporation of typically one to two neutrons, accompanied by one to three high-energy γ rays. The remaining excitation energy and the bulk of the angular momentum are subsequently carried away by the emission of several additional γ rays, each removing approximately two units of angular momentum. This prompt de-excitation process leaves the fragments in their ground states on a timescale of the order of a few nanoseconds. A detailed observation of this prompt γ -ray emission is therefore required to investigate the mechanism responsible for angular momentum generation. Furthermore, since heavy-ion- and charged-particle-induced reactions generate large initial angular momenta that can obscure the intrinsic fragment spin, suitable probes are limited to systems with zero or near-zero initial spin, such as spontaneous fission or neutron-induced fission. Complementary information on the angular momentum distribution in fission fragments has been obtained through systematic measurements of Isomeric Yield Ratio (IYR), which provide a sensitive probe of the spin distribution in the primary fragments. A series of high-precision measurements performed at the IGISOL-JYFLTRAP facility in Jyväskylä within the Uppsala–Jyväskylä collaboration [61–64] have revealed systematic trends in the fragment spin population as a function of mass number, and have provided constraints on theoretical models of angular momentum generation in fission.

A recent high-resolution γ -spectroscopy study by Wilson *et al.* [65], which allowed the separation of γ rays from the two fragments and the systematic investigation of spin trends over large mass ranges, points to an uncorrelated, post-scission spin-generation mechanism. In this mechanism, the fragment spin depends only on the fragment mass, with no observable correlation to the total mass of the fissioning system or to the mass and charge of the complementary fragment.

A macroscopic analogy to the snapping of an elastic band provides an intuitive picture of this mechanism. At scission, the rupture and relaxation of the nuclear neck, schematically illustrated in Figure 1.16, generate restoring forces that impart transverse motion to the neck nucleons, producing independent torques on each nascent fragment. The magnitude of each torque is determined by the number of nucleons in the neck and the precise location of the rupture. As a consequence, the fragment spins are generated independently, lie predominantly in a plane perpendicular to the fission axis, and exhibit no mutual

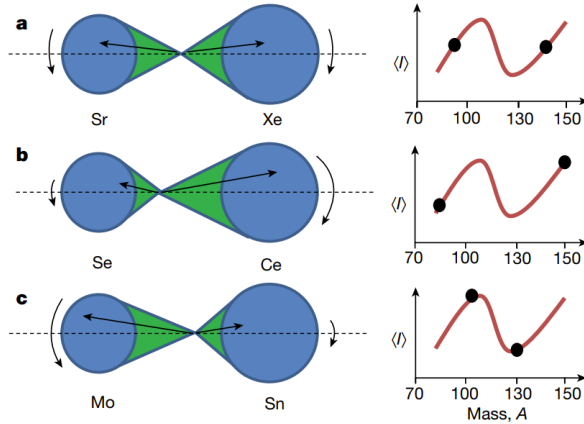


Figure 1.16: Post-scission generation of two independent torques, with neck nucleons highlighted in green. The straight arrows indicate the magnitudes and representative directions of the linear momentum vectors responsible for the associated angular momenta. The dashed line indicates the fission axis. The corresponding positions on the saw-tooth distribution of average fragment spins are shown on the right. Figure from Ref. [65].

correlation, while total angular momentum is conserved. The transformation of the fragments from elongated to more compact shapes simultaneously converts surface energy into internal excitation energy, enabling subsequent neutron evaporation. Angular momentum, excitation energy, and neutron multiplicity are therefore expected to be closely correlated.

While this study provides important insight into fragment spin generation, a comprehensive understanding of the underlying mechanisms still requires experimental data from a wider range of fissioning systems.

1.4 Motivating this work

The preceding sections outlined the role of nuclear fission in the creation of heavy elements in the Universe and the theoretical framework used to describe it. This section brings the two together and states what is missing. *R-process* network calculations require, for every nucleus and its corresponding excitation energies along the path, the probability for fission in comparison with neutron capture and β^- decay probabilities, and, once fission occurs, the mass and charge distribution of the fragments recycled as seeds. The first is governed primarily by the fission barrier height, the second by the structure of

the PES. Both enter r-process calculations as model predictions, since no measured values are available for the relevant nuclei. Sensitivity studies show that the predicted abundances depend appreciably on the fission barriers [66] and fragment yields [67] adopted. Since fission rates depend exponentially on the barrier height, a 1–2 MeV disagreement between predicted barriers for the same nucleus translates into orders of magnitude in the rate, and therefore into a correspondingly uncertain termination point of the r-process path. Such a spread is precisely what current models exhibit in the neutron-rich region. As discussed in Section 1.3.5, a barrier is not a single number but a saddle point on a multidimensional PES, and its calculated height depends on the collective coordinates retained, on the treatment of pairing, and, in the DFT case, on the underlying energy density functional. The functionals themselves are calibrated on experimental data: UNEDF1, an energy density functional from the Universal Nuclear Energy Density Functional collaboration optimised specifically for fission, fixes its large-deformation behaviour using the excitation energies of the fission isomers in $^{236,238}\text{U}$, ^{240}Pu and ^{242}Cm [68] (four data points, all in stable actinides) while semi-empirical descriptions, such as the General description of Fission observables (GEF) code [8], are adjusted to measured yields. The calibration set is thus concentrated on a handful of nuclei close to stability, and predictions for neutron-rich systems are extrapolations well outside it. Different models consequently diverge by several MeV for the same neutron-rich actinide [34], with no data available to discriminate between them. Experimentally, fission has so far been studied almost exclusively for nuclei reachable from a stable or long-lived species, and this is what restricts the available barrier data to a few tens of actinides close to stability.

The reaction mechanism sets a further constraint. Fusion-fission with charged particles is tied by the entrance-channel Coulomb barrier to excitation energies at which shell effects are, to some degree, already washed out (Figure 1.12), so the barrier region itself is not probed; neutron-induced fission and photofission reach low excitation energies but require a manufacturable target, excluding short-lived species. Transfer reactions populate the range around and below the barrier and give access to fission probabilities directly. The ^{239}U measurement of Figure 1.4 has demonstrated that this can be done in inverse kinematics with a solenoidal spectrometer [10]. That measurement, however, used a long-lived ^{238}U beam; extending the approach to the neutron-rich systems relevant to the r-process requires radioactive beams, and with it an excitation energy reconstructed event by event with a resolution sufficient to resolve the onset of fission at the barrier, and fission fragments recorded in coincidence with the reaction tag.

Meeting these three conditions simultaneously is the experimental problem addressed in this thesis. The approach adopted, surrogate (d,pf) transfer in inverse kinematics combined with a solenoidal spectrometer, is developed in Chapter 2, and its realisation in the IS739 experiment at ISOLDE is the subject

of the Chapters that follow. Developing an experimental method capable of reaching these systems, and providing the first input where the models above are currently unconstrained, is the aim of this work.

Chapter 2

Probing fission of neutron-rich nuclei

WHILE the astrophysical importance of fission in neutron-rich nuclei has been motivated in Chapter 1, directly accessing these systems in the laboratory remains challenging. To address this, indirect experimental strategies have been developed, enabling measurements of fission probabilities and barrier heights. This chapter presents such approaches, with particular emphasis on surrogate reactions and inverse-kinematics techniques that make these measurements feasible.

2.1 Direct and surrogate methods

As discussed in Sec. 1.3, the fission barrier represents the energy threshold above which fission becomes a competitive decay channel of an excited nucleus. Experimentally, information on the fission barrier can be obtained by measuring the fission probability as a function of the excitation energy of the fissioning system.

To investigate nuclei as close as possible to the r-process path, the most direct experimental approach would be the measurement of neutron-induced fission of neutron-rich target nuclei. However, such measurements pose severe experimental challenges. The neutron fluxes available at laboratory facilities are typically low compared to those in the r-process, leading to limited reaction rates. In addition, fission fragments are emitted nearly isotropically, requiring detector systems with very large solid-angle coverage to achieve reasonable detection efficiencies. Most critically, neutron-induced fission measurements on short-lived neutron-rich nuclei are often impractical or impossible, as they would require the production, handling, and irradiation of radioactive targets with very limited lifetimes. As a consequence, direct neutron-induced fission

cross-section data are largely unavailable for nuclei far from stability.

These limitations can be addressed by employing the surrogate reaction technique, originally proposed by Cramer and Britt in the 1970s [69]. In this indirect approach, the compound nucleus of interest is populated via an alternative, experimentally accessible reaction, allowing its decay properties to be studied without the need for a neutron-induced reaction on a radioactive target. The surrogate reaction is chosen such that it produces the same compound nucleus, characterized by mass number A and charge Z , as in the corresponding neutron-induced reaction.

Within this framework, the neutron-induced cross section of a nucleus X for a decay channel i , $\sigma_{n,i}^X$, can be factorized as

$$\sigma_{n,i}^A(E_n) = \sigma_{\text{CN}}^{\text{calc}}(E_n) \cdot P_i^{\text{exp}}(E_n), \quad (2.1)$$

where P_i^{exp} is the experimentally measured decay probability of the compound nucleus, and $\sigma_{\text{CN}}^{\text{calc}}$ is the CN formation cross section for the neutron-induced reaction, typically obtained from optical-model calculations.

In a neutron-induced reaction, the compound nucleus is formed by the direct absorption of a neutron, typically resulting in excitation with relatively low angular momentum. In contrast, transfer surrogate reactions such as (d, p) populate the same compound nucleus by transferring a neutron from the deuteron, which generally introduces a broader and different spin-parity distribution due to the inherent angular-momentum transfer in the reaction mechanism [70, 71].

The interpretation of surrogate reaction data therefore requires careful consideration of the differences between the spin-parity population in the surrogate reaction and that expected for neutron-induced fission. In particular, the validity of the surrogate method relies on the assumption that decay probabilities are only weakly dependent on the details of the entrance channel, an approximation related to the Weisskopf–Ewing limit of Hauser–Feshbach theory that holds best when level densities are high, and fission dominates over competing decay modes [71, 72]. Despite these limitations, surrogate reactions remain a valuable tool for accessing fission properties of neutron-rich nuclei inaccessible to direct measurements.

Recent advances in radioactive-beam facilities and inverse-kinematics detector techniques are opening up transfer-induced fission studies in regions previously out of reach, making surrogate (d, pf) reactions a promising route to constrain fission barriers and fission probabilities of neutron-rich actinides relevant to r -process nucleosynthesis [10, 71].

2.1.1 The (d, pf) reaction as a probe of the barrier

Among the surrogate reactions available, single-neutron transfer is the closest analogue to neutron capture, and two features make it particularly well suited

to the measurement of fission barriers. The outgoing proton fixes the excitation energy of the residual nucleus event by event through a measurement of the missing mass, independently of how that nucleus subsequently decays, so the fission probability can be extracted as a ratio of tagged events at each E_x without recourse to a decay model. In addition, a single measurement at fixed beam energy covers a continuous range of excitation energies spanning the barrier, whereas the equivalent neutron-induced measurement requires either a scan in incident energy or a time-of-flight facility. The measurements of Ref. [69] and their successors remain the source of much of the empirical barrier systematics in use today, and recent high-resolution (d, p) work on stable actinide targets has reached excitation-energy resolutions of the order of 10 keV [73] while serving to test the surrogate method quantitatively against known (n, f) cross sections [71].

All of these experiments were performed in direct kinematics, and are therefore restricted to the narrow band of fissioning systems reachable from a target that can be manufactured and handled. Inverse kinematics lifts that restriction, and has been exploited in two distinct ways. Multinucleon transfer between heavy ions populates many fissioning systems in a single experiment and yields fragment mass and charge distributions with excellent resolution, but the excitation energy is reconstructed with limited accuracy and the angular momentum transferred is substantial [74]. Single-neutron transfer with a light target instead preserves the low-spin, well-defined E_x character of the direct-kinematics measurements, and its combination with a solenoidal spectrometer has been demonstrated for $^{238}\text{U}(\text{d}, \text{p}f)$ at HELIOS, yielding the ^{239}U fission probability of Figure 1.4 [10]. That measurement used a long-lived beam; extending the technique to genuinely short-lived beams has not yet been achieved, and is the aim of the present work. The remainder of this chapter develops the two ingredients it rests on: transfer-induced fission in inverse kinematics, and the solenoidal-spectrometer method that recovers the excitation-energy resolution otherwise lost.

2.2 Transfer-induced fission in inverse kinematics

In nuclear reaction studies, experiments are traditionally performed in *direct kinematics*, where a light, stable (or long-lived) projectile impinges on a heavy target nucleus. This approach becomes impractical when studying highly unstable neutron-rich nuclei, as their short half-lives prevent the fabrication and handling of suitable targets. For this reason, experiments involving radioactive nuclei are commonly performed in *inverse kinematics*, where the nucleus of interest is delivered as a beam and directed onto a stable light target, such as deuterium. This approach enables transfer reactions to be studied for short-lived nuclei that are otherwise inaccessible.

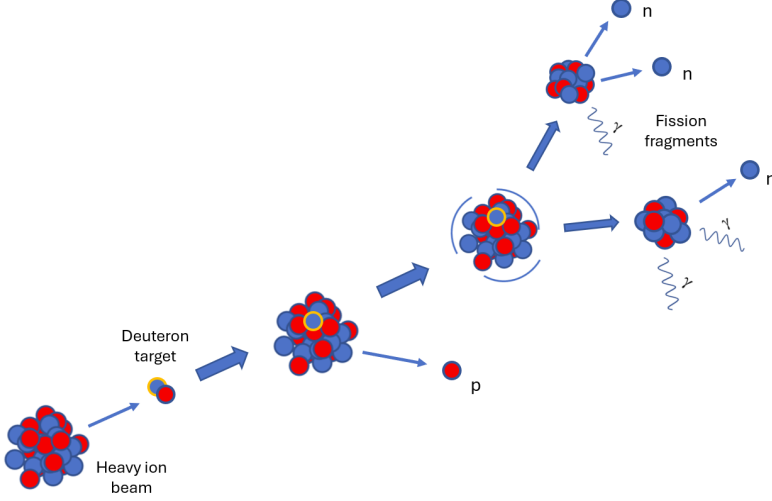


Figure 2.1: Schematic illustration of the (d, pf) reaction in inverse kinematics. A radioactive heavy-ion beam impinges on a deuterium target, leading to the transfer of a neutron (blue) from the deuteron to the projectile and the emission of a proton (red). The neutron transfer populates an excited compound nucleus, which may subsequently decay by fission if the excitation energy exceeds the fission barrier, producing two fission fragments emitted in the forward direction. The fission fragments are formed in highly excited states and de-excite through the emission of prompt neutrons and γ rays.

The (d, pf) reaction can be used as a surrogate for neutron-induced fission in inverse kinematics. To investigate the fission of unstable nuclei, a radioactive beam interacts with a deuterium target, leading to the transfer of a neutron from the deuteron to the beam nucleus and the emission of a proton, as illustrated in Figure 2.1. If the resulting compound nucleus is populated at an excitation energy above the fission barrier, fission becomes a possible decay channel. In this way, transfer-induced fission reactions offer a practical experimental proxy for neutron-induced fission processes. As a consequence of the inverse kinematics, the fission fragments receive a strong kinematic boost in the forward direction. Their opening angle depends on the beam energy and on the transverse momentum imparted during fission, significantly enhancing the detection efficiency compared to direct kinematics¹. This forward focusing is a key advantage for coincidence measurements involving fission fragments, emitted neutrons, and charged particles.

¹In direct kinematics, target-like reaction products often have insufficient kinetic energy to escape the target material, making their detection challenging.

The use of deuterium as a target provides a practical alternative to neutron-induced reactions. Neutrons, being electrically neutral, cannot be confined or manipulated to form a dense target, and their short lifetime (10.18 min [16]) further limits their practical use. Deuterium, by contrast, is a stable and readily available isotope that enables neutron transfer reactions under controlled experimental conditions. A wide range of radioactive beams suitable for transfer-induced fission studies in inverse kinematics is available at the ISOL-type radioactive-ion-beam facility ISOLDE at CERN, enabling systematic investigations of neutron-rich pre-actinide and actinide nuclei.

2.3 The ISOLDE facility at CERN

The Isotope Separator On-Line DEvice (ISOLDE) at CERN (the European Organization for Nuclear Research) in Geneva is dedicated to the production of radioactive ion beams [75]. In the Isotope Separation On-Line (ISOL) method, radioactive nuclei are produced in a thick target and thermalized within the production material. They are subsequently extracted, ionized, and injected into a post-accelerator, where they are accelerated to the final energy required for the experiment. To date, ISOLDE has delivered more than 1000 isotopes spanning 74 elements ($Z = 2$ to 89), with half-lives down to the millisecond range and intensities reaching up to 10^{11} atoms per μA proton pulse [76]. This extensive isotope range enables systematic investigations of atomic and nuclear properties far from the line of β stability. Consequently, ISOLDE has become a key facility for research in nuclear physics and nuclear astrophysics, as well as in weak-interaction physics, solid-state physics, and biomedical applications.

2.3.1 Beam production

What makes CERN truly unique is its accelerator complex shown in Figure 2.2. It consists of a series of interconnected accelerators used to accelerate and collide particles at high energies for various particle and nuclear physics experiments. In our case, the accelerating process starts in the Linear accelerator 4 (Linac4), where negative hydrogen ions H^- are extracted from a bottle of hydrogen gas and are accelerated to 160 MeV. A stripping foil is used to remove the two electrons from the ions when they are injected from Linac4 into the Proton Synchrotron Booster (PSB), leaving only protons. In the PSB, protons are accelerated to 1.4 GeV before being delivered to ISOLDE, which is located nearby. Here, the protons are directed onto a target material, often made of a heavy element like uranium or thorium, with an intensity of up to $2 \mu\text{A}$. Nuclear reactions induced by these highly energetic protons, such as fission, spallation, and fragmentation, yield numerous radionuclides across the nuclide chart.

The target material is contained in a tubular tantalum oven, which can

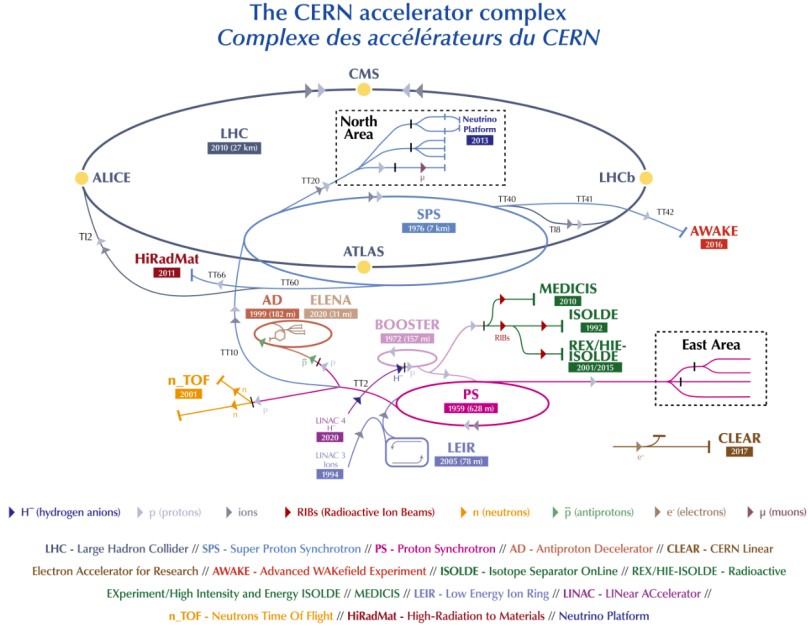


Figure 2.2: Layout of the CERN accelerator complex. Figure from Ref. [77].

be heated to temperatures of typically 2000 °C through resistive heating. This, combined with the porosity of the targets, facilitates the diffusion and extraction of the produced nuclei. As a result, short-lived isotopes can quickly reach the transfer line and the ion source, where they are singly ionized.

Typically at ISOLDE, atoms are positively ionized using the surface ionization technique, where the released atoms come into contact with a hot surface made of a material with a high work function², such as rhenium (Re) or tantalum (Ta). Upon contact with the hot surface, these atoms lose electrons and become positively charged ions. A schematic layout of the standard target-ion source unit used at ISOLDE is shown in Figure 2.3. However, depending on the specific requirements of the experiments, the ionization process can also be performed by the Resonance Ionization Laser Ion Source (RILIS), which uses laser ablation to selectively ionize specific isotopes from the atomic vapor generated by heating the target material. This technique allows for high-purity ion beams of specific isotopes, essential for precision experiments. Another ion

²The work function of a material is conventionally defined as the minimum energy required to extract one electron from its surface. Materials with a high work function require more energy to release electrons from their surface. Consequently, they are less likely to donate electrons to other materials and more likely to accept electrons from other materials. This characteristic makes them effective for surface ionization.

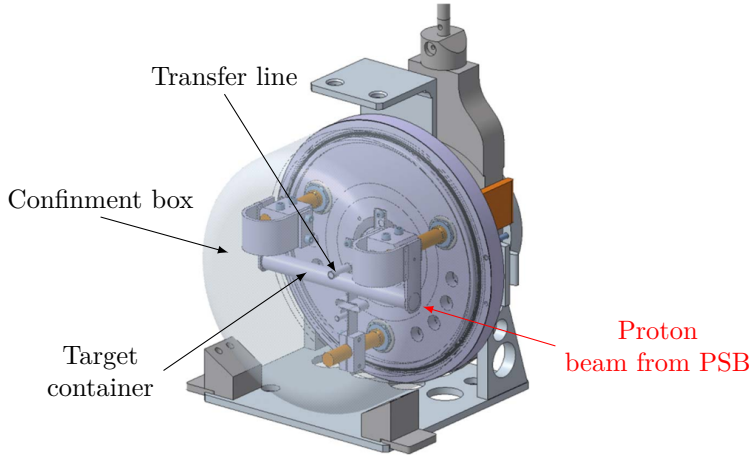


Figure 2.3: Schematic layout of the standard target-ion source unit at ISOLDE. The unit includes a tubular tantalum oven where the target material is resistively heated to facilitate the diffusion and extraction of short-lived isotopes. The proton beam irradiates the target, producing isotopes that diffuse toward the transfer line, which directs them to the ion source (not shown). Surface ionization occurs on a hot, high-work-function surface, such as rhenium or tantalum, creating positively charged ions. These ions are then extracted by electrodes for further processing. Figure adapted from Ref. [78].

source adopted at ISOLDE is the Electron Cyclotron Resonance Ion Source (ECRIS). This plasma ion source is ideal for producing highly charged ions. The plasma is generated from a gas mixture, typically argon (Ar) and xenon (Xe), which is ionized by electrons. These electrons are accelerated between the transfer line and the extraction electrode using an anode voltage of about 130 V. To optimize this ionization process, the electrons are confined within a magnetic field and are heated by microwave radiation. The microwaves resonate with the cyclotron frequency of the electrons, efficiently increasing their energy and enhancing their ability to ionize the gas atoms.

Once atoms are ionized, they are accelerated by a 30 – 60 kV static electric potential. Subsequently, the ionized atoms are separated according to their mass-to-charge ratio in one of the two ISOLDE on-line isotope separator dipole magnets, each equipped with independent target-ion source systems. The first separator, known as the General Purpose Separator (GPS), includes one bending magnet and an electrostatic switchyard that enables the simultaneous extraction of three mass-separated beams. It achieves a mass resolving power³

³The mass resolving power of a mass separator refers to the ability to separate ions of

of approximately 2400. The second separator is the High-Resolution Separator (HRS), which consists of two bending magnets with an elaborate ion-optical system for higher-order corrections. Its mass resolving power exceeds 5000-7000 [79]. Furthermore, an off-line mass separator is available for tests and calibrations. Both separators are connected to a common beam line system to reach various experimental setups. One intermediate destination is REX-TRAP and REX-EBIS, which, after charge breeding, feed the low-energy (up to 3 MeV/u) REX-ISOLDE beam line followed by the superconducting HIE-ISOLDE (High Intensity and Energy ISOLDE) post accelerator. As anticipated, this setup will eventually enable experiments with ions reaching kinetic energies up to 10 MeV/u [80]. The present limit is 8.38 MeV/u with $A/q = 4$ as achieved in the experiment IS708 in November 2024 [81].

REX-ISOLDE

After mass separation, the resulting beam requires a series of refinements: cooling, bunching, and charge-breeding, essential for an efficient subsequent post-acceleration.

The 30 – 60 keV ion beam from ISOLDE is slowed down and continuously injected into the REXTRAP Penning trap. The ions are trapped by a pulsed electrostatic potential alongside a static solenoidal magnetic field. At the same time, the ions are cooled via energy dissipation collisions with a buffer gas, typically Ar or Ne. After a fixed time, which is determined by the required charge breeding time in REX-EBIS, the stopping electric potential at the exit side of the trap is rapidly lowered and the ion bunch is extracted from the trap. The ions therefore escape the trap in a bunch, with a temporal width of approximately 10 μ s to 50 μ s per bunch [82]. The ions are accelerated to 60 keV for transport. Before injection into the REX-EBIS (Electron Beam Ion Source), the ions are once again slowed down, or “retarded”, to ground potential. This step ensures that the ions are at the appropriate low kinetic energy for effective manipulation within the EBIS, where $1+$ ions are bred to a higher charge state to make subsequent acceleration more efficient. The working operation of REX-EBIS is very similar to that of REXTRAP with the difference that in place of the buffer gas, the interaction of ions is done with an electron beam operating in an Ultra High Vacuum (UHV) of at least 10^{-11} mbar. The electron gun delivers a high-intensity beam of highly energetic electrons impinging onto the trapped ions which strips away atomic electrons from the trapped ions. The extracted ions then pass through a mass separator which selects the desired A/q before they enter the linear REX-ISOLDE accelerator [83], illustrated in Figure 2.4. The time structure of the IS739 experiment is illustrated in Figure 2.5: protons

different masses based on their mass-to-charge ratio. This quantity is defined as $R = \frac{m}{\Delta m}$ where m is the mass of the ion of interest and Δm is the smallest difference in mass that the separator can resolve.

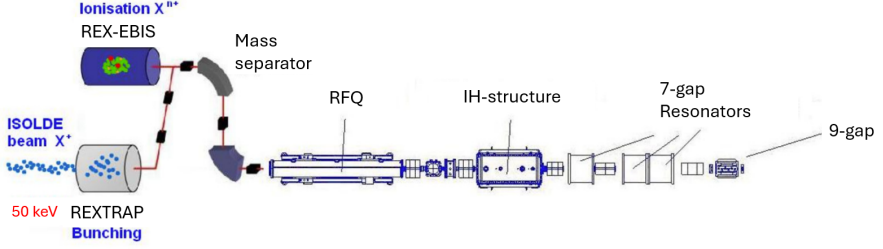


Figure 2.4: REX-ISOLDE present scheme. Figure taken from [84].

are delivered to the ISOLDE GPS production target at intervals that are integer multiples of the 1.2 s PSB repetition rate. The EBIS breeding and extraction cycle was 200 ms. The detector systems mentioned in the figure are described in detail in Chapter 3.

The acceleration of charge-bred ions occurs in steps. First, a Radio Frequency Quadrupole (RFQ) accelerates the beam to 0.3 MeV/u and focuses it using quadrupole electric fields. Next, a buncher re-bunches the beam to help it enter the third component, which is the Interdigital H-type Structure (IHS). The IHS performs acceleration via RF fields parallel and anti-parallel to the beam axis. This drift-tube Linear Accelerator (LINAC) accelerates the beam to 1.2 MeV/u in 1.5 m at the same frequency. The beam is then further accelerated by 7- and 9-gap cavities up to 2.2 MeV/u and 3 MeV/u, respectively.

HIE-ISOLDE

HIE-ISOLDE, a new linear accelerator at the ISOLDE facility, represents a significant energy upgrade. Beginning construction in 2015, it initially achieved beam acceleration to 4.5 MeV/u by 2016 and subsequently reached nearly 10 MeV/u upon its completion in 2018. The accelerator features four superconducting cryomodules, each operated at 4.5 K and 2.3 meters long [85]. These high-energy cryomodules house five superconducting cavities for acceleration and a superconducting solenoid for beam focusing. This design aims a minimum beam energy of 9.2 MeV/u for $2.5 \leq A/q \leq 4.5$ and allows beams with $A/q = 4$ to achieve 10 MeV/u [86]. For the case presented in this thesis, a charge state of around 52+ is expected for ^{229}Ac , corresponding to an $A/q \sim 4.5$, based on the best performances of EBIS charge breeding for radioactive actinide beams [87].

HIE-ISOLDE beams can be sent to three experimental stations as depicted

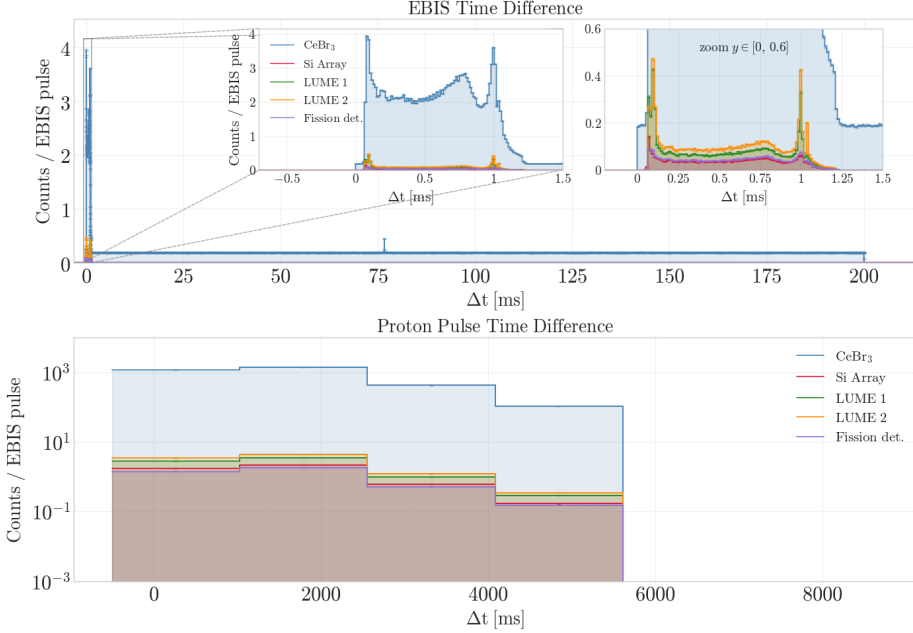


Figure 2.5: Time difference distributions measured in the IS739 experiment. *Top panel:* time difference between detected events and the EBIS extraction pulse, showing the full 200 ms EBIS cycle. The two insets zoom into $\Delta t \in [-0.7, 1.5]$ ms: the left inset shows the full dynamic range, while the right inset restricts the y -axis to $[0, 0.6]$ counts/EBIS pulse. *Top panel:* time difference with respect to the proton pulse (T1 signal), on a logarithmic scale, with period 1.2 s. The staggered structure is due to which pulses of the PSB 1.2 s cycle are delivered to ISOLDE.

in Figure 2.6: an array of high-purity germanium detectors known as Mini-ball, the ISOLDE Solenoidal Spectrometer (ISS), which uses a former Magnetic Resonance Imaging (MRI) magnet, and a third beamline where a large vacuum chamber is used for scattering experiments, the Scattering Experiments Chamber (SEC).

2.4 The solenoidal spectrometer method

In the case of a direct (d,p) transfer reaction, the neutron from the deuteron is transferred to a single-particle state, and the ejected proton emerges with a well-defined kinetic energy determined by the kinematics and the Q -value of the reaction, allowing a direct probe of such states.

While transfer reactions in direct and inverse kinematics are indistinguish-

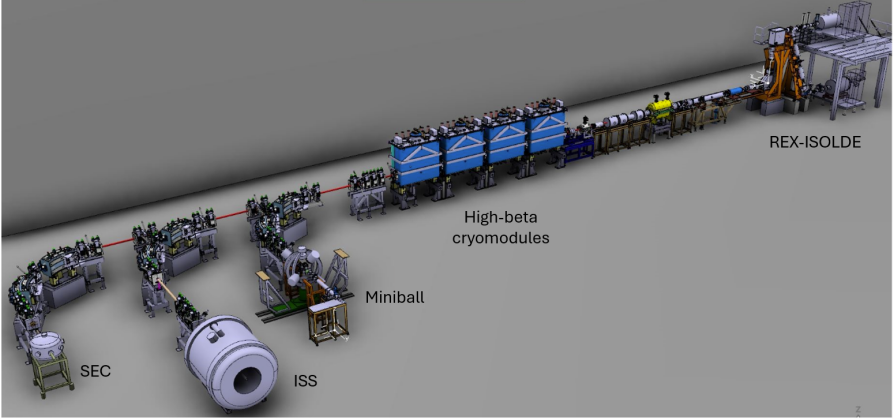


Figure 2.6: Layout of the HIE-linac as it appeared in 2016. On the right, the REX-ISOLDE postaccelerator is visible. Downstream of REX, two high-beta cryomodules are installed and connected to the high-energy beam transport system. The three operational beam lines are linked to Miniball (right), ISS (middle) and SEC (left). Figure from Ref. [88].

able in the Center-of-Mass frame (CM), they differ significantly in the Laboratory frame (LAB). The use of inverse kinematics allows overcoming experimental challenges in studying short-lived isotopes, but the associated kinematics limits the achievable energy resolution in a detector with a given acceptance of laboratory angles. The so-called *kinematic shift* refers to the variation of the ejected proton energy lines, corresponding to different excited states, with the emission angle in the laboratory system, as shown by the dashed lines in Figure 2.7. In inverse kinematics, the velocity of the CN is much larger than the corresponding reaction in normal kinematics, resulting in a greater kinematic shift and a worse resolution. Moreover, when considering forward center-of-mass angles, which are typically characterized by higher yields, a *kinematic compression* of the different energy lines is clearly visible. The combination of these kinematic effects and energy measurements at fixed angles results in limited energy resolution. This is especially pronounced in reactions involving heavy beams, where the resolution can be on the order of several hundred keV [89]. Consequently, resolving individual excited states becomes difficult. In contrast, direct-kinematics measurements can reach energy resolutions of the order of 10 keV, e.g. 11 keV (FWHM) [73].

This deterioration of the energy resolution can be mitigated by the use of a solenoidal spectrometer as suggested in Refs. [91–93]. A schematic diagram of a solenoidal spectrometer is shown in Figure 2.8. The idea is that the reaction is

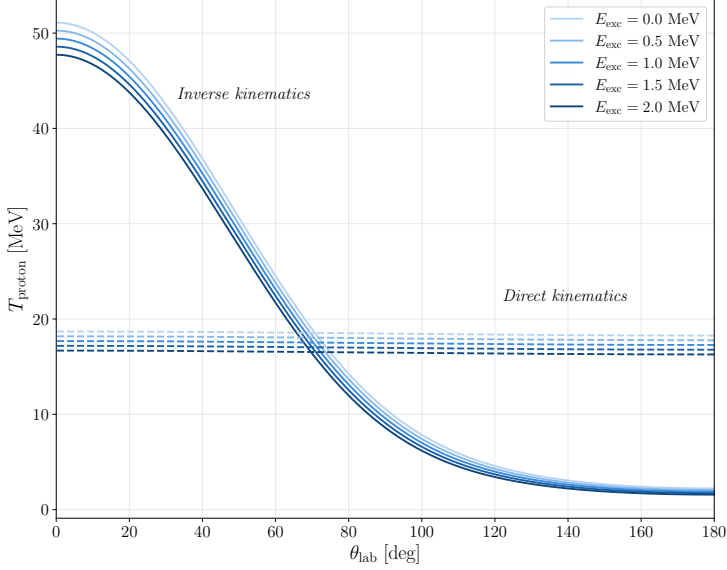


Figure 2.7: Kinematic lines of proton energy versus scattering angle θ_{lab} in the laboratory frame for the $d(^{229}\text{Ac}, p)$ reaction at 8 MeV/u following population of several excited states in ^{230}Ac in both normal (dashed lines) and inverse (solid lines) kinematics. The direct-kinematics lines are not perfectly flat but show a slight angular dependence, barely visible at this scale.

performed in the uniform magnetic field of a solenoidal superconducting magnet. The magnetic field is aligned along the beam direction (z coordinate in the laboratory system), causing any ejected charged particle to follow a helical orbit determined by the combination of its perpendicular and parallel momentum components relative to the magnet axis. The parallel momentum component is crucial for transporting the particle either upstream or downstream. The spiraling orbit will eventually intersect the beam axis again at a position z from the target, after a time equal to the cyclotron period T_{cyc} given by:

$$T_{cyc} = \frac{2m\pi}{Bq} \quad (2.2)$$

where B is the magnetic field, m is the mass of the particle, and q is its charge. The device is therefore dispersive along the axis in terms of the parallel velocity component. Specifically, events populating the same excited state but with different ejectile emission angles will exhibit varying longitudinal velocity components. Consequently, they will return to the axis at different positions z , as illustrated in Figure 2.9.

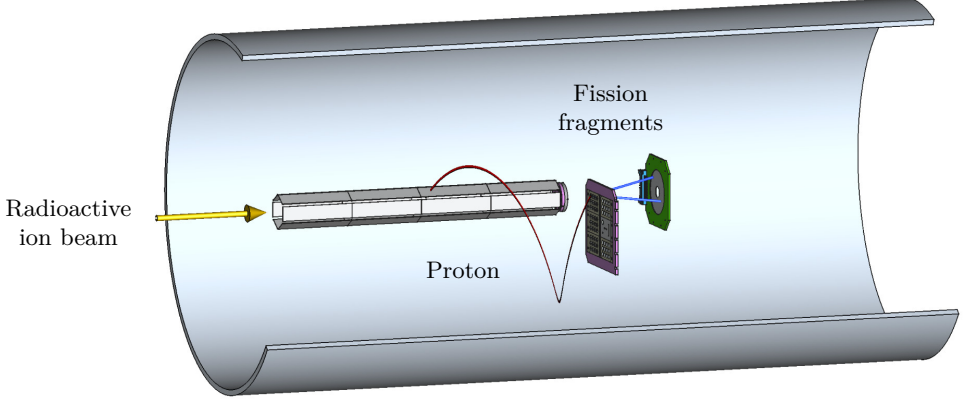


Figure 2.8: Schematic diagram of a solenoidal spectrometer. The cylindrical superconducting solenoid (gray) generates a uniform magnetic field along the beam axis (yellow arrow). Charged particles are deflected in helical trajectories: protons follow tight helical paths (red), while fission fragments (light blue) are boosted in a cone-shaped aperture at forward angles and are detected by a silicon recoil detector positioned downstream. Figure from Ref. [90].

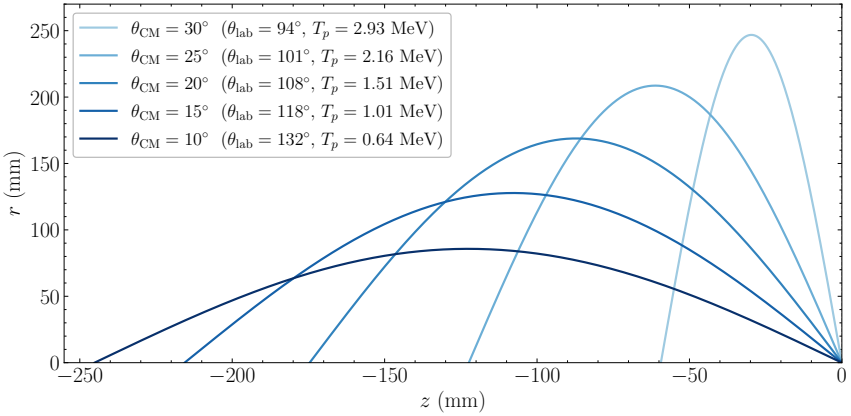


Figure 2.9: Radii r of proton trajectories as functions of z for the reaction $^{229}\text{Ac}(d,p)^{230}\text{Ac}$ at 8 MeV/u and $B = 2$ T, for various emission angles in the CM frame. The recoil nucleus ^{230}Ac is at an excitation energy of 7 MeV; consequently the proton has a fixed energy in the CM frame, and only its emission direction varies.

The operational advantage of the solenoidal spectrometer over a conventional transfer reaction setup is illustrated in Figure 2.10. The top panels show a schematic of each geometry: in the conventional setup (top left), the detector is placed at a fixed laboratory angle θ and records the particle energy E . In the solenoidal spectrometer (top right), the uniform magnetic field $\vec{B}$ along the beam axis causes emitted protons to follow helical trajectories, returning to the beam axis at a position z that depends on their parallel momentum component, where they are detected with both energy E and position z recorded.

The middle panels display the corresponding kinematic lines. In the conventional case (middle left), the lines in the $E - \theta$ plane converge and compress toward backward angles, making it difficult to resolve states that are close in excitation energy. In the solenoidal spectrometer (middle right), the kinematic lines in the $E - z$ plane are nearly parallel and well-separated, a direct consequence of the linear relationship

$$E_{\text{lab}} = E_{\text{CM}} - \frac{mV_{\text{CM}}^2}{2} + \frac{mzV_{\text{CM}}}{T_{\text{cyc}}} \quad (2.3)$$

which shows that E_{lab} depends linearly on z for a given E_{CM} . This effectively eliminates the kinematic compression and shift that affect conventional inverse-kinematics measurements. The practical consequence is most clearly seen in the bottom panels, which show the projected energy spectra at a fixed angle ($\theta_{\text{lab}} = 170^\circ$, bottom left) and at a fixed position ($z = -300$ mm, bottom right). In the conventional spectrum, the peaks corresponding to different excited states overlap significantly due to kinematic compression, severely limiting the achievable excitation-energy resolution. In the solenoidal spectrometer spectrum, the peaks are cleanly separated by an energy difference equal to the difference in excitation energy between the states, demonstrating a substantial improvement in resolution. This feature arises because, when particles are detected along the solenoid axis, laboratory and centre-of-mass energies differ only by a constant offset, so the spacing of excited states is fully preserved in the laboratory frame.

So far, three solenoidal spectrometers have been developed. In chronological order: the Helical Orbit Spectrometer (HELIOS) at ANL⁴, ISS at CERN, and the Solenoid Spectrometer Apparatus for Reaction Studies (SOLARIS) at FRIB⁵. Even though they all share a similar approach, they are designed to receive different types of beams, making their individual scientific programs unique.

⁴Argonne National Laboratory, Chicago, Illinois.

⁵Facility for Rare Isotope Beams (FRIB), East Lansing, Michigan.

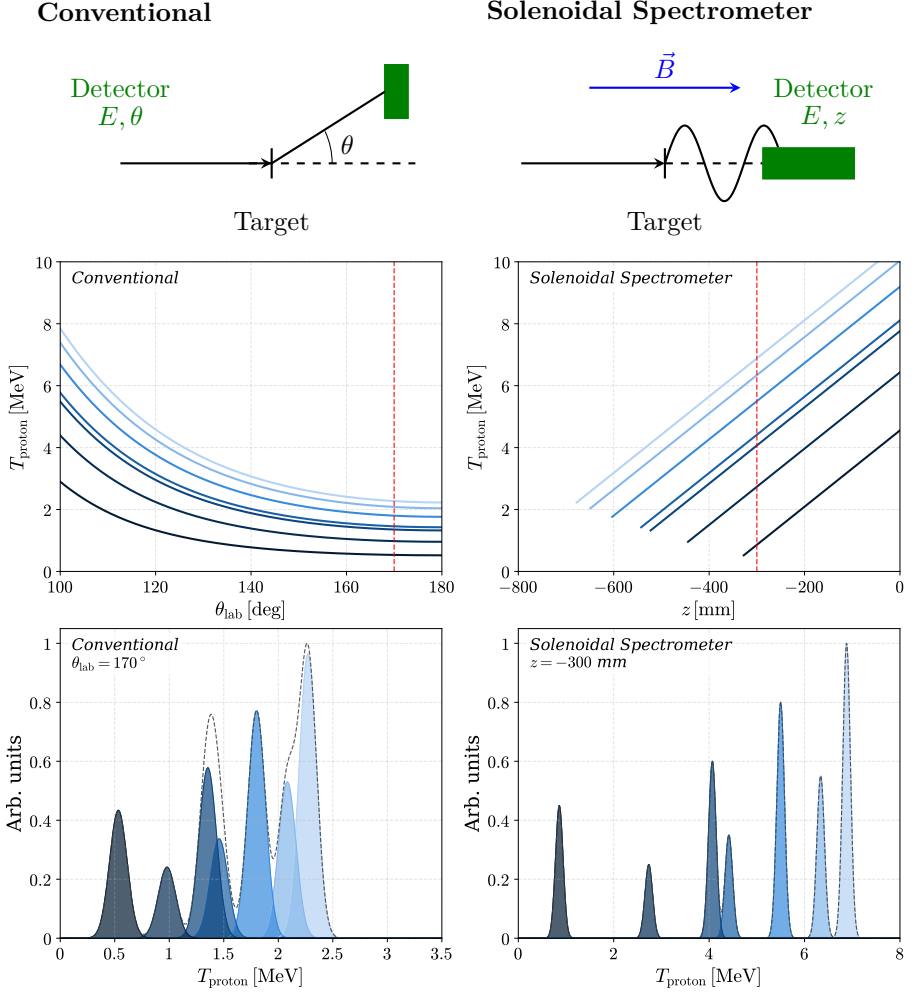


Figure 2.10: Schematic comparison between a conventional transfer reaction setup (left) and the solenoidal spectrometer approach (right) both in inverse kinematics. In the conventional geometry, the detector is placed at a fixed laboratory angle θ and measures the particle energy E . In the solenoidal spectrometer, the uniform magnetic field $\vec{B}$ along the beam axis causes the emitted protons to follow helical trajectories, returning to the beam axis at a position z that depends on their parallel momentum component. The lower panel shows the corresponding kinematic lines in the E - θ plane (left) and the E - z plane (right), illustrating how the solenoidal geometry eliminates the kinematic compression that limits the resolution in conventional inverse-kinematics measurements. Each line represents a *fictitious* excited state of ^{230}Ac used here for illustrative purposes only.

2.4.1 Inverse problem

A solenoidal spectrometer typically provides information about the z coordinate and the deposited energy E of the detected particles, while the cyclotron frequency provides a quantised observable that can suppress ejectiles with unwanted A/q ratios. The primary goal is to extract, from the first two of these measured quantities the excitation energy E_x of the compound nucleus formed in the reaction and the center-of-mass emission angle θ_{cm} of the ejected proton, using a mapping such as:

$$\begin{pmatrix} E \\ z \end{pmatrix} \longrightarrow \begin{pmatrix} E_x \\ \theta_{\text{cm}} \end{pmatrix}. \quad (2.4)$$

In other words, quantities in the laboratory frame need to be transformed into the CM frame. Assuming a 2-body scattering, Figure 2.11 illustrates the kinematic differences for the same process when viewed in the laboratory frame compared to the CM frame, respectively. In the case of interest, **a** and **b** denote the reacting partners, namely the incoming radioactive heavy ion and the deuterium target. Following the scattering event, the ejected proton, referred to as ejectile **1**, and the recoiling nucleus **2**, emerge.

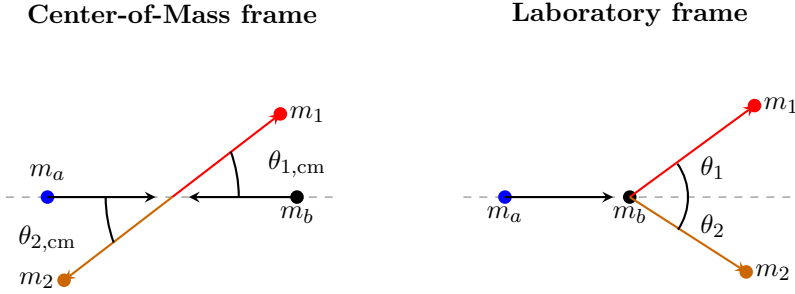


Figure 2.11: Schematic representation of a two-body reaction in the center-of-mass (left) and laboratory (right) reference frames. The reacting partners are denoted by **a** and **b**, while **1** and **2** represent the reaction products. In the CM frame, the angle between the two ejectiles is 180° due to momentum conservation.

The measured energy E and the z -coordinate of the detected particles can be expressed as a function of E_x and θ_{cm} [94]:

$$E = \frac{\gamma}{2E_t} \left[M_c^2 + m_1^2 - (m_2 + E_x)^2 - \beta \cos \theta_{\text{cm}} \sqrt{(M_c^2 - (m_1 + m_2 + E_x)^2)(M_c^2 - (m_1 - m_2 - E_x)^2)} \right], \quad (2.5)$$

and

$$z = \frac{1}{\alpha} \left[\beta(M_c^2 + m_1^2 - (m_2 + E_x)^2) - \cos \theta_{\text{cm}} \sqrt{(M_c^2 - (m_1 + m_2 + E_x)^2)(M_c^2 - (m_1 - m_2 - E_x)^2)} \right], \quad (2.6)$$

where $\alpha = \frac{cZB}{2\pi}$, E_t is the total energy of the system in the CM, γ is the Lorentz factor of the CM system in the laboratory frame, M_c is the total mass of the system, and m_1 and m_2 are the masses of the scattered particles. It can be shown that the mapping between the measured energy and coordinate and the observables of interest leads to the following equations [94]:

$$E_x = -m_2 + \sqrt{M_c^2 + m_1^2 - 2\gamma M_c(E - \alpha\beta z)} \quad (2.7)$$

and

$$\cos \theta_{\text{cm}} = \frac{\gamma(E\beta - \alpha z)}{\sqrt{\gamma^2(E - \alpha\beta z)^2 - m_1^2}}. \quad (2.8)$$

The kinematic lines for the ejected proton in the example reaction $^{229}\text{Ac}(d, p)^{230}\text{Ac}$ at 8 MeV/u in 2 T are reported graphically in Figure 2.12.

Eqs. 2.7 and 2.8 only hold in the unrealistic but ideal case of an ejectile detector with vanishing transverse dimensions. In reality, the detector has a finite size, and corrections to the kinematic calculations become necessary due to ejectiles not returning fully to the beam axis but instead being incident on the detector before reaching the axis. If $\rho \gg a$ (where ρ is the trajectory radius and a is a measure of the detector size) the return hit position is given by the expression:

$$z_{\text{hit}} \approx z_0 \left(1 - \frac{1}{2\pi} \frac{a}{\rho} \right). \quad (2.9)$$

where z_0 is the position on the beam axis where the particle would return in the case of an infinitely small detector. This is only a first-order approximation: outside the $\rho \gg a$ regime, or when the beam is not perfectly aligned with the solenoid axis, the full treatment of Ref. [94] is required. As shown in Figure 2.13, the finite detector size affects the kinematic lines of the ejected protons and can even render the $(E, z) \rightarrow (E_x, \theta_{\text{cm}})$ mapping ambiguous in certain regions.

Two practical limitations of the method should be noted at this point. Elastic deuteron breakup produces protons unaccompanied by neutron transfer, which populate the same region of the (E, z) plane as genuine transfer events and must be separated from them. And the excitation-energy resolution actually achieved is given not by the kinematics recovered above but by the target thickness, the beam energy spread and the detector granularity, so the gain

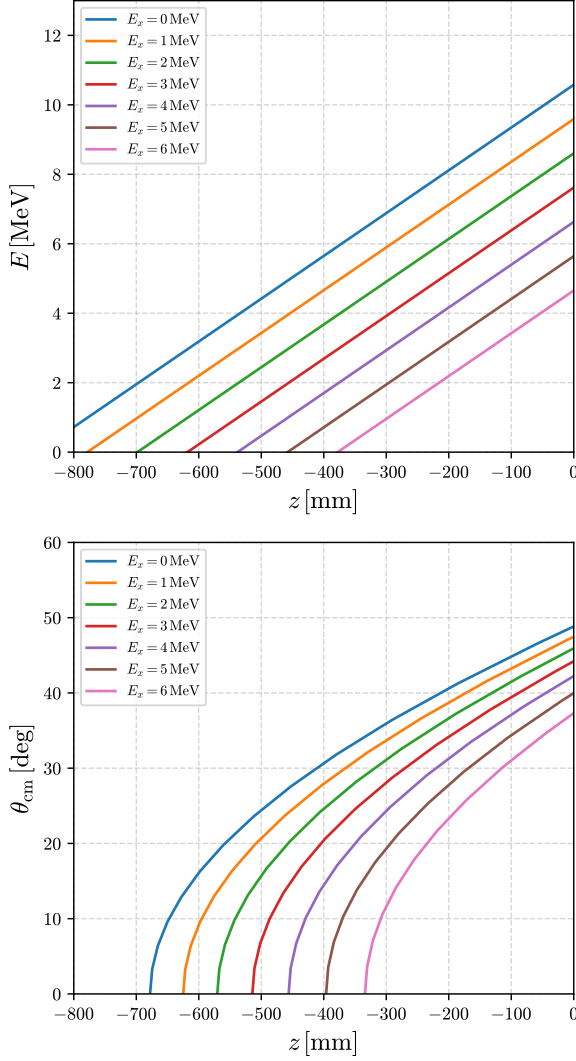


Figure 2.12: Kinematic plots for the $^{229}\text{Ac}(d, p)^{230}\text{Ac}$ reaction at 8 MeV/u in 2 T. The upper panel displays the energies of protons E as a function of z , while the lower panel shows the proton emission angle in the center-of-mass frame, θ_{cm} , as a function of z . Each line represents a fictitious excited state of ^{230}Ac , with excitation energies ranging from 0 to 6 MeV in 1 MeV intervals. This plot assumes no transversal dimension of the ejectile detector array.

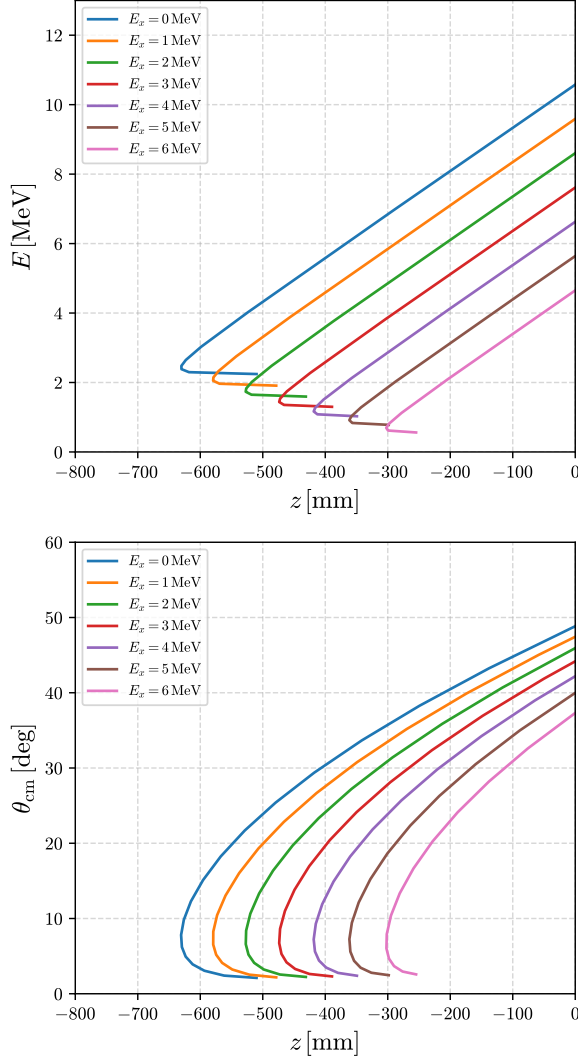


Figure 2.13: Kinematic plots for the $^{229}\text{Ac}(d, p)^{230}\text{Ac}$ reaction at 8 MeV/u in a 2 T magnetic field, with a detector having an axial radius of 11.5 mm. The upper panel displays the energies of protons E as a function of z , while the lower panel shows the proton emission angle in the center-of-mass frame, θ_{cm} , as a function of z . Each line represents a fictitious excited state of ^{230}Ac , with excitation energies ranging from 0 to 6 MeV in 1 MeV intervals. Note how the lower left part of the figure leads to an ambiguous $(E, z) \rightarrow (E_x, \theta)$

illustrated in Figure 2.10 represents an upper limit rather than a guarantee. Both issues are addressed in the analysis of Chapter 9. Neither is specific to the case studied here. With solenoidal spectrometers operating at ISOLDE, ANL and FRIB, and with the reach of radioactive-beam facilities extending towards the neutron-rich actinides, a method established on a well-characterised system can be applied progressively further from stability; the resulting fission probabilities and fragment distributions are also of direct interest to nuclear-data applications. The concrete realisation of the method at ISOLDE, the ISS setup used for IS739, is described in the next chapter.

2.5 Alternative approaches

The experimental approach presented in this thesis belongs to a broader effort to characterise the fission of actinides through observables such as the fission-fragment charge and mass distributions and the fission-barrier height, using a variety of complementary reaction mechanisms and experimental techniques. It is useful to place the transfer-induced approach adopted in IS739 in the context of alternative methods that give access to the same, or neighbouring, fissioning systems.

2.5.1 SOFIA: Coulomb excitation and quasi-free (p, 2p) scattering

A first and particularly powerful approach is the one pursued by the Studies of Fission with Aladin (SOFIA) collaboration at GSI, which exploits inverse kinematics at relativistic energies to identify *both* fission fragments simultaneously in nuclear charge and mass, event by event, over the full fragment range [95, 96]. In the original setup, a relativistic ^{238}U beam at ~ 1 GeV/nucleon impinges on a beryllium target, producing a range of secondary beams. The secondary beams of interest, the fissioning systems, are then directed onto high- Z targets, where fission is induced by electromagnetic (Coulomb) excitation at relativistic energies. The forward-focused, fully stripped fragments are then analysed with a double ionization chamber, which yields the nuclear charge from the energy loss, and with the ΔE - $B\rho$ -ToF technique across the ALADIN/GLAD dipole, which yields the mass from the magnetic rigidity and a high-resolution (~ 40 ps) time-of-flight measurement [95]. This provides the fragment Z and A distributions with excellent resolution, but the excitation energy of the fissioning system is not tagged event by event: Coulomb excitation populates a distribution of E_x rather than a well-defined value.

More recently, the SOFIA setup has been combined with quasi-free proton-knockout (p, 2p) reactions on a liquid-hydrogen target [97]. Here a relativistic ^{238}U beam (540 MeV/nucleon) knocks out a proton, producing an excited ^{237}Pa

fissioning system, and the excitation energy is reconstructed with the missing-mass method from the two outgoing protons measured in the CALIFA calorimeter together with a silicon tracker. This route reaches actinide fissioning systems in the same mass region as $^{232}\text{U}(\text{d}, \text{p}f)$ and adds full fragment identification, but the excitation energy is obtained with a finite resolution set by the knock-out kinematics and the detector performance, in contrast to the sharp, directly measured E_x tag provided by the recoil proton in the $(\text{d}, \text{p}f)$ reaction.

2.5.2 VAMOS and PRISMA: multi-nucleon transfer

A complementary route is offered by transfer- and multinucleon-transfer-induced fission studied in inverse kinematics at large-acceptance magnetic spectrometers, most notably VAMOS at GANIL and PRISMA at LNL Legnaro. In the VAMOS measurements a ^{238}U beam impinges on a light (^{12}C) target a few percent above the Coulomb barrier; inelastic, transfer and fusion channels populate a range of moderately excited actinides, and one forward-boosted fission fragment is fully identified in Z and A by the spectrometer, giving isotopic yield distributions for well-defined fissioning systems [98]. The fissioning nucleus and its excitation energy are tagged event by event through the outgoing target-like partner detected in a silicon telescope, so that up to about nine transfer channels, spanning neutron-rich actinides from U to Cm, can be separated [74, 99]. Crucially, these spectrometer measurements do reconstruct the excitation energy of the fissioning nucleus on an event-by-event basis, but its resolution is set by the kinematic reconstruction of the ejectile in a multi-body channel (and, for MNT, by the spread of transferred mass and Q value), and is therefore coarser than the sharp E_x tag obtained here from the single recoil proton of a clean two-body (d, p) reaction. The same philosophy underlies MNT-fission campaigns at PRISMA, where the identified fragments are coupled to γ -ray spectroscopy to reach systems that particle-capture or fusion cannot access [100].

Limitation

The essential limitation of this approach is that the fissioning systems that can be reached are dictated by the choice of a *stable* primary beam and target: a ^{238}U beam gives access to the region around ^{238}U and, through MNT, to a band of neighbouring actinides, predominantly on the neutron-rich side (U, Np, Pu, Cm). They therefore extend to unstable systems only to the limited degree allowed by the transfer kinematics, and cannot be steered arbitrarily across the nuclear chart. An unstable system such as ^{230}Ac is not naturally populated from a ^{238}U beam, and reaching it requires either a radioactive beam or, as in IS739, a ^{229}Ac beam delivered by an ISOL facility. In this sense, the $(\text{d}, \text{p}f)$ measurement presented here and the secondary-beam approach of SOFIA are complementary to the stable-beam spectrometer measurements: the

former select the fissioning nucleus directly, the latter deliver superior fragment identification over a beam-constrained region of the chart.

Chapter 3

Experimental setup

IN order to measure fission barriers and cross-sections of neutron-rich nuclei in inverse kinematics at ISOLDE, a new experimental setup has been designed. It consists of several detectors, each optimized for this purpose. All detectors operate in the vacuum inside the ISS superconducting solenoid, and each provides different observables which are combined to extract the fission probability as a function of the excitation energy.

When measuring (d, pf) reactions, the distinguishing feature used to identify fission is the detection of a backward-ejected proton in *coincidence* with, ideally, two fission fragments. As already discussed in Sec. 2.4.1, the excitation energy E_x of the fissioning nucleus can be determined from the deposited energy and hit position of the emitted proton according to Eq. 2.7. Knowing the number of fission events $N_{d,pf}$ in an excitation energy interval one can calculate the fission probability P_f for the residual nucleus as a function of the excitation energy as:

$$P_f(E_x) = \frac{N_{d,pf}(E_x)}{N_{d,p}(E_x) \cdot \epsilon_f}, \quad (3.1)$$

where $N_{d,p}(E_x)$ represents the number of (d,p) events, and ϵ_f represents the fission fragment detection efficiency. Additionally, elastically scattered deuterons are detected in the forward direction in order to measure the beam current hitting the target. This is needed to calculate absolute cross-sections. Finally, the total energy of all γ rays emitted as well as their multiplicity, which are ingredients for r-process simulations and for a better understanding of angular momenta of fission fragments, are also measured [65]. Figure 3.1 gives a schematic overview of the detector arrangement.

In the following sections, the target and the individual detectors used to detect the aforementioned particles are described in detail.

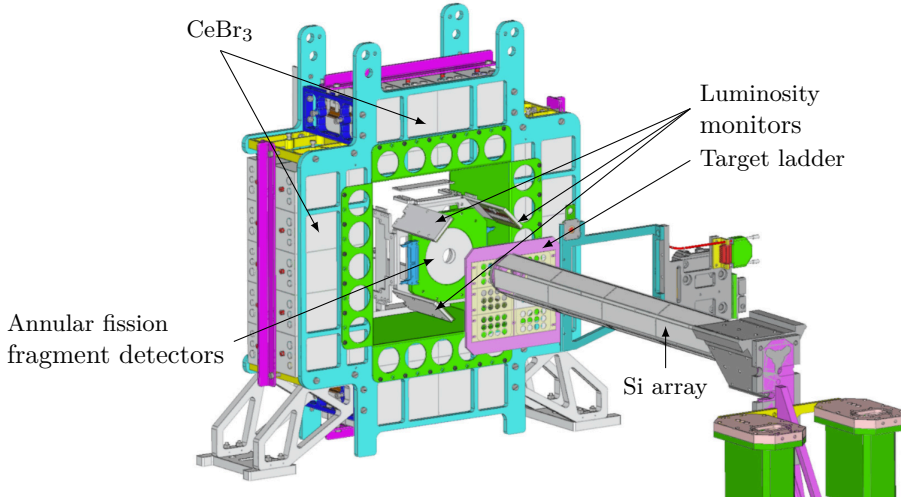


Figure 3.1: Schematic illustration of the detectors surrounding the target inside the vacuum chamber of the ISS magnet. All dimensions and positions are to scale and have been optimized through simulations for fission of ^{230}Ac at an excitation energy of 8 MeV. The hollow upstream silicon array is also shown. The beam enters from the right. Beam diagnostics detectors are not included. Figure from Ref. [90].

3.1 Isolde Solenoidal Spectrometer

As shown in Figure 2.6, the ISOLDE Solenoidal Spectrometer is installed at the second of the three HIE-ISOLDE beam lines. The spectrometer is based on a former MRI magnet, acquired in 2016 from the University of Queensland Hospital in Brisbane, Australia, with a maximum field strength of 4 T. The magnet bore has an overall length of approximately 2.5 m and an inner diameter of about 0.9 m, dimensions that largely determine the geometry and mechanical constraints of the experimental setup. At present, safety constraints in the ISOLDE hall limit the operational magnetic field to 2.5 T. This restriction is expected to be relaxed in the future to allow operation up to the full possible magnetic field of 4 T. However, a higher magnetic field is not necessarily advantageous. The optimal field strength depends on the reaction kinematics and on the desired excitation-energy range. As shown in Figure 2.13, protons from higher excitation energies of the compound nucleus are emitted with lower kinetic energies, and thus smaller transverse momenta. In a stronger field, their trajectories are more tightly bent, so that protons spanning a broad kinematic range are focused onto only a small fraction of the silicon array. This reduces the geometrical acceptance for that excitation-energy region and degrades the

effective position (and hence energy) resolution, as distinct proton energies map onto nearly overlapping positions. The field must therefore be tuned to cover the excitation-energy range of interest across the full length of the array.

3.2 Targets

To enable the (d, pf) and $(d, p\gamma)$ reactions, deuterated plastic targets, CD_2 , with thickness of either 0.5 mg/cm^2 or 1.0 mg/cm^2 were used. These thicknesses represent a trade-off between energy resolution and the maximum achievable luminosity: while a thicker target would increase the interaction rate, it would also degrade the energy resolution. In particular, increasing the target thickness leads to larger energy losses of both the incoming beam and the reaction products within the material, resulting in enhanced energy straggling and broader peaks in the measured energy spectra. Moreover, the higher deposited energy in thicker targets may accelerate target degradation under intense beam irradiation. Given the beam intensities available during the IS739 experiment, a target thickness of 0.5 mg/cm^2 was used in order to minimize energy loss and straggling effects¹. For reference, a ^{229}Ac beam at an energy of 8 MeV/u loses approximately 75 MeV , i.e. $\sim 0.3 \text{ MeV/u}$, while traversing a 0.5 mg/cm^2 CD_2 target. In addition, pure carbon targets of the same two thicknesses were used to perform dedicated background measurements. These measurements allow the contribution from reactions on carbon to be quantified and subsequently subtracted during offline analysis, thereby isolating the signal associated with deuteron-induced reactions.

For the first time at ISS, the targets were mounted on a two-dimensional target ladder, shown in Figure 3.2a, positioned between the upstream silicon array and the downstream detector systems inside the ISS chamber. Each target has a diameter of 10 mm and the position of the target ladder can be adjusted remotely using a motorised system with a positioning precision of 0.05 mm . This capability allows multiple targets to be employed during a single experiment, and enables rapid switching between targets of different thicknesses or materials without breaking vacuum, as well as repositioning if a target begins to deteriorate, which is particularly relevant for beams of ions with high nuclear charge or high beam intensity.

The precise positioning feature also proved useful during data taking, allowing small displacements of the target relative to the beam focus (Figure 3.2b). This multiplied the effective number of targets, which was needed because a new spot had to be selected every hour to counteract the luminosity degradation from localised target damage. The ladder additionally includes apertures of 10 mm and 3 mm , needed to optimize the beam focus during tuning, as well

¹A target thickness of 1.0 mg/cm^2 was tested during IS739, with correspondingly degraded performance.

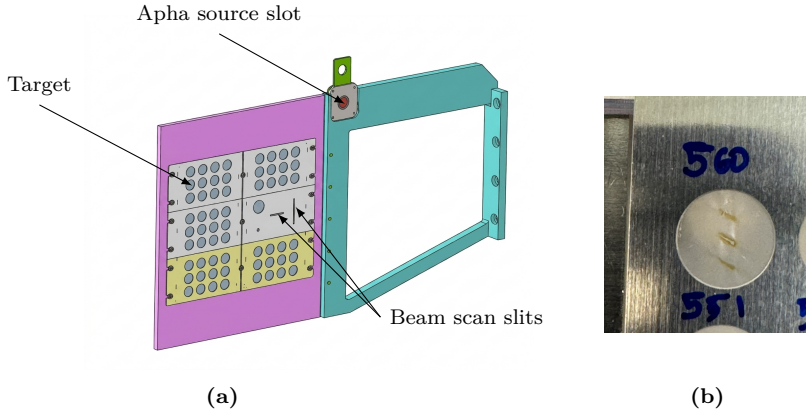


Figure 3.2: (a) CAD (Computer-Aided Design) drawing of the target ladder used at ISS. The target ladder also features a slot for mounting an α -source for calibration of the silicon detector, and slits which can be used to scan the beam profile. In total, the target frame held 48 CD_2 targets (24 of 0.5 mg/cm^2 and 24 of 1 mg/cm^2) and 12 C targets (3 of 0.2 mg/cm^2 , 6 of 0.5 mg/cm^2 , and 3 of 1 mg/cm^2). Of these, 24 CD_2 and 4 C targets were used during IS739. The beam scan slits, together with a downstream Faraday cup, allowed the characterisation of the beam spot at the target plane. (b) Beam spots on one of the CD_2 targets used during the IS739 experiment.

as vertical and horizontal slits for performing beam profile scans, as shown in the FactBox on page 55. Compared to the one-dimensional target ladder used in previous experiments, the addition of a second dimension allows a larger number of targets to be mounted simultaneously. Moreover, the new design includes a dedicated slot for the installation of a double-sided α source for calibration purposes. Since this slot is not shielded, the source could not be kept in place during the experiment and had to be installed separately, which required breaking the vacuum.

Beam profile scan

The transverse beam profile at the target position is measured using two orthogonal slits, one vertical and one horizontal, mounted on the target frame and acting as optical attenuators. The horizontal slit (1.2 cm tall) selects the x profile at a certain y coordinate, while the vertical slit (2 cm wide) selects the y profile. A motorized system drives the target frame across the beam, so that each slit selects a narrow slice of the beam intensity; the current induced on an electrode installed on the target frame and on the downstream Faraday cup is recorded simultaneously as a function of position, providing two complementary measures of the beam current and yielding the intensity profile in each transverse direction independently. Figure 3.3 shows the transverse beam profile measured during the commissioning of the experimental setup. Gaussian fits to the measured profiles yield a beam spot size of $\text{FWHM}_x = 1.40$ mm and $\text{FWHM}_y = 1.81$ mm, confirming the compact and well-focused nature of the beam at the target position.

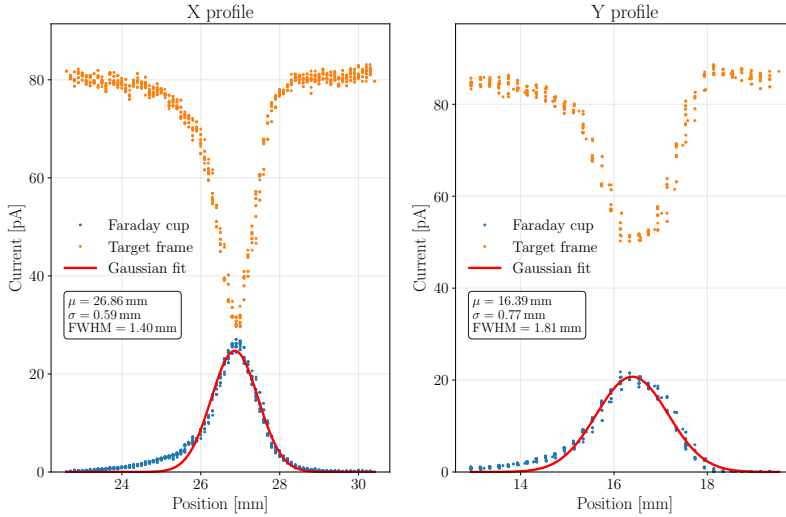


Figure 3.3: Beam profile scan recorded during the commissioning campaign with the ^{22}Ne beam. The scan provides a direct measurement of the transverse beam dimensions at the target position, yielding a beam spot size of $\text{FWHM}_x = 1.40$ mm and $\text{FWHM}_y = 1.81$ mm.

3.3 Position-sensitive silicon array

One of the key products of the (d, pf) reaction is an emitted proton that follows a helical trajectory due to the presence of the uniform magnetic field inside the solenoid. Protons emitted at backward laboratory angles are detected by the on-axis, Liverpool position-sensitive silicon detector array located upstream of the target ladder.

The Liverpool silicon array has a total length of 510 mm and a hexagonal, hollow geometry that allows the beam to pass through its central axis. The distance between the target ladder and the detector array can be adjusted using a motorized system, with a minimum separation of 14.5 mm [101], allowing the excitation-energy range covered by the measurement to be optimized.

The array consists of 24 Double-Sided Silicon-Strip Detectors (DSSSDs), arranged into three identical and independent modules, each covering two sides of the hexagonal structure (i.e., eight detectors per module), as shown in Figure 3.4. Each DSSSD features 128 strips on the front (p-side) with a pitch of 0.953 mm and 11 strips on the back (n-side) with a pitch of 2 mm; both sides have an interstrip gap of 0.129 mm. The silicon chip has overall dimensions of $125 \times 25 \text{ mm}^2$ and a thickness of 1 mm, corresponding to an active area of approximately $121.9 \times 21.9 \text{ mm}^2$ (Figure 3.5).

The detector array is positioned at a radius of 30 mm from the beam axis to the detector surface. It provides a solid-angle coverage of 94% along the beam-axis direction, corresponding to the proton emission polar angle θ , and

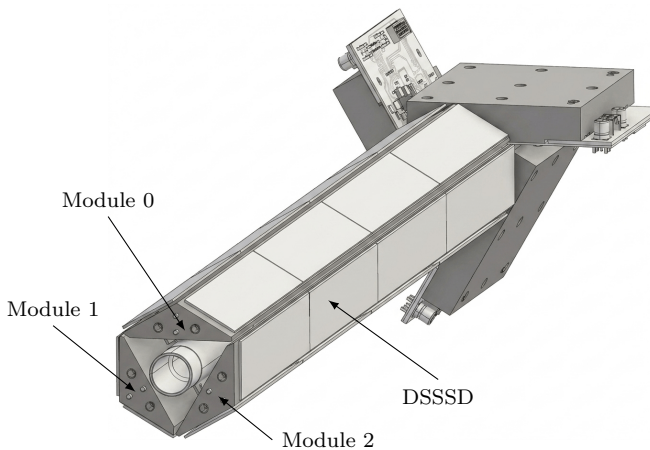


Figure 3.4: Schematic illustration of the hexagonal-shaped silicon array used for detecting ejected protons. The exit towards the target is in the lower left, where also a short multi-turn silencer can be seen. Figure adapted from Ref. [90].

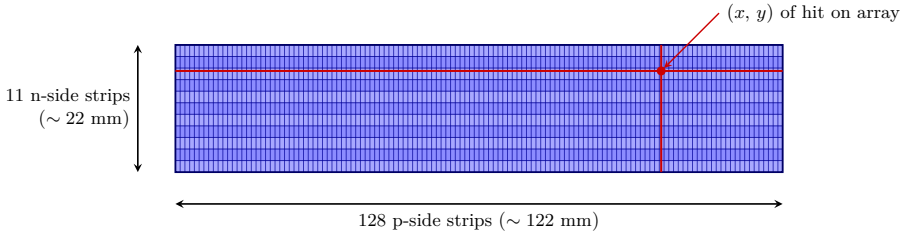


Figure 3.5: Schematic drawing of a single DSSSD, showing the full junction side (p-side) and the ohmic side (n-side).

70% of the azimuthal angle.

Within each module, coincidences between signals from the p- and n-sides of the DSSSDs are used to determine the position of the detected proton. The position along the incoming beam axis, z , is obtained from the index of the hit among the 128 p-side strips, which are paired across the two silicon wafers within a given module. The transverse position in the x - y plane, corresponding to the azimuthal angle of the impact point, is determined from the 11 n-side strips, which are read out independently for each wafer. This configuration allows the system to achieve a Q-value resolution approaching 20 keV [101]; during the IS739 experiment, however, the achieved resolution was approximately 100 keV (FWHM) [102].

Each module of the silicon array is read out by an identical and independent electronic system based on application-specific integrated circuits (ASICs). Six ASICs are installed on each module, with four dedicated to the p-side readout and two to the n-side channels. For the p-side, all 128 channels of each ASIC are utilised, whereas for the n-side only 44 channels per ASIC are required.

Within the ASICs, the signals from the silicon strips are first processed by charge-sensitive preamplifiers, producing fast-rising pulses with amplitudes proportional to the collected charge. The preamplifier output is then split into a timing branch and an energy branch. The timing branch provides time-stamp information with a resolution of the order of several tens of nanoseconds, while the energy branch includes a shaping amplifier with a shaping time of $4 \mu\text{s}$ to optimise the signal-to-noise ratio, followed by a peak-hold circuit to record the pulse amplitude. Both timing and energy information are subsequently stored in the output data buffer.

To suppress noise-induced triggers and preserve timing correlations, the threshold of the timing branch was set to its maximum value. For signals below this threshold, the timing information is extracted from the shaped signal in the energy branch, at the cost of an increased time-walk effect on the order of $0.5 \mu\text{s}$.

3.3.1 Background in the Si array

While only protons can reach the array positioned in the backward direction from (d,p) reactions with a CD₂ target, the situation is quite different for the carbon component of the target. A major source of background is believed to originate from Multi-Nucleon Transfer (MNT) reactions with the carbon nuclei in the target, which can produce, among other possible outcomes, light-charged ejectiles (primarily α particles) also in the upstream direction. Fortunately, the cyclotron period T_{cyc} (as defined in Eq. 2.2) depends solely on the mass-to-charge ratio and the magnetic field strength, independent of the energy or direction of the particle. This allows, in principle, for particle identification by measuring the time-of-flight. A simulated representative time-of-flight spectrum is reported in Figure 3.6. The time-of-flight of α particles is approximately 65 ns or longer, which is distinct from that of protons, which is about 32 ns. This difference *would* allow us to suppress the non-proton signals if the time difference between hits in the array and the fission fragment detectors is measured with sufficient resolution. Inelastic scattering does not produce reaction products in the backward direction, and the probability of emitting light charged particles in a fusion-evaporation reaction is below 1%, according to a PACE4 calculation [103] (see Appendix A in [3]). Finally, an additional contribution to the array singles data beyond (d,p) reactions most likely comes also from deuteron breakup that needs to be taken into account when extracting absolute cross-sections. Deuteron breakup refers to the break-up of deuterons in the Coulomb field of the beam, resulting in free protons, even though no nuclear collisions took place. Background measurements using a pure carbon target of equivalent thickness were conducted to evaluate and subtract the background. It should be stressed that the time-of-flight discrimination described above requires a timing reference, provided by a fission fragment detected in coincidence in the downstream fission detectors. The singles yield $N_{d,p}(E_x)$ of Eq. 3.1, however, does *not* require a fragment: with no recoil detection other than the fragments themselves, no start reference is available and the array time cannot be converted into a time-of-flight. The α -particle (and other) background in the singles data is therefore removed not by a timing cut but through the carbon-target subtraction, which reproduces the MNT and breakup contributions independently of any timing information.

Figure 3.6 shows that, even with good time resolution, it is impossible to disentangle two-turn protons from one-turn α particles. As a result, only single-turn protons are considered, which will consequently reduce the statistics.

3.4 $\Delta E - E$ silicon telescope

In inverse kinematics, fission fragments from the (d,pf) reaction are boosted in the forward direction, resulting in an angular distribution that is strongly

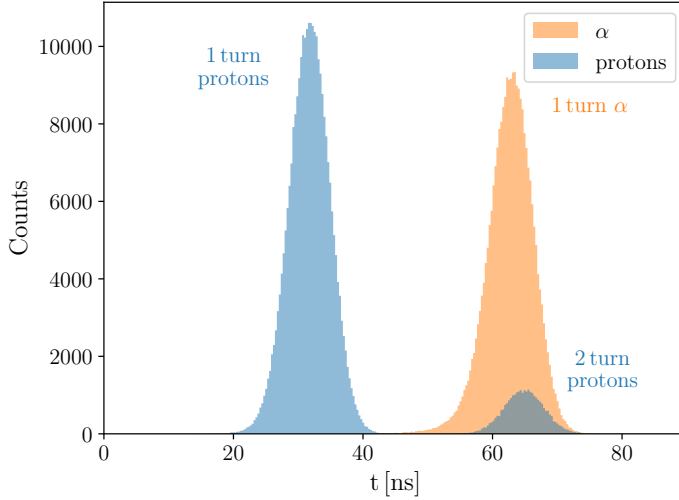


Figure 3.6: Simulated time-of-flight spectrum of protons detected in the Si array DSSSDs sensor with an assumed 9.1 ns FWHM resolution (as obtained at HELIOS [10]). The simulation assumes two isotropic sources of protons and α particles with energies in the range 0.5–10 MeV, with the Si array positioned 15 cm from the target. Two peaks around 33 ns and 66 ns, corresponding to single-orbit protons and α particles, as well as double-cycle protons, can be distinguished.

forward-peaked in the laboratory frame. This corresponds to a cone-shaped emission with an opening angle that depends on the beam energy and the transverse momentum of the fragments. The use of an annular detector geometry centered on the beam axis thus provides efficient detection of both fission fragments simultaneously while allowing any unreacted beam to pass through the central hole. The chosen detector consists of two Micron S3 DSSSDs [104], shown in Figure 3.7, arranged as two layers in a $\Delta E - E$ telescope configuration. The detailed dimensions of this type of detector are reported in Table 3.1. The segmentation of the detectors into rings and sectors enables an unambiguous identification of fission events through the detection of two coincident hits separated by an azimuthal angle of 180° . This signature reflects the back-to-back emission of the two fission fragments in the center-of-mass frame.

Reaction products reaching the detectors first traverse the thin ΔE silicon detector ($65 \mu\text{m}$), where they lose part of their kinetic energy, and may subsequently enter a second, thicker E detector ($1000 \mu\text{m}$), in which they are fully stopped and deposit their remaining energy. In principle, the combined $\Delta E - E$ information can be used for particle identification, since the energy-loss pattern

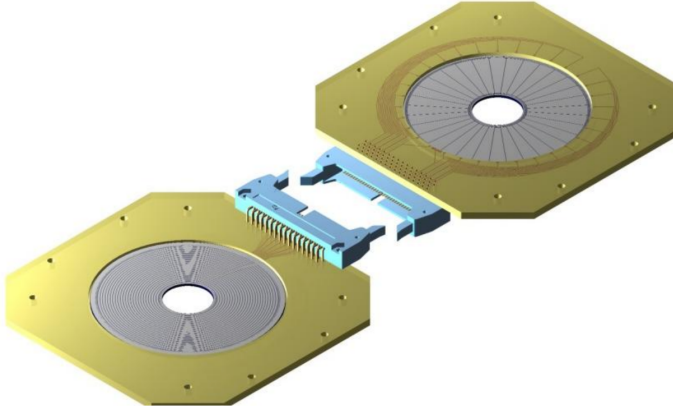


Figure 3.7: The S3 detector and Printed Circuit Board (PCB), viewed from the p-(rings) and n-sides (sectors), were used in a $\Delta E - E$ telescope configuration. Figure adapted from Ref. [104].

depends on the kinetic energy as well as on the atomic number and mass of the detected nucleus.

A $\Delta E - E$ measurement is possible for particles that punch through the ΔE detector and are stopped in the E detector. Typical fission fragments are expected to carry kinetic energies well above 150 MeV, depositing hundreds of MeV in the silicon layers. At such high deposited energies, pulse-height defect effects are expected to become significant and may degrade the achievable energy resolution, making isotopic identification of fission fragments challenging [105, 106]. A major part of the PHD arises from electron-hole recombination in the dense plasma column produced along a heavy-ion track, whose rate scales with the local plasma density and therefore with the electronic stopping power of the incoming ion [107]. In the present setup, the fragments strike the silicon surface at large incidence angles rather than perpendicularly: the deposited energy is spread over a longer path and a larger volume, lowering the plasma density and hence the recombination contribution. This provides a possible explanation for the lack of a strong PHD in the data. Moreover, owing to their large stopping power, a substantial fraction of the fission fragments is expected to stop already in the first detector layer, limiting the range over which a clean $\Delta E - E$ correlation can be established. Nevertheless, as discussed in Chapter 9, these effects are not severe enough to prevent a charge separation sufficient for the identification of fission fragments.

The detector configuration provides a large angular acceptance, which is crucial for efficient fission-event detection and coincidence measurements. In addition, lighter reaction products, such as carbon nuclei scattered from the

Active area	
Active Si inner diameter	22.0 mm
Active Si outer diameter	70.0 mm
Chip dimension	
Chip inner diameter	20.0 mm
Chip outer diameter	76.0 mm
Segmentation junction side	
Number of elements	24 rings
Pitch	886 μm
Segmentation ohmic side	
Number of elements	32 sectors
Pitch	11.25 deg
Thickness (wafer/active)	
ΔE detector	70 / 65 μm
E detector	1004 / 1000 μm
Dead layers	
$\Delta E/E$ ohmic contact	0.65 μm
$\Delta E/E$ junction side	4.6 μm

Table 3.1: Geometric characteristics and segmentation of the Micron S3 silicon detectors used in the $\Delta E - E$ telescope configuration for fission-fragment detection [104]. The ring-and-sector segmentation allows for unambiguous identification of the two fission fragments emitted back-to-back in azimuthal angle.

target, can punch through the ΔE layer and be readily identified using the $\Delta E - E$ technique.

Each silicon detector is mounted on a dedicated Printed Circuit Board (PCB), which provides both mechanical support and electrical routing for the readout of the junction and ohmic contacts. The PCBs ensure a precise alignment of the ΔE and E layers along the beam axis and allow for a compact telescope assembly with minimal inactive material.

Figure 3.8 shows the relative placement of the target, the DSSSD array, and the fission-fragment detectors within the experimental setup. Photographs of the annular silicon detectors used in the IS739 experiment are shown in Figure 3.9.

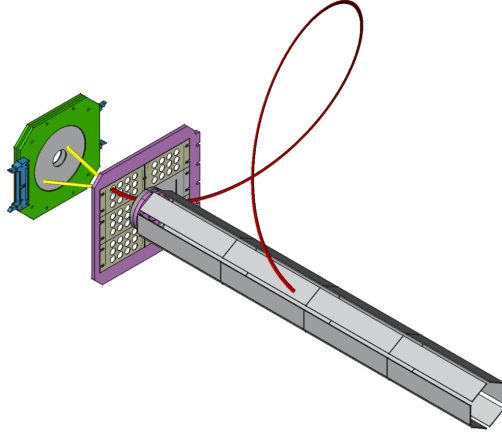
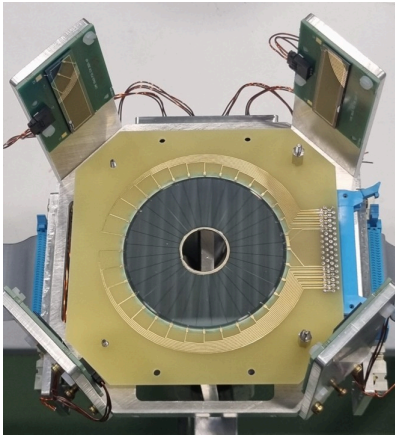
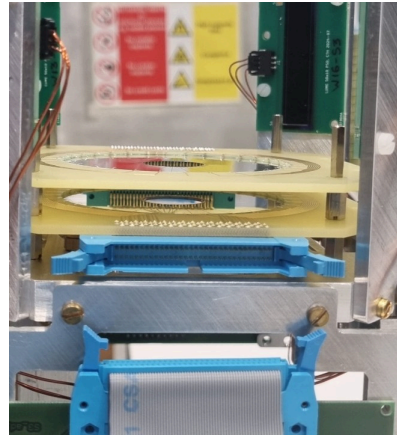


Figure 3.8: Schematic illustration of the experimental setup. The accelerated beam enters from the lower right, passing through the hollow, position-sensitive silicon detector array located upstream of the target ladder. The typical helical trajectory of a proton and the helical arcs of fission fragments are shown. The forward-boosted fission fragments are detected by a $\Delta E - E$ silicon telescope placed downstream of the target, upper left in the figure. Figure from [90].



(a) Ohmic side of the ΔE silicon detector, illustrating the 32-sector azimuthal segmentation.



(b) Side view of the ΔE and E silicon detector layers, showing their mounting on the printed circuit boards (PCB).

Figure 3.9: Overview of the annular $\Delta E - E$ silicon telescope, with inner and outer radius 1.1 cm and 3.5 cm respectively. The ΔE and E wafers are $70\ \mu\text{m}$ and $1004\ \mu\text{m}$ thick. Dead layers: $0.65\ \mu\text{m}$ Si on each ohmic contact, $1.10\ \mu\text{m}$ Si on the ΔE junction side, plus a $3.5\ \mu\text{m}$ SiO_2 layer between ΔE and E .

3.5 CeBr₃ scintillation array

Information on the energy and multiplicity of prompt γ rays emitted during fission can provide constraints for fission models and r-process simulations, and contributes to a better understanding of the angular-momentum distribution in the fission process [65]. For this purpose, γ rays were detected in coincidence with the (d,pf) reaction using CeBr₃ scintillation crystals from the SpecMAT detector developed by the KU Leuven group.

The detector units were integrated into a newly designed box-like mechanical support tailored to the present experimental setup. This geometry was originally conceived to accommodate up to 36 individual CeBr₃ detectors; however, only 28 scintillator units were installed in the final configuration. This choice was dictated by the stringent vacuum requirements to open the vacuum gate to the accelerator beam line and to ensure stable operation under high-vacuum conditions. In the final layout, the crystals are arranged in two rows, with eight detectors mounted in the upper panel and ten detectors placed on each lateral side of the structure. This configuration, optimized through dedicated Monte Carlo simulations, represents a compromise between maximizing solid-angle coverage and detection efficiency while accommodating the limited available space. Mounting the detector around 90° relative to the beam direction also reduces the Doppler correction. A schematic view of the mechanical support and detector arrangement is shown in Figure 3.10.

Each scintillator unit consists of a $48 \times 48 \times 48 \text{ mm}^3$ CeBr₃ crystal optically

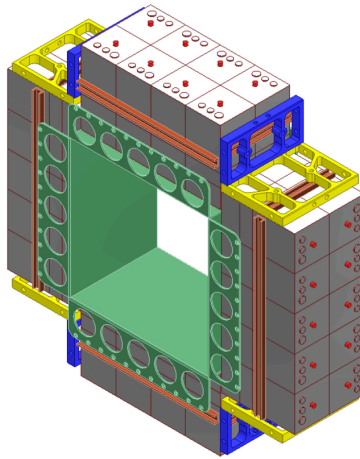


Figure 3.10: Schematic of the new mechanical support for CeBr₃ crystals arranged in a box-like configuration with two square rings. Single CeBr₃ crystals are shown in grey. Figure from Ref. [90].

coupled to a SensL J-series 8×8 Silicon Photo-Multiplier (SiPM) array, with individual $6 \times 6 \text{ mm}^2$ sensors based on $35 \mu\text{m}$ microcell technology [108]. A complete detector unit with a schematic illustration of its internal structure is shown in Figure 3.11. Scintillation photons produced in the crystal following a γ -ray interaction are collected by the SiPM array elements and converted into electrical signals. The SiPM is powered by a built-in, temperature-compensated bias generator, providing stable operation for ambient temperature variations of up to $\pm 5^\circ\text{C}$ around the nominal operating point. The detector requires a low external bias of $+5 \text{ V}$, making it well-suited for operation in vacuum.

The front-end electronics include a built-in pre-amplifier that sums the signals from all 64 SiPM channels to produce a single energy output signal, with a selectable gain in the range $78\text{--}480 \text{ mV/MeV}$. The energy signal exhibits a rise time of about 250 ns and a decay time of $0.55 \mu\text{s}$. A fast timing signal, obtained from the sum of the fast outputs of the central SiPM elements, is also available, although it was not used in IS739. The CeBr_3 detectors provide good energy resolution (approximately 4% FWHM at 662 keV), high detection efficiency, but also an intrinsic background activity due to the presence of a ^{227}Ac contaminant [109] in some of the detectors, while remaining tolerant to strong magnetic fields.

The crystal and readout electronics are housed in an aluminium enclosure with external dimensions of $55 \times 55 \times 110 \text{ mm}^3$, featuring a 1 mm thick entrance window for γ rays and 3 mm thick side walls. To prevent the implantation of charged particles in the active detector volume, an additional 2 mm thick aluminium shield was placed in front of the γ -ray entrance window. The absence of ferromagnetic components allows these detectors to operate reliably in the magnetic field generated by the solenoidal spectrometer.

To complement the schematic views presented above, a photograph of the

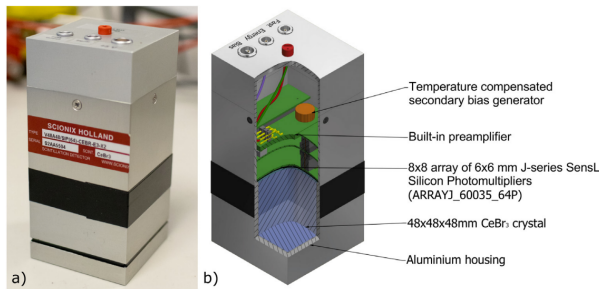


Figure 3.11: A $48 \times 48 \times 48 \text{ mm}^3$ CeBr_3 detector unit: (a) complete detector and (b) cutaway CAD view of the detector. The SiPM array is powered by a temperature-compensated bias generator. The detector operates from a $+5 \text{ V}$ external bias. Figure from Ref. [108].

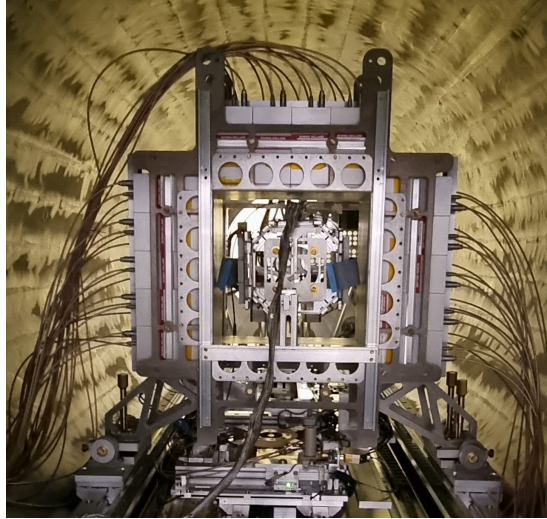


Figure 3.12: The CeBr₃ scintillator array during the installation phase of IS739 inside the solenoidal magnet of the ISS spectrometer.

fully assembled CeBr₃ detector array as installed inside the solenoidal magnet of ISS is shown below in Figure 3.12.

3.6 Luminosity monitor

When extracting fission probabilities, the number of detected fission events must be properly normalized in order to obtain absolute cross sections. This requires knowledge of the product of the number of beam ions that actually strike the target and the areal density of the nuclei in the target. At ISS, the incoming beam intensity is monitored by detecting deuterons elastically scattered from the target. This task is performed by the luminosity detectors, instruments specifically designed to measure the interaction rate between the beam and the target.

Figure 3.13 illustrates, as an example, the differential cross section and energy distribution expected for elastically scattered deuterons, obtained with the FRESKO [110] and LISE++ [111] codes for a ²²⁹Ac beam at 8 MeV/u on a CD₂ target. For a typical beam intensity of $\sim 10^5$ pps and a target thickness of 1 mg/cm², the FRESKO cross section integrated over the LUME acceptance (47°–75°, orange band) corresponds to a few detected deuterons per second. In the example shown, only a small fraction of deuterons emerge at very forward angles near 0°, where their kinetic energy reaches a maximum value of about 31 MeV. The majority are instead scattered toward angles approaching 90°,

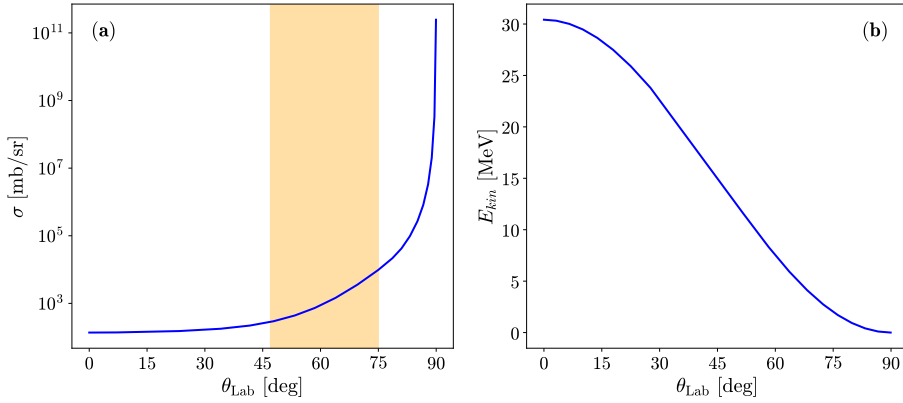


Figure 3.13: (a) Differential cross-section as a function of scattering angle in the laboratory frame for elastically scattered deuterons from an incoming beam of ^{229}Ac at 8 MeV/u provided by FRESCO. (b) Energy as a function of scattering angle in the laboratory frame, calculated using LISE++. Most deuterons are scattered at angles where their energies are very small. The orange shaded region indicates the angular range covered by the LUME detectors.

where their energies drop to nearly zero. Under the latter conditions, many deuterons do not exit the target material and therefore cannot be detected. This makes it necessary to optimize the luminosity-detector geometry to ensure that a sufficient number of deuterons with measurable energies can be recorded. In inverse kinematics, momentum conservation prevents deuterons from being scattered to backward angles, which means that the luminosity detector must be positioned downstream of the target.

For the first time at ISS, the beam luminosity was measured by detecting elastically scattered deuterons with an off-axis luminosity monitor, commonly referred to as the LUME. This system consists of four position-sensitive silicon wafers, each with an active area of $50 \times 10 \text{ mm}^2$ (Figure 3.15). The wafers are mounted parallel to the beam axis, with their sensitive surfaces facing the beam. They are arranged at azimuthal angles separated by 90° , allowing the system to sample scattered deuterons in multiple directions. This configuration helps mitigate the effects of beam-related imperfections, such as misalignment, angular spread, or a finite beam spot on the target, by providing redundant measurements at different angles. The concept of an off-beam-axis luminosity monitor of this kind was independently proposed by B. Kay at ANL and A. Kawęcka, locally, and later adopted in the HELIOS and SOLARIS spectrometers [112].

Finally, the details of the experimental method adopted for the determination of the beam luminosity are presented in the FactBox on page 68.

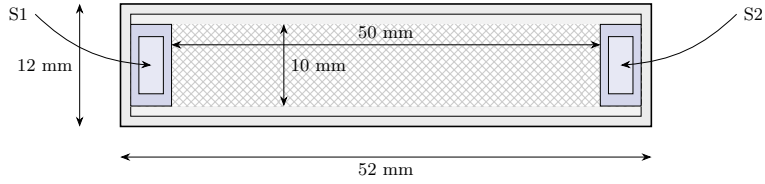


Figure 3.14: Position-sensitive silicon sensor: When a charged particle hits the detector, it deposits energy E . Signals are collected at contacts S1 and S2, which are used to infer the position along the strip through sharing of the signal charge through the resistive front-side contact. The total deposited charge is also measured by a fully covering back-side contact. The figure shows the dimensions of both the board ($12 \times 52 \text{ mm}^2$) and the active area of the silicon wafer ($10 \times 50 \text{ mm}^2$). Figure inspired by Ref. [113].

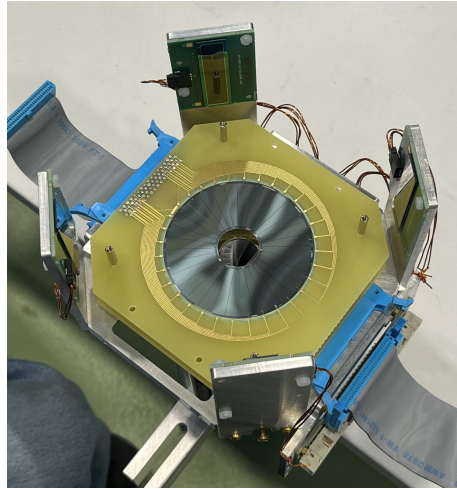


Figure 3.15: Photograph of the off-axis luminosity monitor used at ISS in the 2025 experiments, showing the four position-sensitive silicon wafers mounted on the support structure of the silicon $\Delta E - E$ telescope. The wafers are oriented parallel to the beam axis and arranged at azimuthal angles separated by 90° .

Luminosity Monitor Yields

Accurate beam intensity measurements are crucial for determining absolute quantities, such as cross-sections. Rutherford scattering is widely used for this purpose due to its well-established theoretical framework and known cross-section, making it a reliable method. One of the main advantages is that it allows intensity measurements without altering the beam by using inevitable background events. Additionally, it can be analyzed for individual target species and works effectively over a wide range of scattering angles, especially at low beam energies. Luminosity detectors measure elastically scattered events, allowing to determine the product of the beam particle rate and the target thickness.

Experiment

For a given reaction involving a beam of intensity I_0 (ions/s) incident on a target containing N_t (atoms/cm²) nuclei per unit area, the number of scattered particles J (count/s) is given by:

$$J = I_0 N_t \sigma, \quad (3.2)$$

where σ is the total cross-section. When considering a detector of finite size covering a solid angle $\Delta\Omega$, as illustrated in Figure 3.16, the differential cross-section, $\frac{d\sigma}{d\Omega}(\theta, \phi)$, is more useful. It represents the likelihood of particles being scattered in a specific direction, characterized by the polar and azimuthal angles θ and ϕ .

The experiment luminosity, in units of b^{-1} , can thus be experimentally determined as:

$$I_0 N_t = \frac{Y}{\frac{d\sigma}{d\Omega} \cdot \Delta\Omega \cdot \varepsilon_\pi \varepsilon_\delta}, \quad (3.3)$$

when the absolute efficiency of the detector ε_δ , the beam purity ε_π , and Y , the yield measured by the detector, are all known.

A more accurate value is obtained by using e.g. DWBA models to calculate the differential cross section instead of the pure Rutherford estimate. This product of beam and target is the only quantity that can be easily experimentally determined, as it is difficult to disentangle I_0 and N_t when performing an experiment. The quantity $\frac{d\sigma}{d\Omega} \cdot \Delta\Omega = \sigma_{\text{det}}$ is the cross section for scattering into the detector.

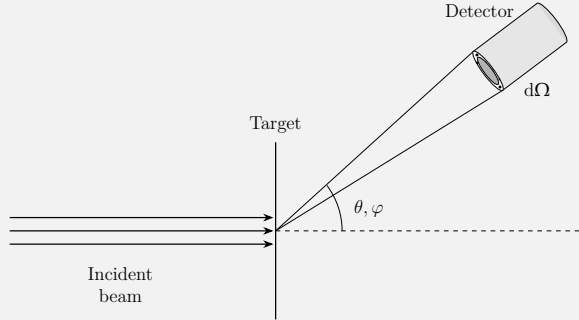


Figure 3.16: Schematic representation of a scattering experiment. An incident beam of intensity I_0 impinges on a target with areal density N_t , and scattered particles are detected within a finite solid angle $\Delta\Omega$, in the direction defined by the polar and azimuthal angles θ and ϕ .

Position-Sensitive Detectors with resistive readout

In the Position Sensitive Detectors (PSD) used for LUME, the position determination relies on charge division along a resistive layer. When a charged particle interacts with the silicon, it creates electron-hole pairs; the liberated charge carriers drift to the front and back surfaces of the detector. On the front, the charge then spreads across the resistive layer toward the electrodes at the ends. The amplitude of the signal collected at each electrode is proportional to the amount of charge reaching it, which in turn depends on the position of the interaction along the detector. Each PSD generates three signals: the total energy output from the contact on the back side of the detector, E , and two signals, X_A and X_B , from contacts on the front side at the two far ends of the strip, as depicted in Figure 3.17.

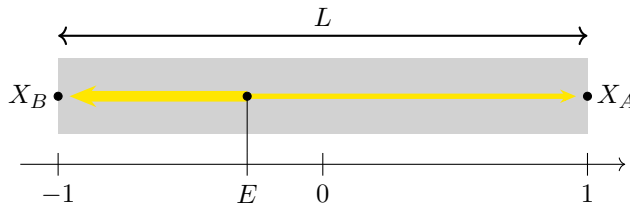


Figure 3.17: Schematic of a Position Sensitive Detector (PSD). A charged particle interacts with the silicon, generating a charge that spreads across the resistive layer. The signals collected at the back contact (total energy signal E) and the front contacts at each end of the strip (X_B and X_A) are used to determine the position of the interaction along the detector.

The relative hit position u along the strip of the PSD can be calculated as follows:

$$u = \frac{X_B - X_A}{E}, \quad u \in [-1, 1]. \quad (3.4)$$

Nominally, $E = X_A + X_B$. When a particle hits the center of the PSD, the signals X_B and X_A have equal amplitudes. However, if the particle hits very close to one edge of the strip — for example, near edge B — then the X_B signal will have a higher amplitude, while the corresponding X_A signal will be smaller. Depending on the electronic settings, X_A could in this case fall below the energy threshold, resulting in an incomplete hit.

As defined in Eq. 3.4, $u \in (-1, 1)$. The absolute hit position on the strip can be calculated with respect to the target distance as:

$$z = \frac{L}{2}u + d_{\text{target}}, \quad (3.5)$$

where L is the length of the PSD, and d_{target} is the distance between the center of the active area of the silicon wafer and the target plane.

3.7 Beam diagnostics detectors

Finally, the two most downstream detection devices are used for beam diagnostics: a Faraday cup and a $\Delta E - E$ silicon detector telescope. The Faraday cup monitors the beam current, while the $\Delta E - E$ detector is typically used to test the purity of the beam. These devices were primarily designed for examining the beam without any obstruction from a target. The $\Delta E - E$ detector, conventionally referred to as the Zero Degree (ZD) detector, is composed of two ORTEC silicon surface detectors, each with an active area of 150 mm^2 [114]. The thicknesses of the two layers are $82 \mu\text{m}$ for the ΔE detector and $486 \mu\text{m}$ for the E detector, values that ensure adequate stopping power for light and medium-mass ions in typical HIE-ISOLDE beam-diagnostic conditions. For very heavy ions such as Ac or U, however, the ΔE layer alone stops the ions completely at the energies available at HIE-ISOLDE, so in this regime the telescope no longer provides $\Delta E - E$ particle identification and the device acts effectively as a single-stage detector. To prevent saturation when operating with intense or

heavy beams, the ZD detector is typically mounted with a pin-hole attenuator placed in front of it, i.e. a foil with many very small holes. The Faraday cup can also be used to monitor the target integrity during the experiment, as heavy beams can degrade the target. This is monitored with the ratio between events of interest and the measured current of the Faraday cup, which should remain constant.

To conclude this descriptive overview of the experimental setup, Figure 3.18 shows the complete system installed inside the superconducting solenoid, with the beam entering from the lower right of the picture.



Figure 3.18: Photograph of the experimental setup installed inside the solenoidal magnet. In the foreground, the Si array is visible, followed along the beam line by the target support structure, the box-like CeBr₃ scintillation array, the LUME detectors, and the ΔE layer of the fission-fragment detector mounted on the yellow PCB board. The beam diagnostics detectors, mounted at the end of the setup, are not visible in this photograph. The beam enters from the lower right.

Chapter 4

Data Acquisition System

THE Data Acquisition (DAQ) system is often described as the backbone of a nuclear or particle physics experiment, as it acts as the essential bridge between the physical signals produced by the detectors and their digital representation for offline and online analysis. It is responsible for continuously capturing, digitising, and storing the signals from all active detectors, while ensuring that the experiment runs reliably and with minimal data loss throughout the measurement campaign.

The DAQ system employed in this experiment comprises three independent subsystems, each dedicated to a distinct class of detectors, as illustrated in Figure 4.1. The first is based on custom ASICs and handles the readout of the Liverpool silicon array. The second, based on CAEN electronics, provides the common clock and synchronisation infrastructure shared by all three subsystems [115]. While this subsystem is also designed to read out ancillary detectors at ISS, none of those were employed in the experiment presented in this thesis. The third relies on Mesytec digitisers [116] and was developed from scratch and integrated into the pre-existing acquisition infrastructure at ISS to manage the readout of the newly installed detectors: the $\Delta E - E$ silicon telescope, the off-axis luminosity monitors, and the CeBr₃ scintillator crystals. All three subsystems operate in free-running mode, meaning that data collection is not initiated by an external trigger. This approach is well-suited to the present experimental conditions, where average beam intensities are not expected to be high, but exhibit very high instantaneous rates at the EBIS releases with long periods without ions, as was shown in Figure 2.5. A trigger-less acquisition avoids the limitations of hardware triggers for the EBIS beam structure: it minimizes dead time during high-rate pulses and enables flexible offline event selection without predefined trigger conditions.

Since the subsystems acquire data independently, time synchronisation between them is essential and is achieved through two complementary mecha-

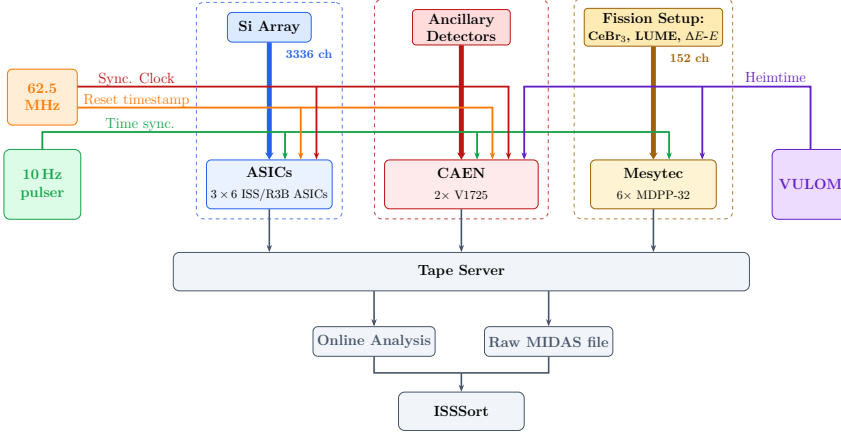


Figure 4.1: Block diagram of the overall DAQ architecture at ISS during 2025.

nisms: a 62.5 MHz clock distributed by the CAEN electronics to both the ASIC and CAEN subsystems, and the so-called Heimtime reference provided by the VULOM module [117] to the CAEN and Mesytec systems. An independent common 10 Hz pulse is used as a redundant cross-check to verify that all subsystems are correctly synchronised, by providing a shared reference timestamp visible to all DAQ systems simultaneously. A more detailed discussion of the synchronisation scheme is given in Section 4.4. Table 4.1 provides an overview of the logic-level signals distributed across the three subsystems; each is described in further detail in the sections that follow.

Signal	Rate	Received by	Purpose
Clock	62.5 MHz	ASIC, CAEN	Common timestamp clock
Timestamp reset	Seldom	ASIC, CAEN	Align time origins at DAQ reset
Heimtime	190 Hz	Mesytec, CAEN	Absolute time reference
10 Hz pulser	10 Hz	ASIC, CAEN, Mesytec	Cross-system sync check
EBIS release	5 Hz	CAEN	Beam gate / event marker
T1 (protons)	0.83 Hz	CAEN	Proton rate monitor

Table 4.1: Logic-level signals distributed across the three DAQ subsystems, with their approximate rates and purpose. Further details are given in Section 4.4.

Throughout this chapter, the following terminology is adopted: a *signal* refers to the raw analogue voltage pulse produced at the output of a detector or preamplifier following a physical interaction. A *hit* denotes a single physical interaction depositing energy in one detector channel, giving rise to one or more

signals that are recorded by the DAQ as amplitude–timestamp pairs. An *event* is a collection of hits, across one or more detectors, that are correlated in time and associated with a single beam interaction.

In the following sections, the three digitizer readouts are described in turn: the ASIC-based readout of the Si array, the Mesytec digitizer system, and the CAEN digitizer system.

4.1 R^3B/ISS ASICs

As described in the previous chapter, the Si array is divided into three independent modules, each comprising six ASICs mounted directly beneath the eight silicon detectors and thermally coupled to a copper cooling block to dissipate heat in the vacuum environment. Figure 4.2 illustrates the readout architecture implemented within each module. Each silicon strip is wire-bonded to the analogue front-end of the corresponding ASIC, which provides 128 readout channels. Within each channel, the signal is processed by a charge-sensitive preamplifier (CSA), a shaping amplifier, a discriminator, followed by an analogue multiplexer, and a common 12-bit analogue-to-digital converter (ADC). For each recorded signal exceeding the discriminator threshold, the system stores two quantities: the amplitude, proportional to the deposited energy, and a timestamp associated with the trigger.

Each module is controlled and read out by a dedicated FPGA-based FMC (FPGA Mezzanine Card) module, housed in a Micro Telecommunications Computing Architecture (μ TCA) crate. The FMC handles the configuration of the ASIC, event buffering, and data transmission, and runs an independent instance of the MIDAS data acquisition software [118], producing its own continuous data stream. A dedicated Clock-Sync-Trigger (CST) module, connected to all FMC boards through the μ TCA backplane, receives the 62.5 MHz reference clock from the CAEN V1495 module, and distributes a common clock and synchronisation signals across the three modules, to ensure that the timestamps assigned by each module are mutually consistent. The CST frequency-multiplies the 62.5 MHz clock to 200 MHz before distribution, the value required by the ASIC front-end electronics. The three data streams are sent to the “tape server” which sends the combined data both to online analysis and writes it to permanent storage in raw MIDAS format. In addition to the readout chain, each module generates an auxiliary logical OR of all discriminator outputs across every channel and ASIC. A trigger width of approximately $2\ \mu\text{s}$ is used, sufficient to capture events involving charge sharing between neighbouring strips or coincident signals from both detector sides, and the system supports trigger rates up to approximately 100 kHz without significant event losses. In the present configuration, the trigger output is only connected to an analogue scaler (rate meter) module for continuous monitoring of the trigger rate, although it can also serve as a valida-

tion pulse to the CAEN V1725 waveform digitiser or as a start/stop signal for a time-to-amplitude converter (TAC) or time-to-digital converter (TDC). Data for the present experiment was recorded for all signals, without any validation requirement.

Each ASIC also incorporates an internal calibration pulser, controlled by an on-chip digital-to-analogue converter (DAC) operated near mid-range to ensure optimal linearity. It is used to test ADC linearity, determine the zero-energy pedestals, and verify inter-module timing synchronisation. The calibration pulse width is approximately 13 μ s, chosen to maximise energy resolution while avoiding spurious triggers, and can be generated internally by the FPGA or injected from an external source. During data-taking, the 10 Hz synchronisation signal was continuously injected into a dedicated unconnected channel (channel 63) of the n-side ASICs numbered 1 and 4, and simultaneously routed to the external CAEN V1725 digitiser. This arrangement provides a persistent cross-check of the time synchronisation between the ASIC-based readout and the external CAEN and Mesytec digitisers. Since both systems receive a synchronous copy of the same pulse, any relative timing offset between the two becomes immediately visible in the data monitoring.

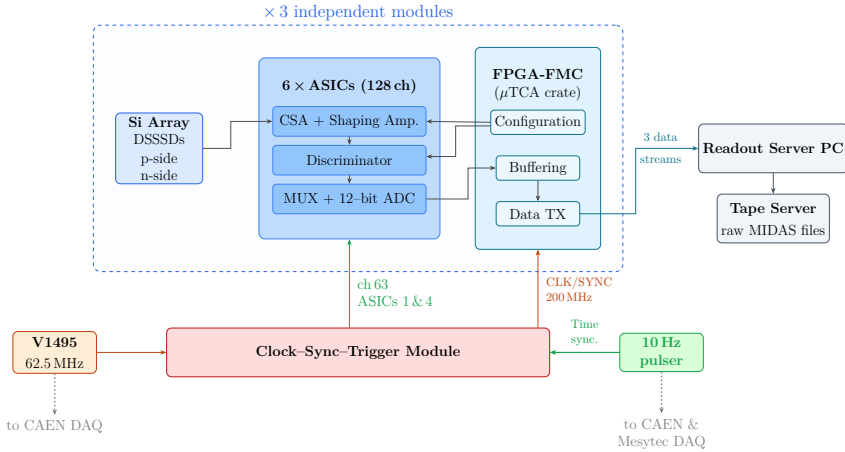


Figure 4.2: Block diagram of the ASIC-based readout system for the Si array. Each of the three independent modules comprises six ASICs adjacent to the detectors inside the vacuum, feeding into a dedicated FPGA-FMC card outside the vacuum. A Clock-Sync-Trigger module distributes the 62.5 MHz clock from the CAEN V1495 and the 10 Hz synchronisation pulse to all modules.

4.2 Mesytec system

The fission detector setup required a dedicated DAQ system, to be operated alongside the existing ISS DAQ. Its development and integration represented a substantial part of the experimental preparation. The new system comprises six Mesytec MDPP-32 modules [116]. These are fast digitizers providing high-resolution time and amplitude information. Each module is assigned to a specific detector subsystem, as shown in Figure 4.3.

The detector signals are extracted from the solenoidal magnet through feed-through connectors installed on the flanges of the vacuum chamber: signals from the Si array are routed through the upstream flange, while signals from the newly installed detectors (the CeBr₃ scintillators, the LUME monitor, and the fission $\Delta E - E$ telescope) exit through the downstream flange. Three independent signal chains feed into the digitisers. The CeBr₃ scintillator signals

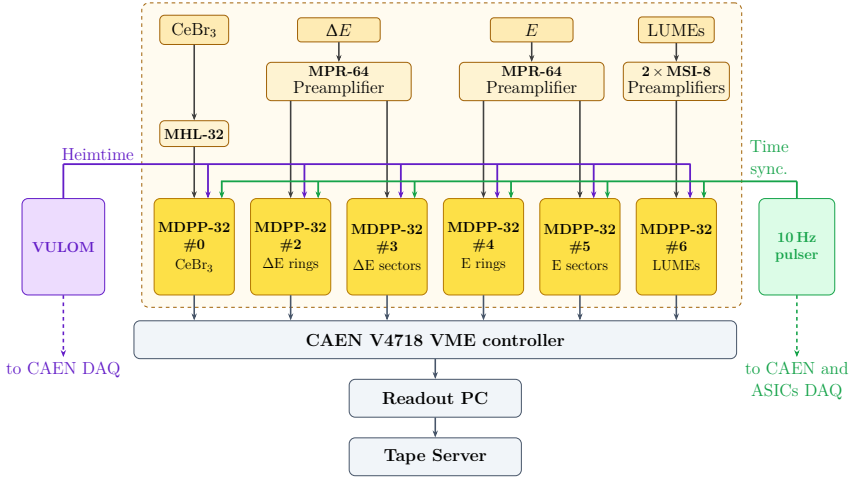


Figure 4.3: Block diagram of the Mesytec-based DAQ system. The six MDPP-32 digitisers are shown in yellow (modules #0, and #2–#6; module #1 was not employed during the IS739 experiment), each labelled with its assigned detector system. The CeBr₃ signals are routed through an MHL-32 connector converter before entering MDPP-32 #0. Signals from the $\Delta E - E$ silicon telescope are amplified by two MPR-64 preamplifiers before reaching MDPP-32 modules #2–#5. The LUME signals are processed by two MSI-8 preamplifiers before reaching MDPP-32 #6. The common 10 Hz reference pulse (green) and a VULOM Heimtime synchronisation signal (purple) are distributed to all six modules. The CAEN 4th generation VME bridge collects all data streams and forwards them to the acquisition PC via Ethernet. Green and purple lines indicate connections shared with the CAEN and ASIC-based DAQ systems for cross-system time synchronisation.

are amplified directly by the SiPMs, so no external preamplifier is required. The signals are routed through an MHL-32 module, used purely as a passive connector converter, into MDPP-32 #0.

The signals from the $\Delta E - E$ silicon telescope are amplified by two MPR-64 charge-sensitive preamplifier modules and distributed to MDPP-32 modules #2 through #5, each dedicated to one detector side: ΔE rings, ΔE sectors, E rings, and E sectors, respectively. Finally, the LUME luminosity monitor signals are processed by two MSI-8 preamplifier modules followed by a second MHL-32 connector converter before reaching MDPP-32 #6. The MSI-8 preamplifiers, in contrast to the MPR-64, support per-channel bias adjustment. All digitised streams are then collected by the readout PC via the CAEN 4th generation VME controller, which aggregates the outputs of the six modules.

4.2.1 MDPP: Mesytec Digital Pulse Processor

All six MDPP-32 modules operate with the Single Channel Processing (SCP) firmware [119], which processes each input channel independently and continuously without requiring an external trigger. For every pulse crossing a discriminator threshold, the firmware extracts both a pulse amplitude, proportional to the deposited energy, and a high-resolution timestamp.

Internally, the digitised signal is split into two parallel pulse processing branches. In the fast *timing branch*, the signal passes through a timing filter followed by a digital Constant Fraction Discriminator (CFD), which generates an amplitude-independent timestamp with a resolution down to 24 ps. In the slow *energy branch*, a pole-zero cancellation stage removes the exponential decay tail of the preamplifier pulse; the corrected signal then enters a shaping filter consisting of a differentiator followed by an integrator, producing the characteristic triangular pulse illustrated in Figure 4.4. The peak amplitude, sampled at a time determined by the CFD via a hold stage, is proportional to the collected charge and therefore to the deposited energy. A baseline restorer corrects for slow baseline drifts throughout the process. The resulting amplitude and timestamp are written to a continuous data stream and buffered before readout by the acquisition PC.

The pulse processing is controlled by a small set of parameters. The *shaping time* sets the Full Width Half Maximum (FWHM) of the triangular output pulse and governs the trade-off between energy resolution and count-rate throughput without pile-up. The *differentiation time* should be matched to the signal rise time to optimise timing resolution, and must not exceed the shaping time. The *pole-zero* constant must be tuned to the preamplifier decay time to avoid under- or overshoot of the shaped signal. The *gain* and *threshold* are adjusted per detector to avoid saturation and to suppress noise, respectively.

In addition to the extracted amplitude and timestamp, the MDPP-32 modules can be configured to record the full signal *traces*, i.e. the sampled waveforms

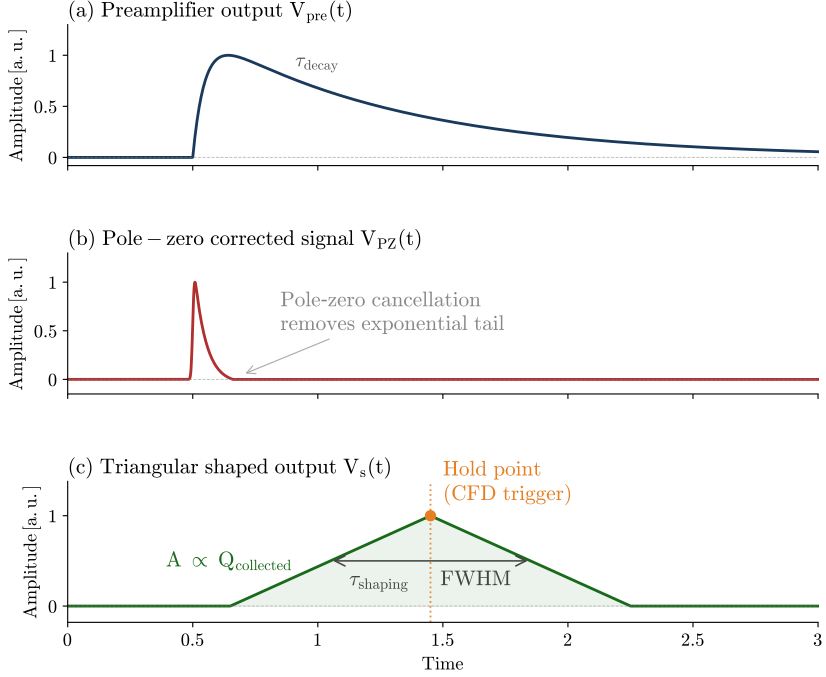


Figure 4.4: Energy branch signal processing chain of the MDPP-32 SCP firmware. (a) Raw preamplifier output with exponential decay constant τ_{decay} . (b) Pole-zero corrected signal after removal of the exponential tail. (c) Triangular shaped output governed by τ_{shaping} which denotes the FWHM of the pulse. The peak amplitude $A \propto Q_{\text{collected}}$ is sampled at the hold point set by the CFD.

of each pulse, enabling offline studies such as pulse-shape discrimination. Traces were recorded for the $\Delta E - E$ and LUME detectors throughout the entire experiment, while trace acquisition for the CeBr3 scintillators was disabled from Run 107 onward. A detailed analysis of these traces falls outside the scope of the present work and is left for future studies.

4.2.2 MDPP synchronisation

Inter-module timestamp synchronisation is achieved through a VULOM module providing the Heimtime protocol signals [120], which distributes a common time reference to all six digitisers simultaneously. The protocol is based on a periodic reference pulse at 190 Hz broadcast to all modules. Between consecutive reference pulses, additional pulses whose arrival time, measured relative to the

preceding reference, encodes the value of an incrementing counter representing time. Each digitiser timestamps this auxiliary pulse with its local clock, and since the counter value is unambiguously determined from the pulse positions, all local timestamps can be anchored to a common absolute time axis without any shared clock line or hardware trigger (see Fact Box on page 85). The Heimtime signal is also sent to one CAEN digitiser channel to connect with the ASIC-CAEN timescale.

Online monitoring of hit patterns, count rates, and energy spectra during the experiment was performed using PLUTT [121], a lightweight scriptable monitor for ROOT-based data streams.

4.3 CAEN system

The CAEN VME-based system at ISS consists of a VME8100 crate controlled via an A2818 PCIe card and a V2718 VME controller. Within the crate, a V1495 logic module generates the 62.5 MHz common clock distributed to the V1725 digitisers, which is also passed to the CST card to derive the 200 MHz clock for the ASICs. Although the CAEN system is designed to read out the ancillary detectors commonly used at ISS, i.e. the Zero Degree detector, the recoil detector, and the on-axis luminosity monitor ELUM, none of these were used in the present experiment and are therefore not discussed further. Nevertheless, the CAEN electronics infrastructure plays a central role in the overall DAQ architecture: the EBIS release signal is received as a NIM signal by the V1725 digitisers, which use the constant-fraction discriminator (CFD) of the DPP-PSD firmware to assign a precise timestamp to each pulse. A schematic overview of the signal flow is shown in Figure 4.5.

4.4 Time synchronisation

Combining data from three independent DAQ subsystems — the ASIC-based readout, the Mesytec and CAEN digitisers — requires that all recorded signals can be placed on a common time axis. Since each subsystem operates in free-running mode, no hardware trigger exists to impose a common time origin. Time synchronisation must therefore be established and maintained through a combination of distributed hardware signals and software corrections applied in the readout.

4.4.1 Absolute timestamps principles

The fundamental challenge is not only that different subsystems use different clocks, but that several local timestamp counters are inherently ambiguous. A

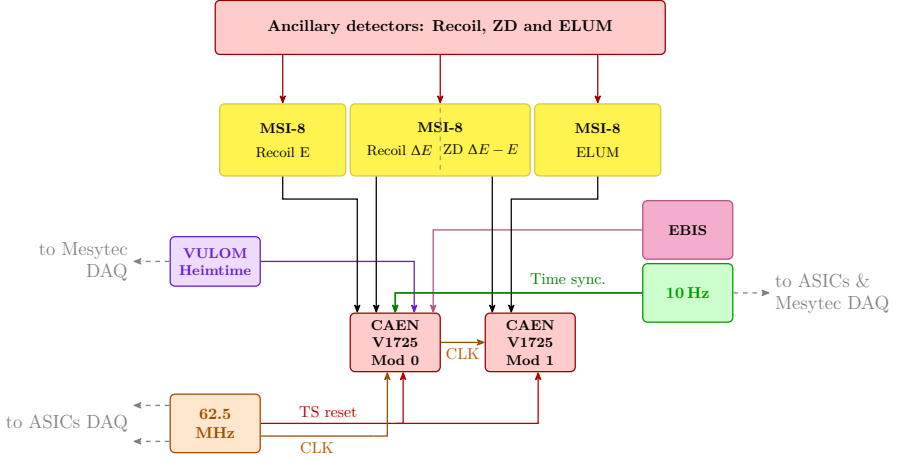


Figure 4.5: Block diagram of the CAEN DAQ showing the clock distribution and timestamp synchronisation scheme. The ancillary detectors (Recoil, ZD, and ELUM) are typically read out via Mesytec MSI-8 preamplifiers; these detectors are not employed in experiment IS739. The V1495 module distributes a 62.5 MHz clock (orange) and a timestamp reset signal (red) to both V1725 digitiser modules. The 10 Hz pulser (green) provides a common synchronisation check signal to all three DAQ subsystems. The EBIS signal (magenta) is received by one module, and the VULOM Heimtime signal (purple) is also forwarded to the Mesytec DAQ.

counter that starts from zero when the acquisition begins provides no information about its relationship to any external reference: two systems may start at different moments, drift relative to each other, or, more insidiously, silently lose clock cycles due to transient faults without any internal indication that something has gone wrong. As illustrated in Figure 4.7, a single lost cycle causes all subsequent timestamps to be offset by exactly one unit, producing a dataset that appears internally self-consistent but is in fact misaligned. A 62.5 MHz clock has a period of 16 ns. With detector time resolutions of order 10 ns, a single-cycle jump is enough to severely misalign event timing.

Absolute timestamps for event synchronisation

In experiments where multiple independent DAQ systems operate in parallel, each driven by a local clock, reliable event correlation requires a shared absolute time reference. Without one, a system that misses a single clock cycle will continue operating without any internal indication of the loss: its local counter increments normally, events are recorded without apparent gaps, and the resulting misalignment with respect to other systems remains invisible. Detecting it would require elaborate analysis of the time distribution of the affected signals across many events, and even then the exact moment of the loss could not be pinpointed. Providing each recorded event with an absolute timestamp — a globally synchronised label reflecting its true position within a master clock timeline — eliminates this ambiguity and makes such faults immediately detectable and correctable.

The following three scenarios illustrate the role of absolute timestamps in ensuring reliable event correlation between two independent DAQ systems, progressing from ideal conditions to fault detection and correction.

Scenario 1: Normal operation. Both systems A and B share the same global clock. Every physical event is recorded with an identical timestamp by both systems, making correlation in the analysis stage straightforward and unambiguous.

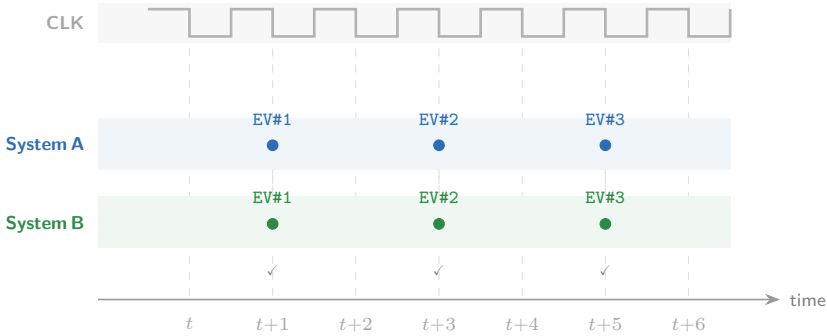


Figure 4.6: Scenario 1: Normal operation. Both systems record each physical event with the same local timestamp; the counters match and correlation is unambiguous.

Scenario 2: Lost cycle. A transient fault causes System B to miss one clock cycle. Because no shared absolute reference exists, the loss is not directly visible: the local counters increment normally, and both

datasets appear self-consistent, with no internal indication that anything has gone wrong.

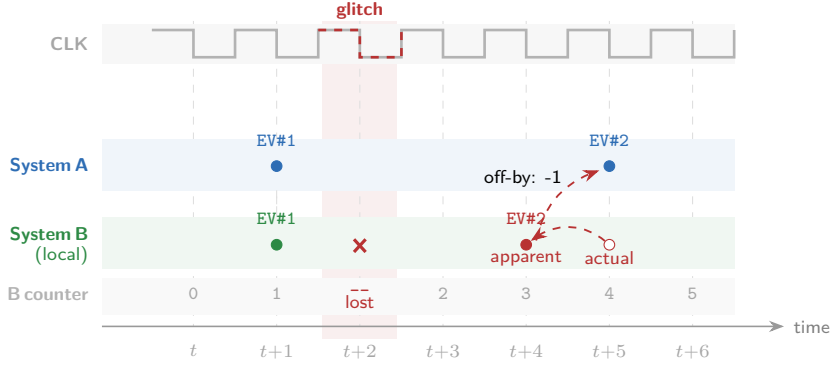


Figure 4.7: Scenario 2: Lost cycle. The local counter of System B continues normally after the fault at $t+2$, silently offsetting all subsequent timestamps by -1 . Without an external reference, the misalignment cannot be detected.

Scenario 3: Detection and correction via absolute timestamps. The same fault now occurs in the presence of a shared absolute time reference. Comparing the timestamps across the two systems immediately exposes the discrepancy, and the affected timestamps can be corrected before the datasets are merged.

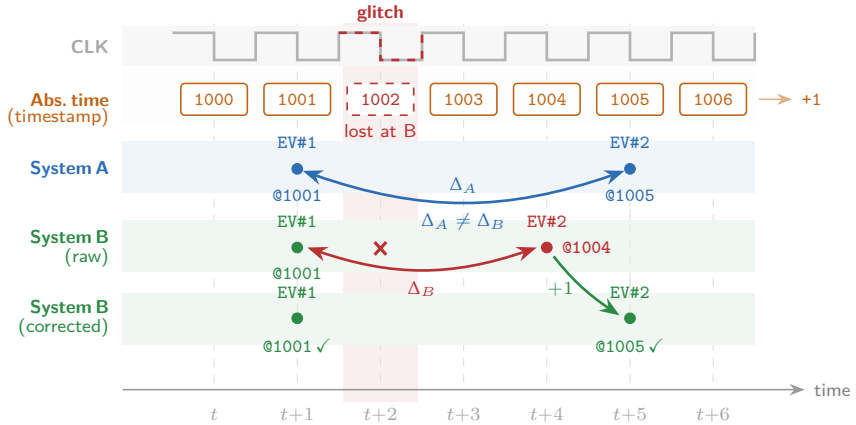


Figure 4.8: Scenario 3: Detection and correction via absolute timestamps. With a shared time reference, each system continuously records absolute timestamps for every event. Under normal operation, the difference $\delta = t_A - t_B$ between the timestamps of the two systems remains constant. When a clock glitch causes System B to miss one cycle, this constant offset shifts: System B records EV#2 at @1004 while System A records it at @1005, changing δ from its expected value. This deviation is detected and corrected quickly, typically within 1 second. Thus data recording can continue uninterrupted. Once the shift is identified, all subsequent System B timestamps are again correctly recorded, restoring full alignment.

4.4.2 ISS clock distribution and timestamp reset

The master clock is generated by the CAEN V1495 logic module at 62.5 MHz and distributed to the V1725 waveform digitisers via a daisy-chain configuration: each module accepts an external clock input and forwards it to the next, ensuring all CAEN modules share a common clock source. The same 62.5 MHz signal is simultaneously forwarded to the CST card of the Si array DAQ. This arrangement, illustrated in Figure 4.5, guarantees that the ASIC and CAEN subsystems are driven by a single common clock. Although the clock frequency is shared, the internal timestamp counters of each subsystem start independently when the acquisition is initiated. Alignment to a common time origin is achieved by a synchronisation routine, the so-called “Magic Sync”, executed after any of the participating DAQ systems have been restarted. It sends a simultaneous timestamp reset signal to the S-IN input of each V1725 module and to the CST card of the Si array DAQ. In practice, the CST card requires multiple reset signals before it reliably resets; as a safety measure, the routine always sends ten resets in rapid succession, after which synchronisation is presumed stable.

4.4.3 Aligning the Mesytec subsystem

The Mesytec subsystem does not share a hardware clock with the CAEN and ASIC systems, as the MDPP modules do not support a high-precision external clock input and therefore must rely on their internal timing. Rather than distributing a shared clock line, the Heimtime protocol encodes an absolute time reference into a sequence of NIM pulses: a periodic base pulse is broadcast to all modules at approximately 190 Hz (every 2^{19} local clock cycles, corresponding to ~ 5.24 ms at 100 MHz). Superimposed on this stream, a 32-bit absolute timestamp is encoded once every 2^{26} clock cycles (approximately 0.67 s) as a sequence of 32 pulse pairs, where a long inter-pulse separation of 0.655 ms represents a logical 1 and a short separation of 0.164 ms represents a logical 0 [120].

Heimtime

Heimtime is one concrete implementation of absolute timestamping for DAQ frameworks used in nuclear and particle physics experiments. It assigns each recorded event a unique temporal label encoded as a 56-bit counter, ensuring that rollover does not occur on any experimentally relevant timescale. The system is implemented within the TRLO II firmware running on VULOM and TRIDI boards [120]. Beyond recording an absolute instant in time, Heimtime decoding also tracks local counter wrap-around cycles, enabling complete reconstruction of the event timeline in offline analysis with a timing resolution limited only by the receiver. The pulse structure of the protocol is illustrated in Figures 4.9 and 4.10.

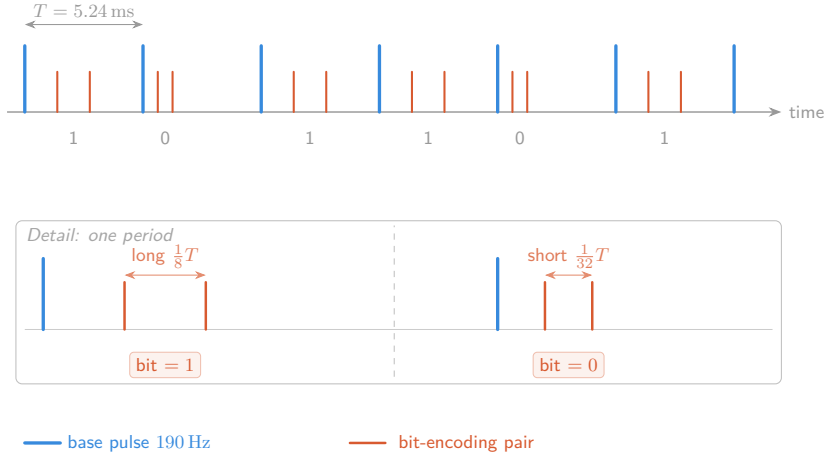
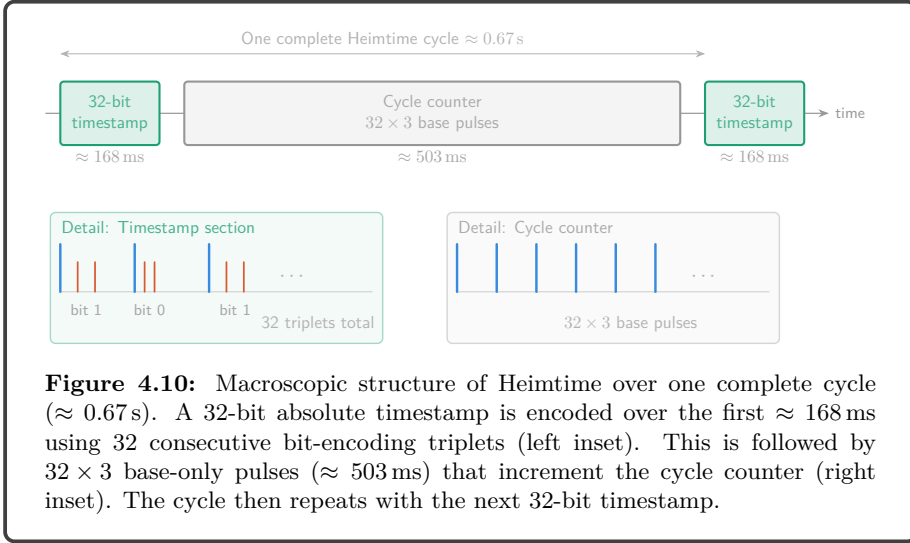


Figure 4.9: Heimtime pulse structure. Periodic blue pulses mark the base reference (190 Hz, $T = 5.24 \text{ ms}$). Between consecutive base pulses, red pulse pairs encode one bit of the absolute timestamp: a long inter-pulse gap ($\frac{1}{8}T$) encodes a logical 1, a short gap ($\frac{1}{32}T$) encodes a logical 0. A complete 32-bit timestamp is transmitted over 0.67 s. Pulse separations are not drawn to scale.



Each digitiser timestamps these auxiliary pulses with its local clock; since the counter value is unambiguously determined by the pulse positions within the local 100 ms window, all timestamps can be mapped to a common absolute time axis in software. In the processing during data recording, reception of a single complete 32-bit message is sufficient to anchor the local timestamp counter to the absolute time axis; subsequent pulses are tracked by dead-counting, and the decoded timestamps are continuously monitored for consistency with previous values to cross-check against lost pulses or decoding errors. A schematic illustration of the Heimtime pulse structure is given in the FactBox on page 85.

4.4.4 Cross-system monitoring

Cross-system synchronisation between all three subsystems is monitored continuously by distributing a 10 Hz reference pulse to the CAEN, ASIC, and Mesytec systems simultaneously. This provides a common signal visible in all three data streams at once, allowing any relative time offsets to be measured and corrected for in the offline analysis. On the ASIC side, the pulse is additionally injected into the analogue front-end of channel 63 of ASICs 1 and 4 in each module, producing a charge signal that is read out identically to a detector hit/signal and provides a persistent per-channel timing reference.

Chapter 5

Data sorting

DATA sorting is a fundamental step in data analysis, as it organizes large amounts of raw information into structured and interpretable forms, enabling the identification of meaningful patterns and improving the efficiency of subsequent analysis tasks. The raw data produced during the IS739 experiment are recorded in MIDAS-EBYE format by the front-end DAQ system (Chapter 4) as a continuous stream of digitised signals from all active detector subsystems. Each signal carries a hardware timestamp and an ADC value, but no higher-level structure: hits from the silicon array, the annular fission detector, the LUME luminosity monitor, and the CeBr₃ scintillator array are interleaved in the data stream with no *a priori* grouping into physics events or strict timesorting. Hits from each individual channel are, however, in chronological order. Converting this raw stream into calibrated, time-ordered, and physically meaningful events is accomplished using `ISSort` [122], a dedicated C++ framework developed by the ISOLDE Solenoidal Spectrometer collaboration, built upon the ROOT data analysis framework [123]. The sorting pipeline proceeds in four sequential steps, illustrated schematically in Figure 5.1: conversion from raw data format and energy calibration, time sorting, event building, and histogramming. Each of these steps are described in detail in the following sections.

5.1 Conversion and energy calibration

The first step involves decoding the raw MIDAS data on a block-by-block basis, parsing the binary content of each 64 kiB data block into typed packets. These packets are categorized according to the experiment’s three readout subsystems: the ASIC-based silicon array, the VME Mesytec modules, and the auxiliary CAEN timing and trigger signals. Each packet contains a timestamp provided by hardware, a module and channel identifier, and the raw value of the digitised detector signal. The resulting decoded hits are stored in a flat ROOT

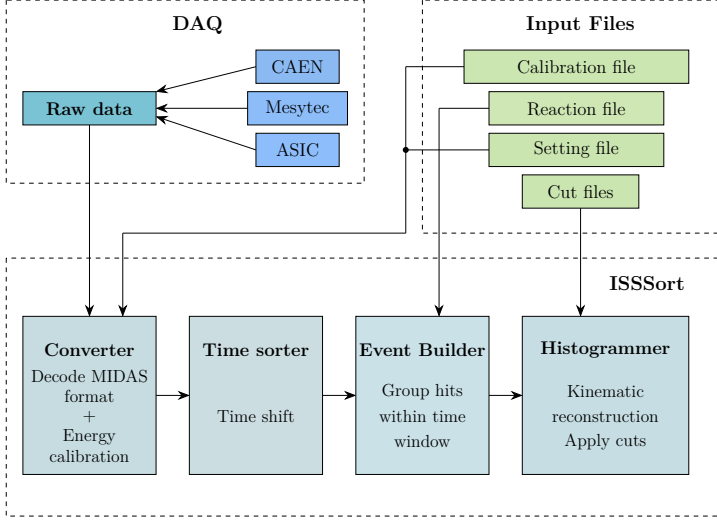


Figure 5.1: ISSort data processing workflow. Data from the DAQ are analysed in several steps, each controlled by configuration text files.

tree, designated as the `iss_sort` tree, which serves as the input for subsequent analysis stages.

Energy calibrations are applied to the ADC data during this step. For the ASIC-based silicon array and the CeBr_3 scintillators, the calibrated energy E is obtained from the raw ADC value q via a second-order polynomial,

$$E = o + g \cdot q + g_2 \cdot q^2, \quad (5.1)$$

where the offset o , gain g , and quadratic correction g_2 have been determined channel-by-channel from dedicated calibration source runs. For the annular fission fragment telescope and LUME detectors, a linear calibration is applied such that the energy is obtained as

$$E = o + g \cdot q, \quad (5.2)$$

with calibration coefficients determined on a channel-by-channel basis.

All calibration parameters are read at startup from an external configuration file (`calibration.dat`), using a dedicated calibration handler. This file provides channel-by-channel constants, including energy calibration coefficients, thresholds, and timing offsets, allowing calibration constants to be updated without recompiling the analysis code. However, any changes still require re-sorting the data, a process that can be time-consuming. Per-channel thresholds are applied to suppress noise contributions below a configurable level. In addition, time corrections are implemented within the same framework: fixed time

offsets are applied to all detector channels, and a time-walk correction is applied to the silicon array in order to compensate for amplitude-dependent timing shifts and thus improve the overall time resolution.

The detector geometry and electronics mapping, including the ASIC-to-strip correspondence and the assignment of Mesytec channels to physical detector elements, are specified through a separate external settings file (`settings.dat`) that is also passed to the programme at runtime.

5.2 Time sorting

`ISSSort` sorts and merges all hits into a single, globally time-ordered sequence. This ordered stream is then written to the `iss_sort` tree. Because data from different channels can arrive out of order due to differences in buffer sizes and read-out latencies, this stage is the most I/O-intensive step of the analysis pipeline.

The ASIC-based silicon array and the Mesytec VME modules operate on independent clocks without a common hardware trigger, but raw timestamps from these different types of readout systems do have a shared time reference. As described in Section 4.4, cross-system synchronization verification is achieved using periodic pulser signals sent simultaneously to all subsystems, providing common reference points throughout the run.

5.3 Event building

With a globally time-sorted data stream available, the event builder can group individual hits into physics events. An event is initiated by any hit above threshold and remains open for a configurable event time window, typically of the order of a few hundred ns. All hits arriving within this window are collected into a common buffer and then processed by a set of detector-specific finder functions.

For the silicon array, the `ArrayFinder` function correlates p- and n-side hits on each DSSSD wafer. A valid array event requires a prompt coincidence between at least one p-side and one n-side signal on the same wafer, evaluated using walk-corrected timestamps. Time walk, i.e. the energy-dependent variation in the ASIC signal time, is corrected channel by channel using parameters derived from calibration data, yielding timestamps precise enough to optimize the separation of genuine p-n coincidences from accidental ones. When two adjacent strips on the same side fire within the prompt coincidence window, their energies are summed through a charge-addback procedure that recovers the full deposited energy in these cases where the charge cloud straddles a strip boundary. Events in which the n-side signal falls below threshold are retained as p-side-only in a dedicated branch of the output tree. Each reconstructed array event is stored as an `ArrayEvt` and added to the output event structure.

The **CdFinder** function reconstructs charged-particle events in the annular detectors by combining signals from their segmented layers, e.g. the ΔE and E detectors in the case of the IS739 experimental setup. The reconstruction is seeded by hits in the ΔE layer, which acts as the trigger for particle identification. Sector hits in the ΔE layer are first examined for charge sharing: adjacent sectors firing within a prompt coincidence window are merged via energy add-back and treated as a single particle. Each resulting cluster defines a candidate particle, with its sector and timestamp determined by the highest-energy contribution. For each candidate, a corresponding ring signal is assigned by searching for the best match in time and energy within a coincidence window. Subsequently, signals in the remaining detector layers (the E detector in the case of the IS739 experimental setup) are associated with the particle by requiring time coincidence and geometrical consistency (same sector within a small tolerance). Charge-sharing effects are again treated via addback when neighbouring strips fire simultaneously. The final reconstructed particle thus consists of a set of energy deposits across multiple layers, from which ΔE - E correlations and total energies can be derived. Each particle is stored as a **CDEvt** and added to the output event structure.

The **LumeFinder** function reconstructs events in the LUME detector by correlating signals from its different readout channels within a prompt time window. The trigger is provided by the back (E) signal, and for each such hit the algorithm searches for matching near (n) and far (f) signals with the same detector ID and timestamps compatible within a configurable coincidence window. If matching signals are found, their energies are associated with the same event; otherwise, missing components are set to zero. When both near and far signals are present, a position-like variable is constructed from their energy asymmetry, providing information on the interaction point. Each valid combination is stored as a **LumeEvt** and added to the output event structure.

The **GammaRayFinder** function processes hits from the CeBr_3 scintillator array, applying prompt time conditions between individual crystals and storing the resulting γ -ray events as **GammaRayEvt** entries in a separate branch.

Coincidences between the various detection systems are resolved at this stage by requiring that the corresponding detector events fall within configurable time-coincidence windows. These coincidence conditions are defined in an external configuration file (**reaction.dat**), where the relative time windows between different detector systems can be adjusted. The complete set of correlated hits from all subsystems, within a given time window for event building, is written as a single entry to an output ROOT tree of **ISSEvts** objects, one output file per input file, appended with the suffix **_events.root**.

5.4 Kinematic reconstruction and histogramming

In the final step, the event trees from all input runs are chained together, and a set of default physics histograms is produced. Reaction kinematics are introduced at this stage via another configuration file (`reaction.dat`), which specifies the beam and target nuclei, their masses, beam energy, the magnetic field strength, and the relevant geometric parameters of the spectrometer and other detectors.

The excitation energy E_x of the recoil nucleus is reconstructed event by event from the measured proton energy E_p^{meas} and hit position z_{meas} along the spectrometer axis. The reconstruction proceeds through the following stages:

- **Pulse–Height Correction (PHC):** the measured detector charge E_p^{meas} must be corrected for the non-linear response of silicon. The energy required to create an electron–hole pair, ε , is not a constant but decreases weakly with increasing electronic stopping power, since less energy is needed to create another pair in a region where one has already been created [124]. As a consequence, the collected charge is not strictly proportional to the deposited energy, even for a single ion species, and a calibration established at one energy is biased at others. Following the formalism of Lennard et al. [124], the effective response can be expressed as

$$\frac{dE_{\text{det}}}{dx} = \frac{e_0}{e_0 - k(dE/dx)_e} \frac{dE}{dx}, \quad (5.3)$$

where $(dE/dx)_e$ is the electronic stopping power, $e_0 \simeq 3.67$ eV is the ionization energy per electron–hole pair in silicon [125], and k is a material-dependent constant, here 0.288 pm/e-h pair is used. Since $k(dE/dx)_e > 0$, the detected charge slightly exceeds the value expected from a linear response, the excess growing with stopping power and hence at low proton energies. The correction is pre-computed as a numerical integral over the proton range and stored in lookup tables, which are inverted at runtime to convert E_p^{meas} into the true proton energy E_p^{PHC} .

- **Iterative Energy–Loss Corrections:** the PHC-corrected energy E_p^{PHC} is then subjected to two successive energy–loss corrections, applied iteratively until convergence. First, the energy lost by the proton in the silicon dead-layer d_{dead} is recovered:

$$E_p^{(1)} = E_p^{\text{PHC}} + \Delta E_{\text{dead}} \left(E_p^{\text{PHC}}, \frac{d_{\text{dead}}}{|\cos \theta|} \right), \quad (5.4)$$

where θ is the entrance angle of the proton trajectory with respect to the detector plane. As shown in Figure 5.2, the finite dimensions of the detector array and the specific incidence angle θ introduce a spatial offset

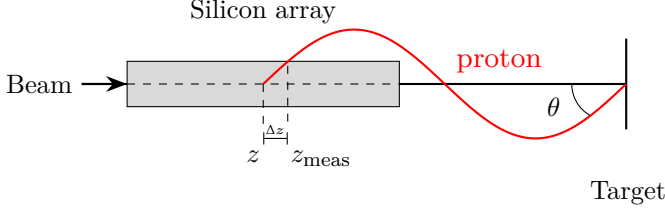


Figure 5.2: Schematic representation of the silicon array showing the ejectile trajectory. The proton is detected at the position z_{meas} along the magnet axis instead of the true interaction coordinate z , due to the finite size of the silicon array.

between the position z on the beam axis and the measured hit coordinate z_{meas} . This geometric effect must be accurately modelled to correctly reconstruct the trajectory of the ejected proton.

Since the probability of a reaction occurring is uniform throughout the target thickness, the reaction is assumed to take place, on average, at the center of the target, and the beam energy is corrected for energy loss in the upstream half of the target accordingly. Therefore, the energy lost by the proton traversing half the target thickness is recovered:

$$E_p^{\text{react}} = E_p^{(1)} + \Delta E_{\text{target}} \left(E_p^{(1)}, \frac{t/2}{|\sin \theta|} \right), \quad (5.5)$$

where t is the total target areal density expressed in mg/cm^2 (specified in `reaction.dat`).

The energy loss function E_{loss} is evaluated using stopping powers calculated with SRIM [126] and interpolated via an Akima [127] spline. Since θ itself depends on E_p^{react} through the kinematic reconstruction, the two corrections are applied iteratively until convergence, defined as a relative change in the reconstructed z position smaller than 10^{-5} .

Once the reaction observables have been reconstructed, the excitation energy E_x , proton energy E_p^{react} , z -position z , and center-of-mass scattering angle θ_{CM} are correlated in two-dimensional histograms. User-defined graphical cuts on 2D projections (such as the $E_p^{\text{react}}-z$ plane) can be applied to select specific reaction channels or suppress backgrounds. The calibrated histograms are written to a ROOT file with suffix `_hist.root`.

5.4.1 Custom analysis

For the IS739 experiment, the standard ISSort histogramming pipeline provided essential near-line monitoring capabilities during beam time, while the

physics analysis presented in this work was carried out with a custom ROOT-based framework developed by the author. This bespoke analysis framework enabled flexible kinematic cuts, custom observable selections, and specialized analysis tasks that would not have been achievable with the standard histograms alone, allowing the extraction of the physics results tailored to the specific goals of the measurement.

Chapter 6

Commissioning with stable beam

THE transition from assembly to beam operation requires a structured commissioning phase, during which the performance and reliability of the newly installed detector systems are assessed under realistic operating conditions. In the present experimental configuration, one of the key signatures of the $(d, p f)$ reaction is the coincident detection of a proton in the silicon array together with two heavy fission fragments. Reconstructing this coincidence reliably requires the correct temporal alignment of the independent data-acquisition systems associated with the various detectors, as well as an accurate understanding of the energy deposited in each detector. Verifying this synchronization and validating the energy response are therefore central goals of the commissioning campaign. The tests and validations performed during the first operation of the new apparatus with a stable beam in June 2025 are documented in this Chapter.

6.1 Magnet Vacuum Conditioning

Once the experimental setup is installed inside the solenoidal magnet, the entire volume must be evacuated to a vacuum level compatible with opening the gate valve towards the accelerator. This requirement ensures that contaminants do not migrate from the experimental area into the beamline, where they could compromise the surface properties of the superconducting cavities of the HIE-ISOLDE accelerator. The gate valve can therefore only be opened once the vacuum inside the experiment chamber reaches the specified threshold, which for the current ISS configuration is set at $8 \cdot 10^{-7}$ mbar.

Vacuum inside the magnet is achieved by means of a manually operated pumping system that combines two complementary technologies:

- **Turbo-Molecular Pump (TMP):** a turbomolecular pump removes gas

by transferring momentum through rapidly rotating blades. It is primarily effective for heavier species such as N_2 , O_2 , and CO_2 , and requires a backing pump to start and operate, allowing the combination to be started from atmospheric pressure [128]. It is employed during the initial pump-down.

- **Cryo-pump:** a cryogenic pump removes gas via cryocondensation and cryotrapping on surfaces cooled to cryogenic temperatures. It is particularly effective for water vapour and heavier gases, but cannot pump He and has limited efficiency for H_2 due to its relatively high vapour pressure at cryogenic temperatures [128]. It is used to achieve the final vacuum level and to maintain a clean and stable environment.

The pump-down is performed in stages. The backing pump, together with the turbomolecular pump, is employed to evacuate the system from atmospheric pressure to the high-vacuum regime. In order to minimize the evacuation time, the system is alternated between the turbomolecular and cryogenic pumps multiple times, progressively reducing the pressure until the level required for opening the gate valve is reached. This iterative approach ensures efficient evacuation while preventing damage to the turbomolecular pump due to pressure instabilities. The system is operated manually, with continuous pressure monitoring provided by gauges installed in proximity to the magnet volume.

The presence of numerous internal components, including detection systems, cabling, and mechanical supports, increases the amount of residual gas within the volume. In addition, the large internal volume of approximately 1.6 m^3 leads to significantly longer pump-down times compared to smaller vacuum chambers. As a result, even with continuous operation at full capacity, reaching the low pressure required for opening the gate valve needed approximately two weeks, as shown in Figure 6.1. This was a critical constraint. Pump-down for the commissioning experiment had to start on May 23, 2025 to allow for beam tuning to start 12 days later on June 3, 2025.

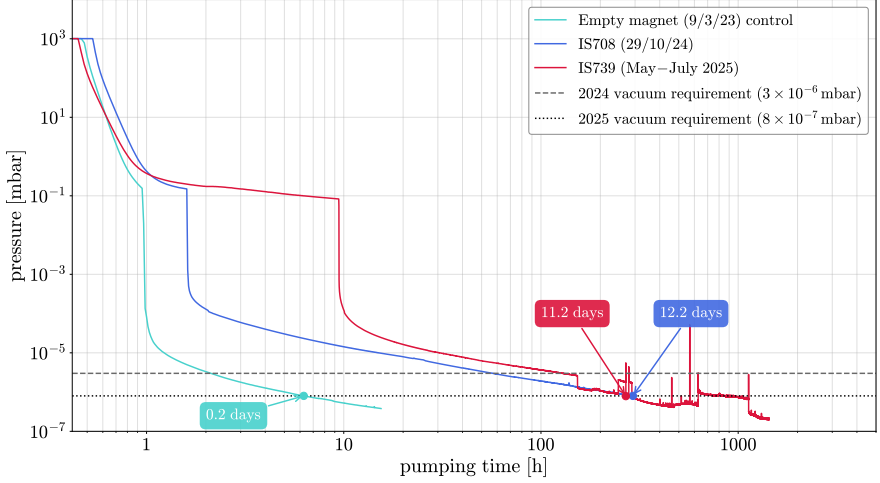


Figure 6.1: Pressure evolution inside the solenoidal magnet as a function of pumping time. The red curve shows the pump-down curve recorded for the IS739 experiment (May–July 2025), which utilized a strategic, multi-stage operation alternating between the turbomolecular and cryogenic pumps to accelerate the evacuation process. The blue curve shows the corresponding evolution measured during a previous experiment (IS708, October 2024), included for reference; notably, the 2024 setup did not include the fission and CeBr_3 detectors. The cyan curve represents the pump-down of the empty magnet, i.e., without any internal instrumentation, and provides a lower bound on the achievable pumping time. The horizontal lines indicate the vacuum thresholds required to open the gate valve towards the accelerator line: $3 \cdot 10^{-6}$ mbar for the 2024 configuration and $8 \cdot 10^{-7}$ mbar for the 2025 configuration. As indicated by the annotation, the IS739 pump-down required approximately 11.2 days of continuous operation to reach the required threshold. Despite the higher outgassing load from the internal detectors, the 2025 pump-down was significantly faster than the 2024 reference, thanks to the installation of a cryogenic pump before the 2025 campaign and to alternating between the turbomolecular and cryogenic pumps. Adapted from Ref. [129].

6.2 $^{22}\text{Ne}(\text{d}, \text{p})^{23}\text{Ne}$

The commissioning phase took place from 3 to 10 June 2025, followed by the IS739 experiment from 10 to 20 July 2025, as illustrated in Figure 6.2. Since opening the vacuum system between these two phases was not possible without restarting the pump-down procedure, the experimental setup had to be fully assembled and geometrically optimised prior to the commissioning, with no possibility of mechanical adjustments thereafter. As a consequence, the detector

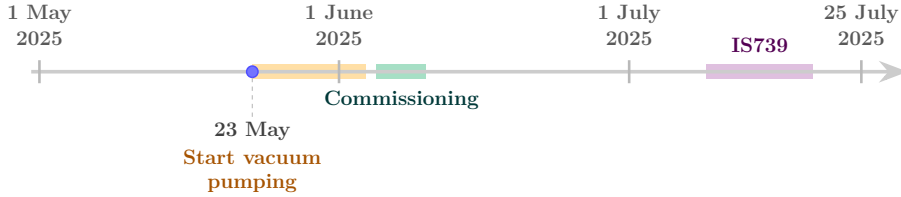


Figure 6.2: Timeline of the IS739 experimental campaign at ISOLDE. The vacuum pumping of the setup began on 23 May 2025, followed by the commissioning phase carried out from 3 to 10 June 2025. The IS739 physics run took place from 10 to 20 July 2025. The chamber was not opened in between.

positions were fixed according to the geometry optimised for the IS739 fission experiment with $^{229/230}\text{Ac}$, which constrained the available configurations during commissioning. Only in the case of a severely malfunctioning setup would the risk of opening the system have been accepted.

The commissioning of the fission setup therefore proceeds through a series of successive steps. First, signals must be established from each detector and each individual channel. These signals are then evaluated to ensure they exhibit adequate amplitude and satisfactory energy resolution. Subsequently, energy and time alignment are carried out, followed by a full calibration across all channels. Only once these requirements are met does it become meaningful to investigate physics-level observables, such as the coincident detection of back-to-back fragments and the reconstruction of the complete fission signature with sufficient angular precision. For the purposes of the present commissioning, it is sufficient to note that the critical distance between the target and the $\Delta E - E$ telescope was set to 8.5 cm.

To investigate the correlation between a hit in the Si array and a signal in the fission-fragment detector, a suitable (d,p) reaction must be selected. In particular, the reaction should produce a recoil nucleus emitted with a sufficiently large angular aperture to intercept the active area of the detector. This requires that the recoil angle, determined by the reaction kinematics, exceeds the minimum value necessary to overcome the inner radius of the ΔE layer of the fission-fragment detection system. The choice of a suitable stable beam is, however, strongly constrained: even for light stable beams, the kinematics of the (d,p) reaction does not allow the production of recoil nuclei at sufficiently large angles to intercept the $\Delta E - E$ telescope. As a consequence, while the detection of backward-emitted protons can be tested, the full correlation with the recoiling nucleus in the fission-fragment detector cannot be reproduced using a stable beam. This is illustrated in Figure 6.3, which shows the calculated trajectories of the ^{23}Ne recoils and the emitted protons for the $^{22}\text{Ne}(\text{d},\text{p})^{23}\text{Ne}$ reaction at 6 MeV/u in a 2 T magnetic field. In all cases, the recoils pass through

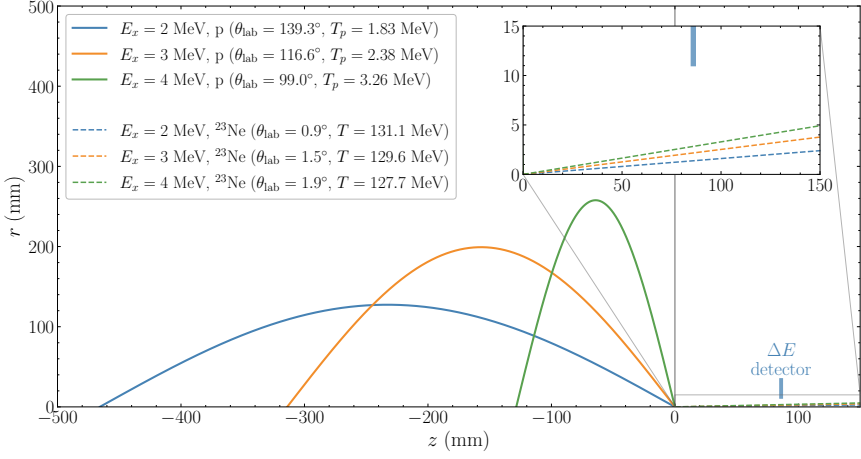


Figure 6.3: Example trajectories for the $^{22}\text{Ne}(\text{d}, \text{p})^{23}\text{Ne}$ reaction at 6 MeV/u in a 2 T magnetic field. The trajectories shown correspond to the excitation energies yielding the largest ^{23}Ne laboratory recoil angles θ_{lab} . The radial coordinate r is shown as a function of the axial position z . Dashed lines correspond to the trajectories of the ^{23}Ne recoils, while solid lines represent the emitted protons. Different colours indicate different excitation energies of the recoil nucleus, $E_x = 2, 3$ and 4 MeV. The blue vertical band marks the position of the ΔE layer of the annular fission detector, placed 8.5 cm downstream from the target. In all cases, the ^{23}Ne recoils pass through the central annular opening of the detector and therefore do not intercept the active area, as shown in the inset.

the central annular opening of the ΔE layer and do not intercept the active area of the fission detector.

6.2.1 Possible reactions

Although no recoil nucleus is expected to reach the annular fission detector, ^{22}Ne nevertheless represents a particularly suitable choice for the commissioning of the experimental setup, offering a rich set of well-defined signatures that allow multiple detector systems and coincidence conditions to be tested simultaneously.

The de-excitation of the first excited state in ^{23}Ne produces a 1016.9 keV γ ray detectable in coincidence with protons in the Si array, providing a direct test of the CeBr₃ array performance and of the proton- γ coincidence logic. The competing (d, n) reaction produces a 440 keV γ ray that should be strongly suppressed when gating on the Si array.

Elastic scattering of ^{22}Ne on the C component of the target produces events

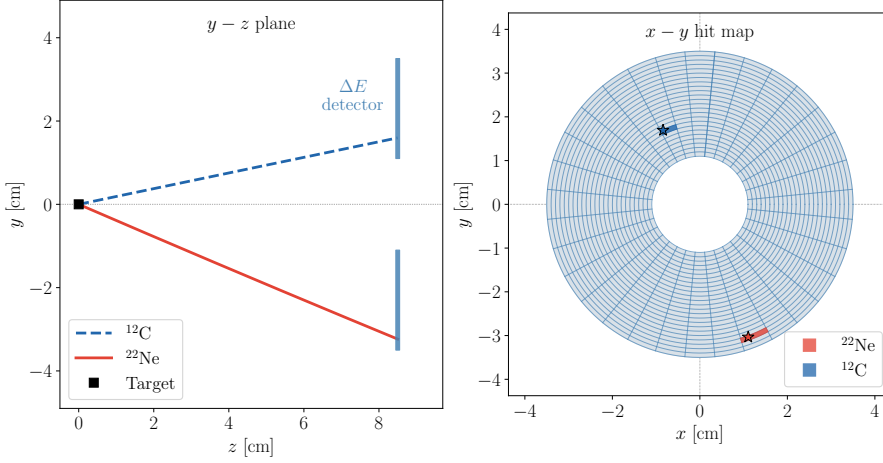


Figure 6.4: Simulated Rutherford scattering event of a ^{22}Ne beam at 6 MeV/u impinging on a ^{12}C target of $500\,\mu\text{g}/\text{cm}^2$. *Left panel:* Trajectories of the scattered ^{22}Ne and ^{12}C nuclei in the y - z plane, propagated through a magnetic field of $B = 2\,\text{T}$. The annular ΔE detector, positioned at $z = 8.5\,\text{cm}$ downstream of the target, is indicated in blue. *Right panel:* Corresponding hit positions on the segmented annular detector in the transverse x - y plane, showing the two nuclei arriving on opposite sides of the detector, consistent with back-to-back emission.

in which both scattered nuclei have large transverse momentum and can be detected in the fission detector, providing a benchmark for the angular resolution and the two-hit separation capability of the system. A representative simulated event of Rutherford scattering is shown in Figure 6.4, illustrating the back-to-back kinematics of the two recoiling nuclei and their respective hit positions on the annular detector. The annular fission detector can further be characterised through the response of its ΔE and E layers to different ion species: ^{12}C ions from elastic scattering are energetic enough to punch through both layers, whereas ^{22}Ne ions up to approximately 110 MeV are expected to stop in the ΔE layer.

Elastic scattering of ^{22}Ne on deuterium yields recoil deuterons depositing less than 1 MeV in the ΔE layer and a few MeV in the E detector, allowing the particle-identification capability of the system to be evaluated under realistic conditions. Inelastic channels on carbon and deuterium contribute additional statistics for testing the Si array-LUME coincidence logic.

From a practical standpoint, neon is a noble gas, chemically inert and routinely used as a buffer gas in REXTRAP, making it straightforward to extract from the production target and deliver as a stable, reproducible beam. For all

these reasons, ^{22}Ne represents both a scientifically rich and technically reliable choice for the commissioning campaign.

6.2.2 Beam energy

The last aspect that needs to be addressed is the choice of the beam energy. Figure 6.5 shows Ptolemy–DWBA [130] calculations for the $^{22}\text{Ne}(\text{d}, \text{p})^{23}\text{Ne}$ reaction at different beam energies and for the various single-particle states populated in ^{23}Ne . The top panel shows the differential cross section in the centre-of-mass frame for several assumed ^{22}Ne beam energies, calculated for a fixed excitation energy of 2 MeV in ^{23}Ne . The bottom panel displays the differential cross sections associated with different single-particle states in ^{23}Ne , computed for a fixed beam energy of 4 MeV/u and an excitation energy of 2.5 MeV. From the DWBA calculations shown in Figure 6.5, the differential cross section for the (d, p) reaction is larger at 4 MeV/u than at the 6 MeV/u typically used in previous ISS campaigns. Although this would in principle favour operating at the lower energy, other considerations point towards maintaining the higher value. In particular, multi-nucleon transfer channels and reactions producing recoils at larger scattering angles are expected to benefit from a higher beam energy, and 4 MeV/u may be insufficient for such processes. There are also clear operational advantages in adopting the same 6 MeV/u beam energy used by Miniball. Since both Miniball and ISS share neighbouring HIE-ISOLDE beam lines, a single accelerator tuning at 6 MeV/u allows for a straightforward switch between the two experimental stations, significantly reducing the time required for beam preparation. For these reasons, a ^{22}Ne beam at 6 MeV/u represents a practical and efficient compromise between optimising the reaction yield and ensuring smooth accelerator operation during the commissioning campaign.

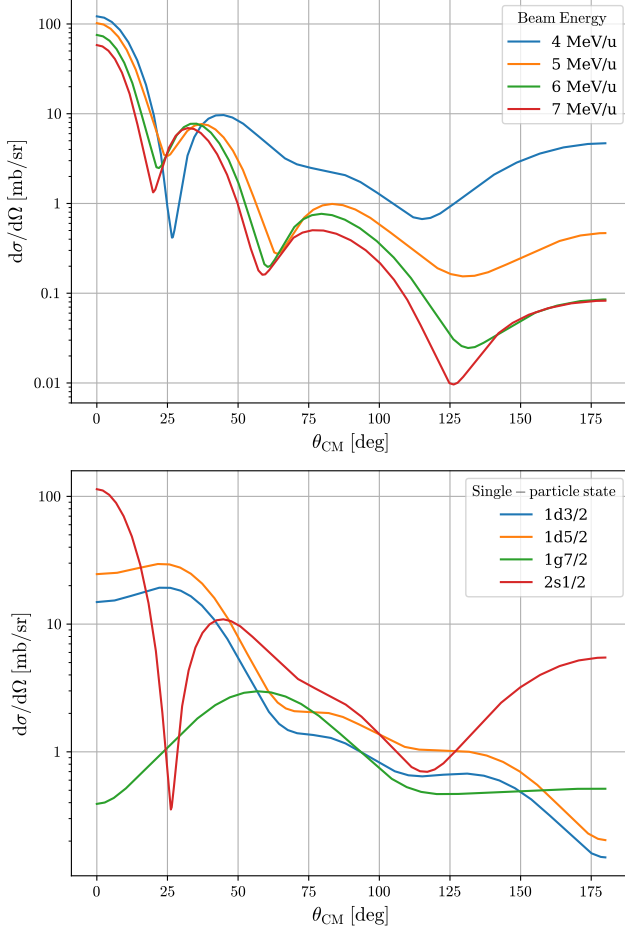


Figure 6.5: Ptolemy-DWBA differential cross sections for the $^{22}\text{Ne}(d,p)^{23}\text{Ne}$ reaction, shown in the centre-of-mass frame. *Top panel:* angular distributions for several ^{22}Ne beam energies, calculated for a fixed excitation energy of 2 MeV in ^{23}Ne . *Bottom panel:* angular distributions for different single-particle states in ^{23}Ne , computed for a beam energy of 4 MeV/u and an excitation energy of 2.5 MeV.

6.3 Beam-response of the setup

The ^{22}Ne beam was produced in the 8^+ charge state at an intensity of 5×10^6 pps (particles per second), corresponding to a current of 33.4 epA.

The identification of charged particles produced in the various reaction channels open at this beam energy relies on their energy loss in matter, which is described by the Bethe–Bloch formula [131]. For non-relativistic heavy charged particles, its leading behaviour is:

$$\frac{dE}{dx} \propto \frac{MZ^2}{E}, \quad (6.1)$$

where M is the particle mass, Z its atomic number, and E the energy. In a $\Delta E - E$ telescope a particle deposits a fraction of its energy ΔE in the $65 \mu\text{m}$ thick front detector and stops in the $1000 \mu\text{m}$ thick back detector, depositing its residual energy E . Consequently, particles with different M and Z trace distinct bands in the $\Delta E - E$ plane, enabling unambiguous identification of the particle species. When the energy resolution is sufficient, isotopes of the same element can be resolved, since the mass dependence shifts their bands apart. This is indeed what is observed in Figure 6.6, which shows the $\Delta E - E$ matrix recorded during the first exposure of the annular silicon telescope detector to the beam. The main panel reveals the simultaneous presence of multiple isotopic bands, from α particles up to ^{22}Ne , demonstrating the opening of several reaction channels and the isotopic separation achieved by the telescope. The topmost band, at high $\Delta E - E$ and low E , corresponds to ^{22}Ne beam particles elastically scattered off the $549 \mu\text{g}/\text{cm}^2$ CD_2 target. The inset highlights the low-energy region, where p , d , t , α , ^6Li , and ^7Li bands are resolved, confirming the isotopic separation capability of the detector for light species at low energies. The particle identification obtained from the $\Delta E - E$ matrix can subsequently be used to assign the charge Z to the detected particles.

The upper panel of Figure 6.7 shows the charge distribution of particles identified in the $\Delta E - E$ analysis. The charge assignment was performed by selecting the corresponding isotopic bands in the $\Delta E - E$ spectrum is shown in Figure 6.6. Owing to the achieved energy resolution, isotopic separation is observed not only for the three hydrogen isotopes (p , d , and t), but also for heavier species such as Li ($Z = 3$) and C ($Z = 6$).

Beyond single-particle identification, a key requirement for the IS739 experiment is the capability of the ΔE and E layers to record and separate two simultaneous hits within the same acquisition time window. The lower panel of Figure 6.7 shows the correlation between the charges of two coincident hits recorded in the ΔE detector. Distinct correlation patterns are visible, reflecting the different reaction channels populated at this beam energy.

Moreover, the commissioning with the ^{22}Ne beam provided a first opportunity to verify whether the ΔE layer of the annular detector is capable of

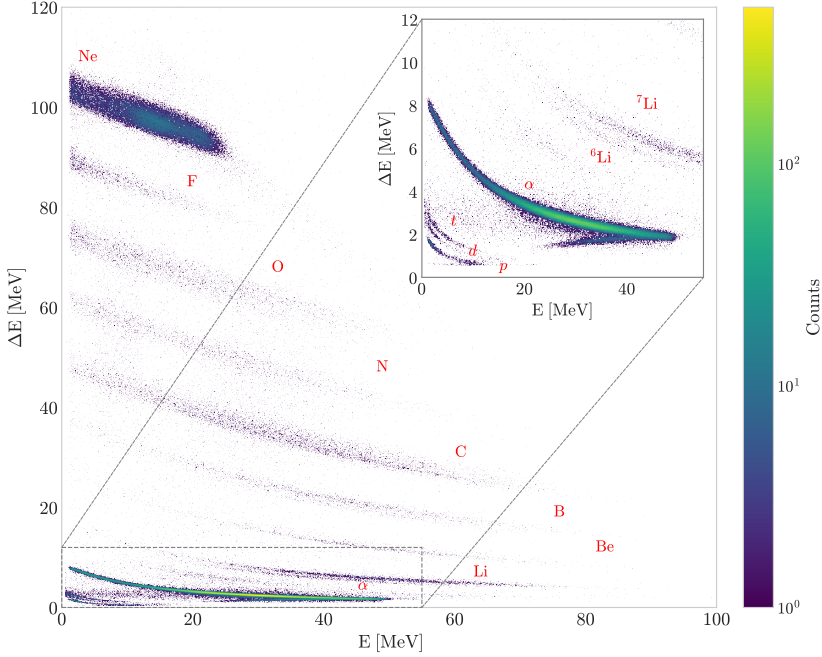


Figure 6.6: $\Delta E - E$ matrix recorded during the commissioning of the detector array with the ^{22}Ne beam. The main panel shows the clear separation of reaction products from α particles up to ^{22}Ne , with the topmost band corresponding to ^{22}Ne beam particles elastically scattered off the CD_2 target. The opening of multiple reaction channels is evident from the simultaneous presence of several isotopic loci. The inset highlights the low-energy region, where p , d , t , α , ^6Li , and ^7Li are clearly resolved, demonstrating the isotopic separation capability of the telescope.

resolving reaction products emitted back-to-back in the center-of-mass frame, exploiting its azimuthal segmentation into 32 sectors. As shown in the top panel in Figure 6.8, the sector-sector correlation matrix displays a prominent band offset by approximately 16 sectors from the main diagonal, which is the clear signature of back-to-back topologies with an azimuthal opening angle close to 180° . The observation of this structure demonstrates that the ΔE layer is capable of resolving azimuthally opposite hits under realistic beam conditions, confirming its suitability for fission-fragment detection in the IS739 experiment. The bottom panels in Figure 6.8 show the hit map recorded in the annular ΔE and E detectors. The signals in the two layers confirm the proper operation of the telescope configuration and the correct geometrical alignment of the system. A localized hot spot is visible on the left-hand side of the inner rings in both detectors, which can be attributed to a slight beam misalignment. This

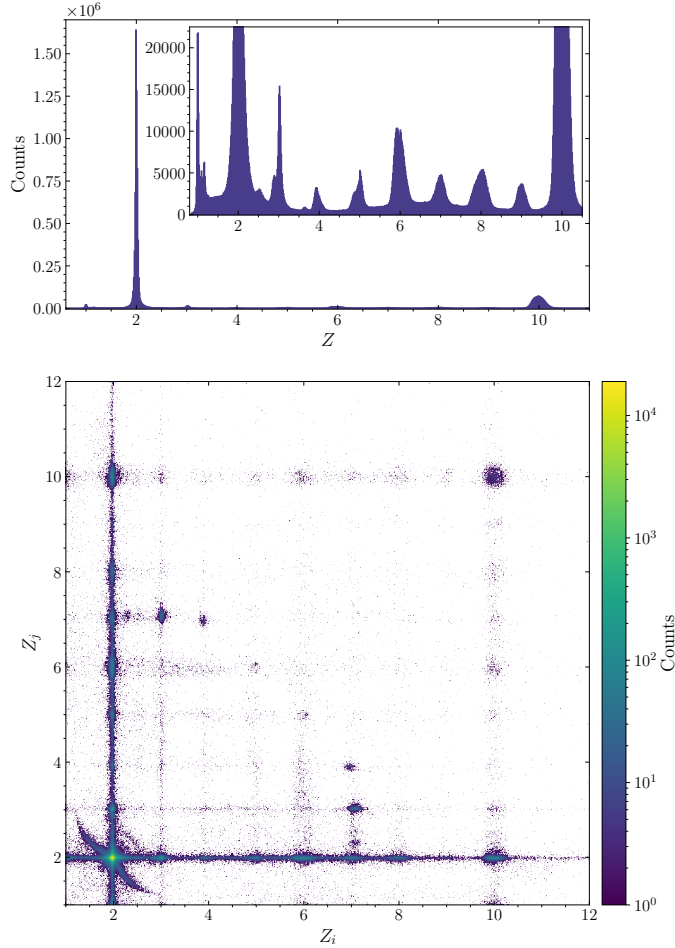


Figure 6.7: *Top panel:* Charge distribution of particles identified in the ΔE detector from the $\Delta E - E$ analysis. The atomic number assignment was obtained from the bands visible in Figure 6.6. The spectrum exhibits pronounced peaks corresponding to different reaction products detected during the experiment. The inset shows the low-statistics region on an expanded scale, highlighting the identification of intermediate- Z species. *Bottom panel:* Correlation between the charges of all pairs of hits recorded in the ΔE layer within the same acquisition time window (1 μ s). The charge assignment is obtained from the corresponding band in the $\Delta E - E$ spectrum. Distinct correlation structures associated with different reaction channels are observed, including contributions consistent with carbon recoils produced by scattering of the beam off the carbon component of the CD_2 target. Note that correlations with $Z_i + Z_j > 10 + 6$ must be random coincidences.

feature highlights the sensitivity of the annular detectors to beam positioning. Beyond validating the detector performance, these hit maps proved to be a powerful diagnostic tool during the beam tuning phase: variations in the position, intensity, or symmetry of the hit pattern provide immediate feedback on beam misalignment or focusing issues, allowing for rapid optimization of the experimental conditions.

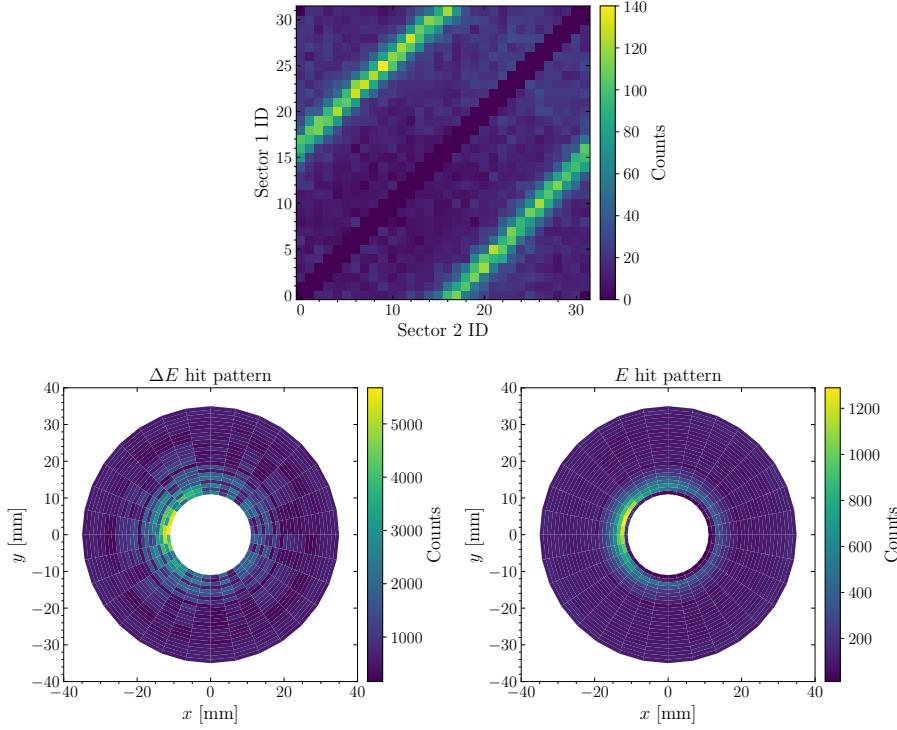


Figure 6.8: *Top panel:* Sector-sector correlation matrix of the ΔE detector recorded during commissioning with the ^{22}Ne beam. Each entry corresponds to an event in which two hits were registered simultaneously in two different sectors. A symmetric band, offset by ~ 16 sectors from the main diagonal, provides clear evidence of back-to-back topologies with an azimuthal opening angle close to 180° . *Bottom panels:* Hit patterns in the annular silicon ΔE (left) and E (right) detectors operated in telescope configuration. A localized hot spot on the left side of the inner rings indicates a slight beam misalignment during beam commissioning. Note that ring 9 of the E detector shows no counts, due to a digitizer issue resolved after the commissioning. Ring numbering increases outward from the innermost ring.

6.3.1 Luminosity Monitor

The commissioning run with the ^{22}Ne beam also provided a first validation of the in-beam response of the LUME luminosity monitor. Figure 6.9 shows the detector signal amplitude (in ADC units), as a function of the hit position along one of the four position-sensitive detectors, recorded with a CD_2 target (left panel), alongside the corresponding simulation (right panel). Three distinct kinematic lines are visible in the experimental spectrum and can be unambiguously identified by comparison with the simulation: the two uppermost lines correspond to elastically and inelastically scattered deuterons from the CD_2 target, while the third, lower-lying line is consistent with elastically scattered protons. This particle-species discrimination is made possible by the position sensitivity of the detectors, which allows the kinematically determined amplitude–position correlation unique to each scattered species to be resolved. Figure 6.10 shows the corresponding spectrum obtained with a pure carbon target. As expected, no deuteron lines are present. However, kinematic lines consistent with elastically and inelastically scattered protons are visible, which are not expected from the nominal C target composition and are attributed to water contamination, which introduces a hydrogen component in the target. The clean identification of these proton lines illustrates the sensitivity of the LUME detector to target impurities. It is worth noting that LUME adopts an off-axis geometry, in contrast to the conventional luminosity monitors used at ISS, which are typically placed on the beam axis and rely on total count rates within specific energy intervals without position information. The off-axis, position-sensitive approach demonstrated here is crucial for particle-species discrimination through kinematic lines, providing a direct handle on target composition and purity.

6.3.2 Protons - Si array detector

Figure 6.11 presents the signal amplitude of the upstream silicon array as a function of the hit position along the beam axis z . The four sections represent the four rows of Si wafers that are mounted on each module of the Si array. Several kinematic lines with positive slope are clearly visible, reflecting the characteristic energy–position correlation of protons emitted in the $^{22}\text{Ne}(\text{d}, \text{p})^{23}\text{Ne}$ reaction: protons populating different single-particle states in ^{23}Ne are kinematically focused to return to the beam axis at different positions depending on their energy and thus polar angle in the laboratory system, giving rise to the distinct bands observed in the spectrum.

A diagonal feature of opposite slope is also present. This structure does not follow the expected reaction kinematics and is presumably caused by scattering of the beam against material in the experimental setup. Its opposite slope with respect to the reaction lines makes it easily distinguishable from the physics signal, allowing for its removal through appropriate gating.

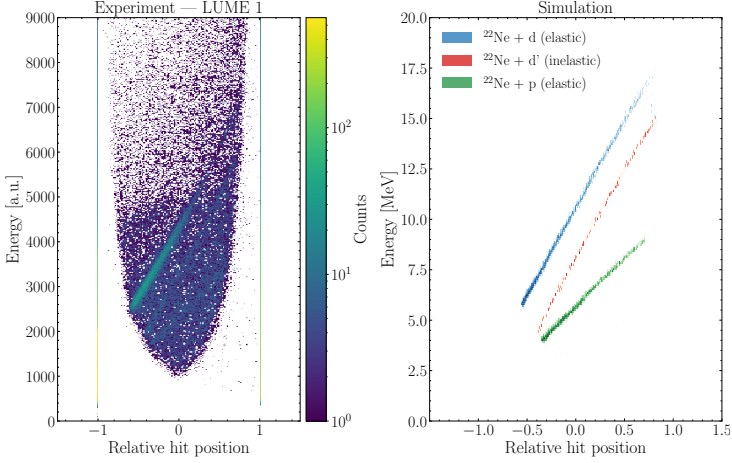


Figure 6.9: Detector signal amplitude (arbitrary units) versus relative hit position along a LUME detector, recorded with a ^{22}Ne beam on a CD_2 target (left), and corresponding simulation (right). The beam enters from the left. Three distinct kinematic lines are identified: elastically and inelastically scattered deuterons ($^{22}\text{Ne} + \text{d}$, $^{22}\text{Ne} + \text{d}'$) and elastically scattered protons ($^{22}\text{Ne} + \text{p}$), the latter attributed to water contamination in the target.

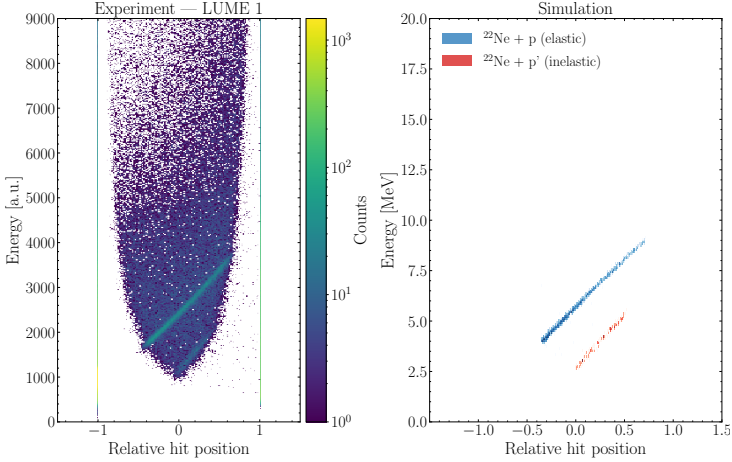


Figure 6.10: Detector signal amplitude (arbitrary units) versus relative hit position along a LUME detector, recorded with a ^{22}Ne beam on a pure carbon target (left), and corresponding simulation (right). The beam enters from the left. The observed parallel kinematic lines are consistent with elastically scattered protons, attributed to water contamination in the target. No deuteron lines are present, in contrast to the CD_2 data (Figure 6.9).

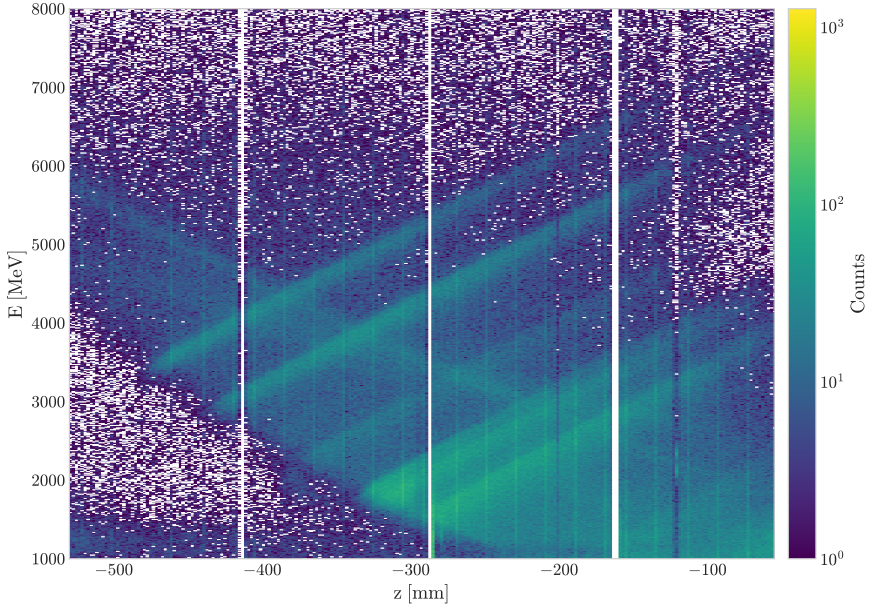


Figure 6.11: Energy deposited versus hit position along the beam axis z recorded by the upstream silicon array during commissioning with a ^{22}Ne beam on a CD_2 target. The four sections represent the four rows of Si wafers that characterize each module of the Si array. A few noisy strips have been gated out, as can be seen in the figure. Several kinematic lines with positive slope are visible, corresponding to excited states populated in ^{23}Ne via the $^{22}\text{Ne}(d, p)$ reaction. A diagonal feature of opposite slope is also observed, presumably arising from scattering of the beam against material in the setup.

Following Eq. 2.7, the excitation energy spectrum of ^{23}Ne can be reconstructed from the measured energy and the hit position of the detected protons on the Si array. Figure 6.12 shows the resulting E_x spectrum obtained from data collected with the CD_2 target (blue), overlaid with the scaled carbon target spectrum (red), which serves as an estimate of the carbon-induced background. The lower panel shows the background-subtracted spectrum, where several peaks are clearly visible and can be associated with known excited states in ^{23}Ne , as indicated by the dashed lines.

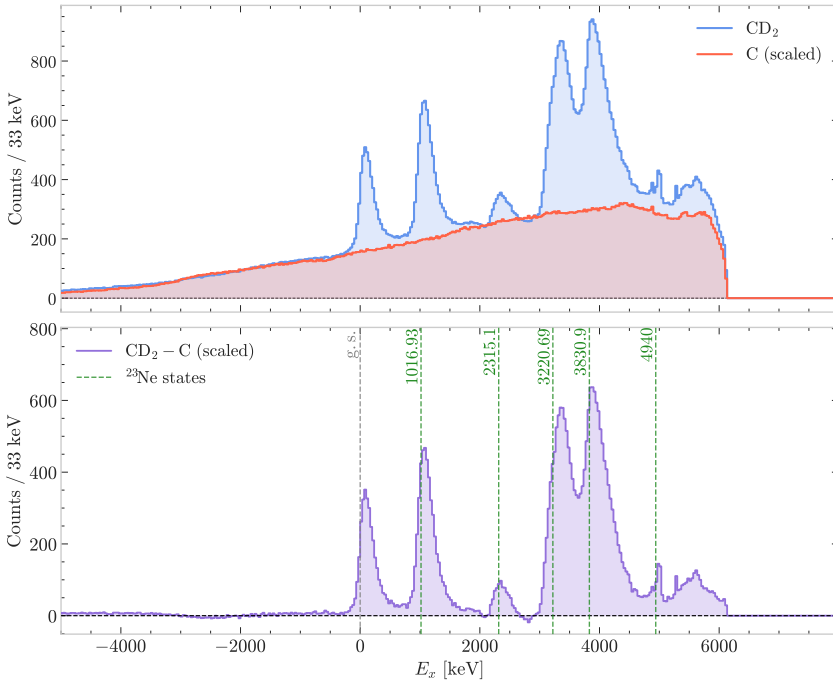


Figure 6.12: Excitation energy spectrum of ^{23}Ne reconstructed from protons from the $^{22}\text{Ne}(\text{d}, \text{p})$ reaction during stable-beam commissioning. *Top panel:* spectra obtained with the CD_2 target (blue) and the scaled carbon target (red), the latter providing an estimate of the carbon-induced background. *Bottom panel:* background-subtracted spectrum. Dashed vertical lines indicate known excited states in ^{23}Ne ; the ground state is marked as g.s. The carbon target spectrum is normalised to the CD_2 data in the region $E_x \in [-3000, -1000]$ keV, where no (d, p) reaction yield is possible.

6.3.3 γ - CeBr₃ array

For the first time at ISS, the installation of the new CeBr₃ scintillator array enabled the study of γ -ray correlations with the other detector systems. As an illustrative example, Figure 6.13 shows γ -ray energy spectra obtained in coincidence with protons associated with populating the individual excited states of ²³Ne identified in Figure 6.12. Each spectrum was extracted by applying a graphical cut on the corresponding kinematic band in the E - z matrix (upper panel), selecting events associated with a specific excited state, and requiring a prompt time coincidence (1 μ s) between the CeBr₃ array and the upstream silicon array. The resulting state-gated γ -ray spectra are shown in the lower panels, ordered from the ground state to the 4th identified excited state.

To further enhance the visibility of γ -ray lines in the state-gated spectra, a background subtraction was performed. For each kinematic gate, the time-vetoed γ -ray spectrum, normalized to the gated one, was subtracted to remove the underlying continuous background. The resulting background-subtracted spectra are shown in Figure 6.14, where discrete γ -ray transitions associated with the de-excitation of the recoiling ²³Ne nucleus are clearly resolved. The identified γ -ray transitions and their corresponding energies are summarized in Table 6.1. For each transition, the table reports the fitted energy values, the Doppler-corrected energies, and the literature values for the assigned transitions. The proton data alone place the fourth observed excited state in the 3800–4000 keV region, where several closely spaced levels lie within the excitation-energy resolution of the upstream silicon array and cannot be individually resolved. The identification of the 1672.6 keV γ -transition, however, unambiguously corresponds to a decay from the 3987.8 keV state, thereby pinning down which member of the multiplet is populated. Based on these identified transitions, Figure 6.15 shows the corresponding partial level scheme. The scheme illustrates the cascade of γ -ray transitions depopulating the excited states down to the ground state, with transition energies labeled on the arrows connecting the corresponding energy levels.

Furthermore, by relaxing the requirement of a detected proton, the ungated γ -ray spectrum reveals the characteristic 440.6 keV line, a well-known signature of the ²²Ne(d, n)²³Na reaction, as shown in Figure 6.16. This was anticipated in the motivation for the choice of this commissioning reaction (Section 6.2).

The setup is now ready for the radioactive beam!

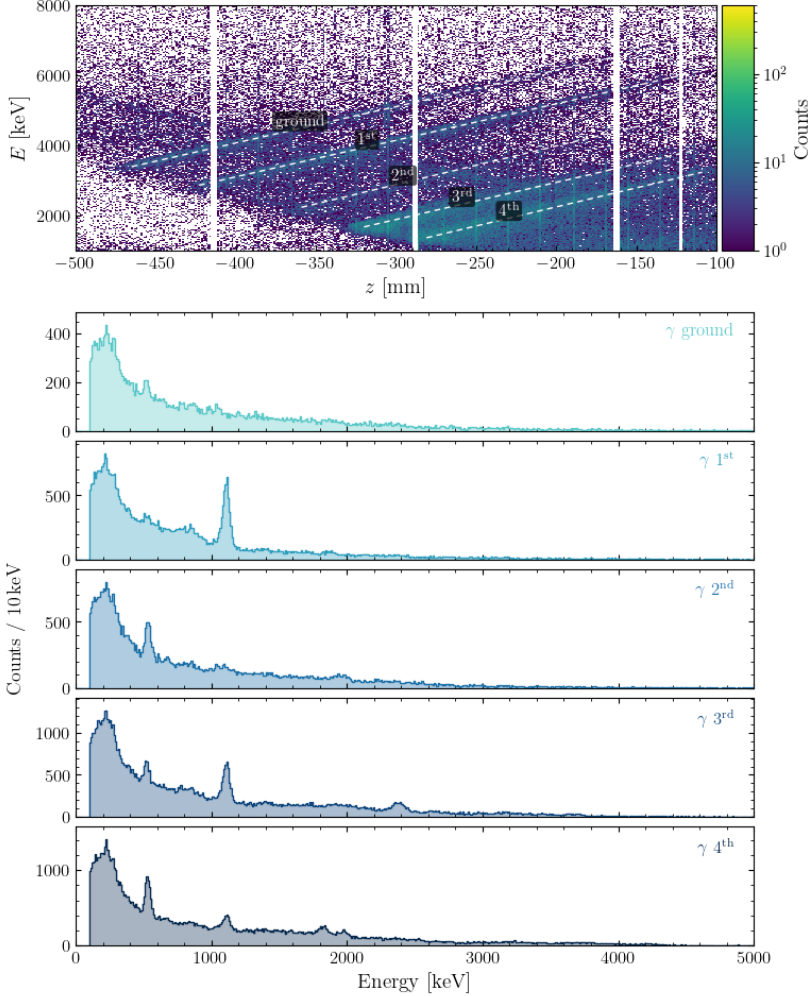


Figure 6.13: *Top panel:* energy deposited in the upstream silicon array versus hit position z along the spectrometer axis. The dashed lines highlight the kinematic bands associated with the ground state and four excited states of ^{23}Ne observed in this measurement. *Lower panels:* γ -ray energy spectra measured by the CeBr₃ array in prompt time coincidence with the silicon array, gated on each individual state via graphical cuts. This represents the first demonstration of a proton- γ coincidence capability at ISS.

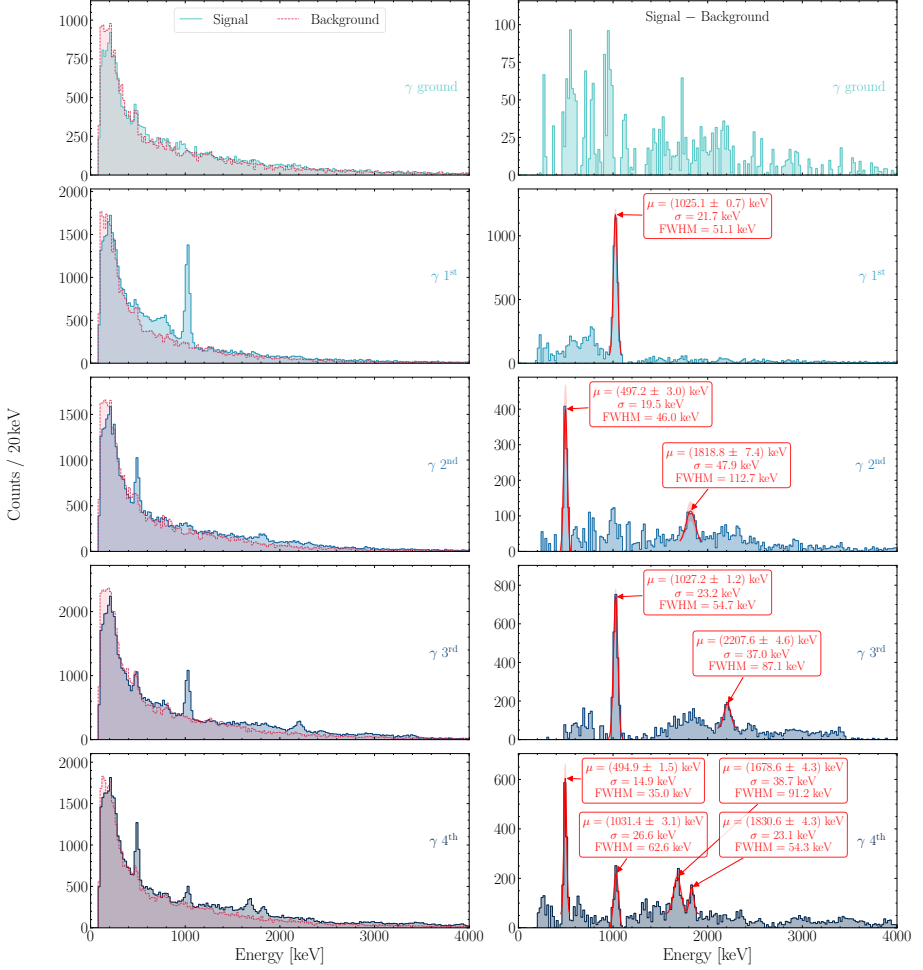


Figure 6.14: Left panels: state-gated γ -ray spectra (filled histograms corresponding to Figure 6.13) with the normalized time-vetoed spectrum superimposed as background estimate (dashed red lines). Right panels: background-subtracted spectra for the ground state and first four excited states of ^{23}Ne , highlighting discrete γ -ray transitions above the continuum.

Table 6.1: Identified γ -ray transitions in ^{23}Ne with fitted energies, Doppler-corrected energies, literature values [132], and assigned transitions numbered according to the excitation bands seen in Figure 6.13. Uncertainties represent the statistical errors from the fitting procedure.

Fitted E_γ [keV]	Doppler corrected E_γ [keV]	Literature [keV]	γ Transitions
1st Excited state (1016.9 keV)			
1107.5 ± 0.9	1025.1 ± 0.7	1016.9	$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+$
2nd Excited state (2315.1 keV)			
535.4 ± 2.8	497.2 ± 3.0	492.6	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$
1958.8 ± 9.6	1818.8 ± 7.4	1822.3	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$
3rd Excited state (3220.7 keV)			
1109.9 ± 1.5	1027.2 ± 1.2	1016.9	$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+$
2389.1 ± 5.6	2207.6 ± 4.6	2203.6	$\frac{3}{2}^- \rightarrow \frac{1}{2}^+$
4th Excited state (3831/3987 keV)			
535.3 ± 1.8	494.9 ± 1.5	492.6	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$
1112.0 ± 3.4	1031.4 ± 3.1	1016.9	$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+$
1813.3 ± 5.5	1678.6 ± 4.3	1672.6	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$
1979.3 ± 5.8	1830.6 ± 4.3	1822.3	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$

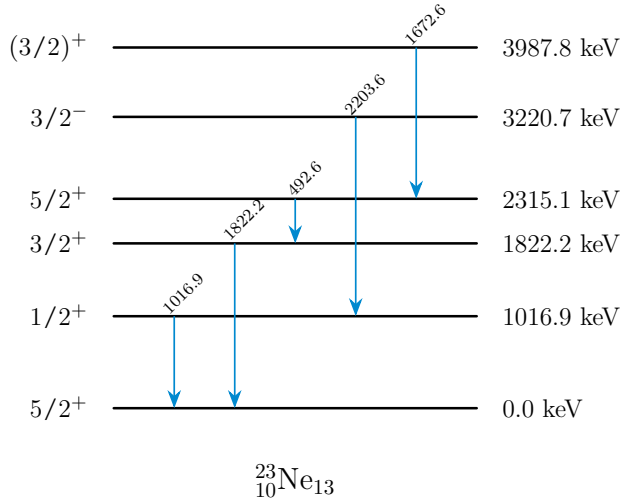


Figure 6.15: Partial decay scheme of ^{23}Ne constructed from the observed data, with identified γ transitions taken from the NuDat database [132].

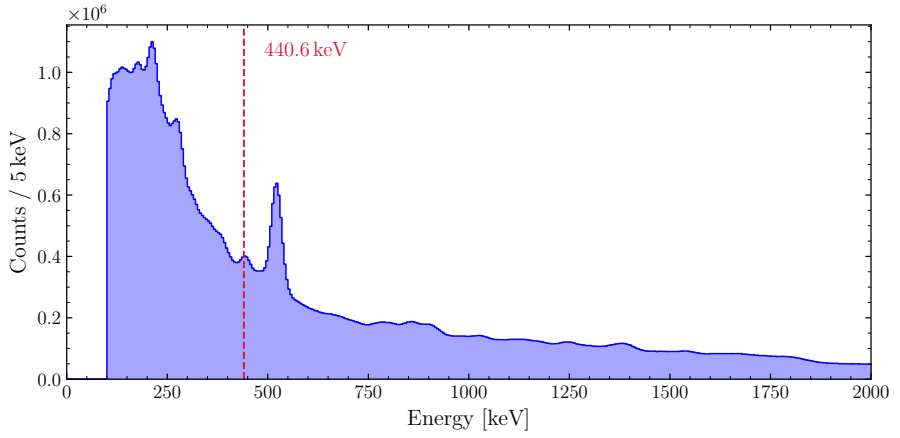


Figure 6.16: Ungated Doppler-corrected γ -ray energy spectrum measured by the CeBr₃ array, showing the characteristic 440.6 keV γ -ray line (dashed red line) associated with the $^{22}\text{Ne}(d, n)^{23}\text{Na}$ reaction. This line is absent in the proton-gated spectra, confirming its association with the (d, n) channel.

Chapter 7

IS739 experiment

THE r-process path spans regions of the nuclear chart far from the valley of β -stability. Due to the extreme neutron excess and the technical challenges of producing and isolating such exotic nuclei, beams of most of the isotopes involved are currently unavailable. The work presented in this thesis aims to establish a new experimental method for the systematic study of fission of neutron-rich nuclei. This method involves using radioactive beams in inverse kinematics within a solenoidal spectrometer, initially applied to less exotic nuclei. However, it can later be extended to more neutron-rich nuclei, closer to the r-process path, as experimental beam production advances. The data thus obtained can be used to test theoretical models for nuclei within experimental reach, refine these models, and extrapolate properties of nuclei that are not yet accessible. This process will enhance the predictive power of these models for isotopes that remain beyond current experimental capabilities, such as those crucial to the r-process.

The reaction originally proposed for the first measurement using this novel approach was $^{229}\text{Ac}(d, pf)$ at 8 MeV/u. Unfortunately, experimental challenges made this not possible, and a change in the isotope to be studied was needed during the beam time. However, before delving into that, it is important to introduce the theoretical framework and the rationale behind the initial selection of ^{230}Ac .

7.1 The GEF model

The semi-empirical “GEneral description of Fission observables” (GEF) model code predicts observables for fissioning nuclei via spontaneous fission, neutron-induced fission, and, more generally, for the fission of a compound nucleus from any entrance channel with specified excitation energy and angular momentum. It offers a consistent description of a wide range of experimental observables,

including the properties of the fission fragments at scission, such as masses, charges, excitation energies, and angular momenta, as well as their kinetic energies. Additionally, GEF models the de-excitation of the fission fragments, providing prompt-neutron and prompt-gamma multiplicities for each fragment, along with the corresponding prompt-neutron and prompt-gamma energies and angles. All of this information is provided by the code on an event-by-event basis, making it useful as an event generator for simulation purposes. GEF can describe a wide range of isotopes, from polonium (Po) to seaborgium (Sg), at excitation energies up to about 100 MeV, including multi-chance fission, and it provides predictions for nuclei even if no experimental data is available [8]. Owing to its basis in general physical laws, GEF is credited with good predictive power across essentially all fission observables while preserving their mutual correlations.

7.1.1 Basic ideas of the GEF model

GEF describes fission through general physical principles such as conservation laws, statistical mechanics, and macroscopic potential-energy arguments, while taking the effect of nuclear shell structure and pairing into account. It is not, however, a full microscopic or even microscopic-macroscopic calculation. This keeps computational cost low and makes the model applicable to a wide range of nuclear systems. For more detailed information, please refer to the official documentation in Ref. [8].

Fission Barriers

As discussed in Section 1.3, the fission barrier height strongly influences the fission decay width. GEF estimates fission barriers by combining the macroscopic liquid drop model with empirical shell corrections, following the microscopic-macroscopic approach [133]. According to the topographic theorem [134], only the shell correction energy at the ground state is considered, while the overall shape of the potential energy surface on the path to scission is primarily determined by the macroscopic fission barrier. The fission barrier height B_f is therefore approximated as:

$$B_f \approx B_f^{\text{mac}} - \delta U_{\text{gs}} \quad (7.1)$$

where B_f^{mac} represents the macroscopic barrier, and δU_{gs} is the shell correction energy at the ground state. This approach is illustrated in Figure 7.1.

Fission channels

The concept of fission channels, introduced in Section 1.3.5, provides the framework for understanding how different valleys in the potential energy surface lead

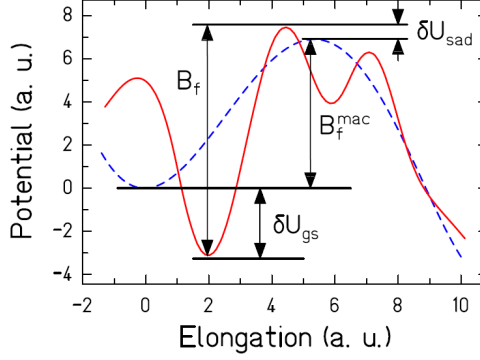


Figure 7.1: Schematic illustration of the potential energy along the fission path relative to the macroscopic ground-state energy for a nucleus deformed in its ground state. The spherical shape is located at zero elongation. The macroscopic potential is shown by the dashed blue line, while the full potential, including shell effects, is represented by the solid red line. δU_{sad} denotes the shell corrections at the saddle, whereas δU_{gs} represents the shell correction energy at the ground state. Figure from Ref. [8].

to distinct fragment mass distributions. In GEF, the statistical population of these channels is determined by the interplay between the macroscopic potential and microscopic shell effects.

The macroscopic potential favors symmetric fission, while shell effects can stabilize asymmetric configurations. As illustrated in Figure 7.2, the relative position of the symmetric splitting with respect to the shell-stabilized asymmetric configurations varies with the nuclear charge of the fissioning system, directly affecting the shape of the mass distribution. To reproduce the observed mass and charge distributions across a wide region of the nuclear chart, GEF employs four fission channels: the symmetric SL channel and three asymmetric channels (S1, S2, and SA). The concept of quantum oscillators is additionally used to model charge polarization, which determines the deviation from the Unchanged Charge Distribution assumption, whereby each fragment retains the same proton-to-neutron ratio as the fissioning nucleus [135].

Energy sorting

A key feature of GEF is its treatment of excitation energy partition between the emergent fragments. Following the assumption that fragment properties are largely determined near the fission barrier — well before scission — the available intrinsic excitation energy E_x must be statistically distributed between the two

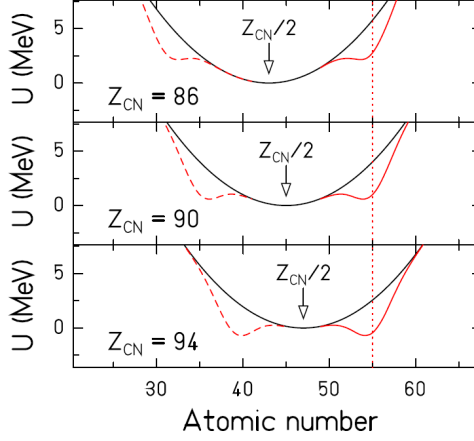


Figure 7.2: Schematic illustration of the potential energy at the outer fission barrier as a function of the charge asymmetry of the fission fragments. The black curve represents the macroscopic potential, which is minimized at symmetry, while the red curve includes the additional binding effect from an assumed shell at $Z = 55$ in the heavy fragment. Figure from Ref. [8].

emerging fragments. In GEF, this partition is governed by the level densities ρ_L and ρ_H of the light and heavy fragments, respectively. Assuming thermal equilibrium, the average excitation energy of the light fragment is calculated as:

$$\langle E_L \rangle = \frac{\int_0^{E_x} E_L \rho_L(E_L) \rho_H(E_x - E_L) dE_L}{\int_0^{E_x} \rho_L(E_L) \rho_H(E_x - E_L) dE_L}. \quad (7.2)$$

In the pairing correlation regime, where the level density exhibits an exponential dependence on excitation energy, the system behaves as two coupled microscopic thermostats. Since the logarithmic slope of the level densities is proportional to $A^{2/3}$, the most probable configurations are those where the available excitation energy is concentrated in the heavy fragment — a phenomenon known as *energy sorting* [136, 137]. This mechanism has direct consequences for the predicted prompt-neutron multiplicities and fragment kinetic energies.

7.2 Identification of a candidate nucleus in ^{230}Ac

The choice of the candidate nucleus was guided by extensive use of the GEF model to predict fission probabilities compared to neutron separation energies for neutron-rich actinides ($89 < Z < 103$). Table 7.1 reports a selection of potentially suitable nuclei. Among possible candidates, Pa and Th isotopes exhibit

Isotope	S_n [MeV]	Inner barrier [MeV]	Outer barrier [MeV]	P_f first chance [%]
^{237}Pa	5.9	5.5	5.8	11.0
^{238}Pa	4.7	5.7	6.2	11.0
^{235}Th	4.7	5.9	6.5	7.0
^{236}Th	5.8	5.6	6.2	4.5
^{229}Ac	6.3	6.2	6.8	3.5
^{230}Ac	4.9	6.4	7.1	3.0
^{231}Ac	6.1	6.1	6.6	2.3
^{228}Ra	6.3	6.9	7.8	0.4
^{229}Ra	4.5	6.9	7.8	0.3
^{230}Ra	6.1	6.8	7.8	0.2
^{233}U	5.7	5.85	5.67	75.8

Table 7.1: Predicted neutron separation energy S_n , inner and outer fission barriers, and first chance fission probability P_f , according to the GEF model. The importance of the ^{233}U isotope, highlighted in the last row, will become clearer in the discussion below.

higher fission probabilities. However, their refractory¹ nature prevents efficient extraction from the primary ISOLDE uranium target, precluding their use as beams. Therefore, ^{230}Ac has been selected, based not only on the predicted fission barrier shown in Figure 7.3, but also on the available beam intensities and production capabilities of the facility. The ^{230}Ac compound nucleus can be formed in (d, p) reactions using a ^{229}Ac beam, which can be extracted in molecular form as $^{229}\text{AcFF}^+$ from either thorium carbide (ThC_x) or uranium carbide (UC_x) targets with CF_4 gas injection. This technique is known to strongly suppress isobaric contamination, resulting in negligible contributions from Ra and Fr isotopes as was discussed with the beam production team [138].

In addition to these considerations, the choice of ^{230}Ac was motivated by the scarcity of experimental information on its fission properties at low excitation energies. Only two β -delayed fission events have been reported, but the evidence remains inconclusive, suggesting a fission barrier in the range 5.7–6.8 MeV [139], while measurements based on heavy-ion induced fission at higher excitation energies indicate a value of 5.37 MeV [140]. More recently, a study of ^{230}Ac yielded only a lower limit on the β -delayed fission probability [141]. These discrepancies, together with the higher value predicted by the GEF model (7.1 MeV), made ^{230}Ac a particularly compelling case for an investigation.

Finally, feasibility estimates based on the previous proof-of-principle exper-

¹The term *refractory* refers to the property of a material that makes it resistant to heat and chemical wear. This implies that refractory elements are difficult to extract due to their high melting points and strong chemical bonds.

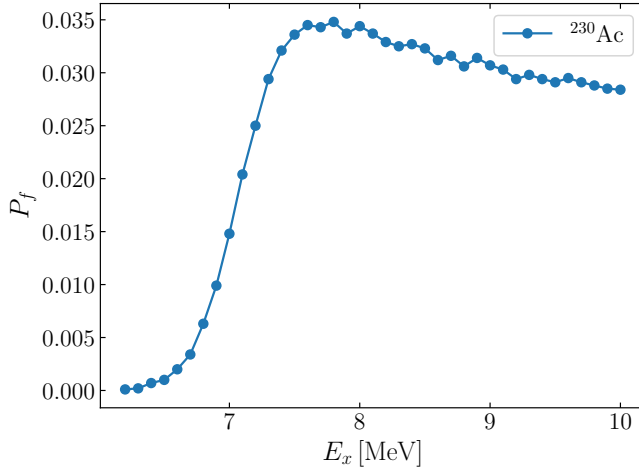


Figure 7.3: GEF prediction of fission probability P_f as a function of excitation energy E_x for ^{230}Ac .

iment performed at ANL using the HELIOS solenoidal spectrometer [10] indicate that, after scaling to the present case, a ^{229}Ac beam with an energy of $\geq 8 \text{ MeV/u}$ and an intensity on the order of 10^5 particles per second on target would be required to achieve sufficient statistics. Such conditions were considered to be within the capabilities of ISOLDE, according to expert estimates [138], assuming typical production yields and a transmission efficiency of about 1%. Further details on the scaling procedure used to obtain these estimates are provided in Appendix A.

Once these beam requirements were established and the specific physics case to be studied had been selected, extensive Monte Carlo simulations were performed to optimize the geometry of the experimental setup for this particular reaction channel and kinematic conditions. A key aspect was determining the optimal position of the annular silicon telescope used for the detection of the fission fragments. The position was optimized by varying the distance of the detector from the target and evaluating the corresponding solid angle coverage in order to maximize the detection efficiency for both fission fragments. Figure 7.4 shows the geometric efficiency curves for detecting the light fragment only, the heavy fragment only, and both fragments in coincidence, as a function of the detector-to-target distance. The simulations assume an incoming ^{229}Ac beam at 8 MeV/u , leading to the formation of ^{230}Ac at an excitation energy of 7 MeV . The most significant result is the efficiency for coincident detection of both fragments, which reaches approximately 80% at a detector-to-target

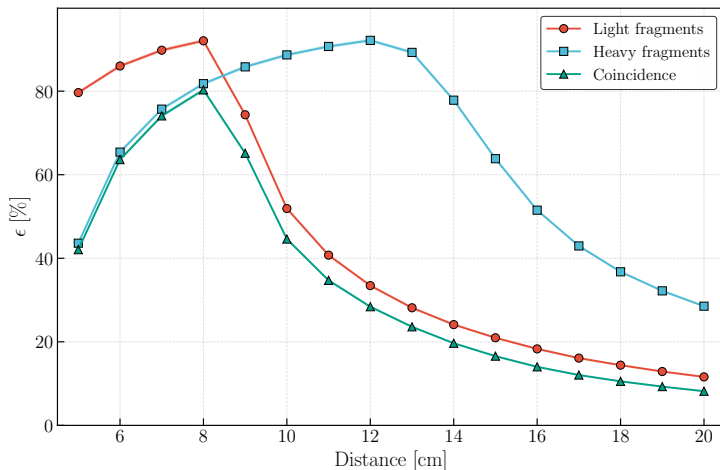


Figure 7.4: Geometric efficiency curves for detecting fission fragments as a function of the distance between the ΔE detector and the target. The solid green line represents the efficiency for coincident detection of both light and heavy fragments. The red dot-dashed line indicates the efficiency for detecting only the heavy fragment, while the dashed blue line represents the efficiency for detecting only the light fragment. These simulations assume a fissioning ^{230}Ac nucleus with $E_x = 7$ MeV. Error bars represent the statistical uncertainty of the Monte Carlo model. Heavy fragments, slower in the centre-of-mass frame, are focused into a narrower forward cone and thus peak at larger distances.

distance of 8 cm. This also confirms that this detection system would provide excellent overall efficiency at this configuration. However, due to spatial constraints during the installation of the setup inside the ISS magnet, a slightly larger distance of 8.5 cm between the target and the ΔE layer was ultimately adopted. As far as the upstream silicon array is concerned, the distance between the target and the active edge of the first row of silicon wafers was set to 36.7 mm in order to optimize the geometric acceptance for detected protons resulting from higher excitation energy single-particle states populated in ^{230}Ac . Regarding the LUME monitor system, the optimal configuration places the four PSDs at 7.5 cm radially from the beam axis, with their centers located 4.5 cm from the target plane. The active sides of the detectors face the beam axis and are aligned parallel to it, with the four plates rotated 90° around the beam axis relative to each other. This configuration was also determined by taking into account the constraints of limited space within the experimental setup. Further details on the complete geometric configuration and optimization procedure are provided in Ref. [3].

The proposal of the IS739 experiment was accepted by the CERN program

advisory committee (ISOLDE and Neutron Time-of-Flight Experiments Committee) was accepted in December 2023 and the experiment was scheduled to run in July 2025.

7.3 Change of isotope: ^{233}U

The challenging experimental conditions encountered early during the beam time ultimately led to a change in the isotope to investigate, shifting the focus of the experiment from ^{230}Ac to ^{233}U . This section describes the sequence of technical issues that motivated this decision and the physics arguments that made ^{233}U a well-suited alternative.

7.3.1 Technical issues with the ^{229}Ac beam

Several days prior to the scheduled beam time, it became clear that the beam energy would be lower than specified in the proposal, due to progressive degradation of the RF cavities in the accelerating line of the HIE-ISOLDE linac. As explained by the machine supervisors, the issue concerned the achievable gradients in certain cryomodules, and, given the mass of the beam, compensation via higher charge states was not feasible. The final beam energy was 7.34 MeV/u, pushed the feasibility margin of measuring the fission barrier of ^{230}Ac to its limit, since its GEF-predicted fission barrier lies around 7 MeV. The impact of this energy reduction on the detection of fission fragments is illustrated in Figure 7.5, which shows GGLAND-simulated [142] hit maps on the ΔE detector for ^{230}Ac fissioning at $E_x = 7$ MeV, comparing the nominal beam energy of 8 MeV/u with the delivered 7.34 MeV/u.

Difficulties with beam production added to the energy constraints. A ThC_x target was initially selected to produce a ^{229}Ac beam in difluoride form ($^{229}\text{AcF}_2$), but this proved impossible due to saturation of the HIE-ISOLDE ion trap (EBIS), likely caused by a ^{229}Ra contaminant. An attempt to produce the beam in monofluoride form (AcF) yielded intensities at least two orders of magnitude below expectations ($\sim 10^5$ pps instead of 10^7 pps), with an additional complication arising from an uncertain RaF contamination fraction. Following recommendations from the ISOLDE target group, the production target was subsequently changed to a UC_x target, which had been previously irradiated with protons in 2022. Despite several days of attempts, the ^{229}Ac beam intensity remained persistently low. In consultation with the beam experts, the decision was taken to switch to a ^{232}U beam to continue the experiment.

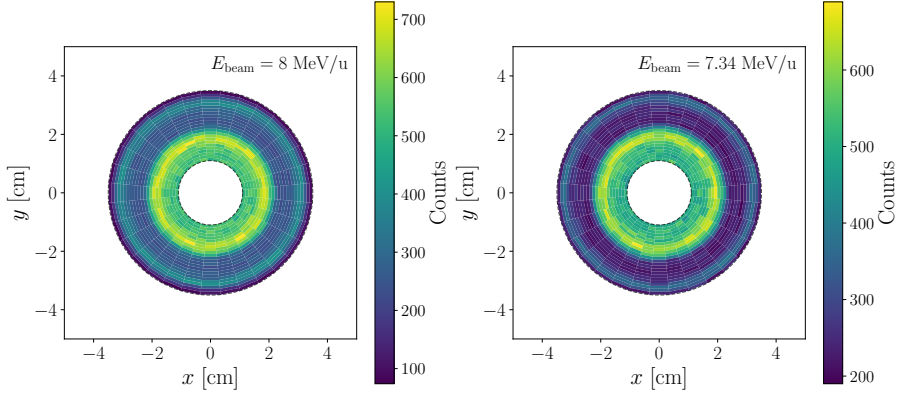


Figure 7.5: Simulated hit maps on the ΔE detector, positioned 8 cm downstream from the target, for fission fragments from ^{230}Ac fissioning at $E_x = 7$ MeV. The inner and outer rings correspond to the heavy and light fragment groups, respectively. *Left panel:* nominal beam energy of 8 MeV/u as specified in the proposal. *Right panel:* reduced beam energy of 7.34 MeV/u as delivered during the IS739 experiment. At lower beam energy, the fission-fragment emission is less forward-focused, so the light-fragment ring shifts toward the detector edge, making incomplete detection of the light fragments more frequent.

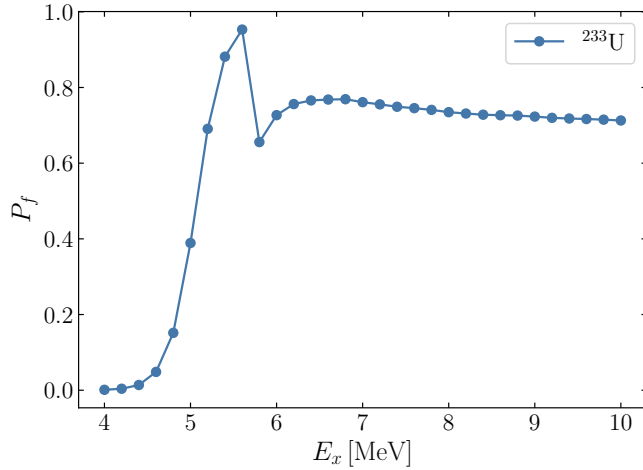


Figure 7.6: GEF prediction of the fission probability P_f as a function of excitation energy E_x for ^{233}U .

7.3.2 Physics motivation for switching to ^{232}U

From a beam production standpoint, ^{232}U has a high yield from a UC_x target, and, with a half-life of 68.9 years, residual activity from the 2022 proton irradiation was expected to be available in the target without requiring fresh PS Booster irradiation. This proved crucial on two occasions: during the first weekend of the run, when target experts were unavailable for another attempt at ^{229}Ac , and on a subsequent day when the PS Booster was offline due to a water leak.

7.3.3 Fission of ^{233}U in the literature

Historically, ^{233}U was first identified in 1947 [143], and early estimates of its fission cross section date to 1953 [144]. While several datasets exist on ^{233}U fission at low excitation energies, including Refs. [145–147], none were obtained via the $^{232}\text{U}(\text{d},\text{p}f)$ transfer reaction. The IS739 experiment therefore represents the first measurement of the $^{232}\text{U}(\text{d},\text{p})$ and, naturally, the $^{232}\text{U}(\text{d},\text{p}f)$ transfer reactions, extending the proof-of-principle carried out at ANL to a radioactive beam facility. The fissioning system it selects, ^{233}U at a few MeV above the barrier, has nonetheless been characterised before by other techniques, providing a reference against which the present data can eventually be compared.

Its fission barrier is well established: evaluated and experimental compilations place $B_f(^{233}\text{U})$ at about 6 MeV [148, 149], a value that GEF [8] reproduces and that is directly comparable to the $B_f = 6.42(12)$ MeV extracted for the neighbouring ^{239}U in the analogous $^{238}\text{U}(\text{d},\text{p}f)$ measurement at HELIOS [10].

Fragment observables are also available. Electromagnetic-induced fission of ^{233}U at radioactive-beam energies [150] was used to populate the system at $E_x \approx 11$ MeV, somewhat higher than the present transfer-induced signal. There the nuclear-charge yield is markedly asymmetric, with the heavy component centred at $Z \approx 54$ and a suppressed symmetric valley, and the total kinetic energy follows the same structure, with two maxima of about 175 MeV and a minimum near symmetry of about 158 MeV. Compared with thermal-neutron-induced fission of the same compound nucleus ($^{232}\text{U}(n_{\text{th}}, f)$), the general features of the charge and TKE distributions are preserved, while the higher excitation energy enhances the symmetric yield, raises the near-symmetric TKE by a few MeV, and reduces the proton even–odd effect [150]. These trends set the expectation for the transfer-induced measurement, which accesses ^{233}U at lower and sharply defined excitation energy.

It should be noted that all experimental decisions described above were necessarily taken under significant time pressure, without the possibility of dedicated simulations. The beam time and detector geometry had been optimised for the ^{230}Ac case, including the assumption that a beam energy of 8 MeV/u would be available. Of the ten scheduled days of beam time, only five full days

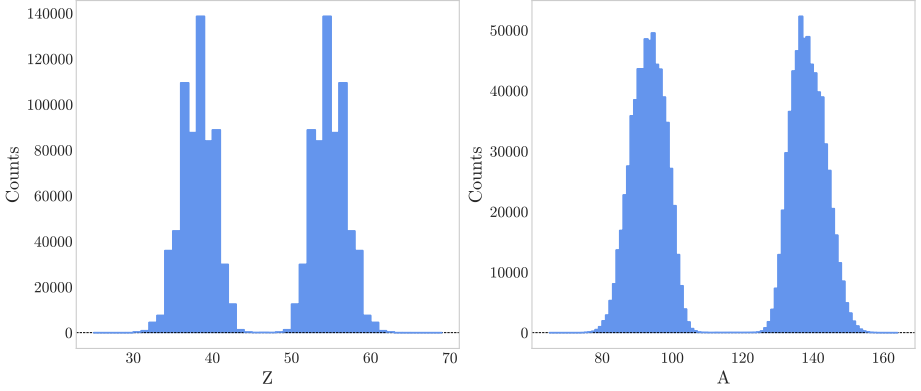


Figure 7.7: Simulated charge (Z , left) and mass (A , right) distributions of fission fragments from ^{233}U at $E_x = 7$ MeV, as predicted by GEF [8]. The asymmetric two-peaked structure reflects the well-known mass asymmetry in actinide fission, with the heavy fragment group centred around $A \sim 132$ – 140 and the light fragment group around $A \sim 90$ – 100 .

were ultimately available for data taking with the uranium beam.

To conclude this part, some simulations are presented to illustrate the expected characteristics of the fission fragments from ^{233}U .

Figure 7.7 shows the simulated charge Z and mass A distributions of the fission fragments produced in ^{233}U fissioning at an excitation energy of $E_x = 7$ MeV. The distributions exhibit a clear asymmetric structure, with two well-separated peaks corresponding to the light and heavy fragment groups. Figure 7.8 shows the simulated laboratory-frame emission angle θ_{lab} of the fission fragments. The distribution presents two distinct peaks, corresponding to the heavy fragments focused at smaller angles ($\theta_{\text{lab}} \sim 14^\circ$) and the light fragments emitted at larger angles ($\theta_{\text{lab}} \sim 21^\circ$ – 23°), as expected from momentum conservation in the fission process. Finally, Figure 7.9 shows the simulated detection efficiency ϵ as a function of the target-to-detector distance for fission fragments from ^{230}Ac (top) and ^{233}U (bottom) fissioning at $E_x = 7$ MeV, assuming a beam energy of 7.34 MeV/u. The vertical dotted line indicates the target-to-detector distance adopted during the IS739 experiment (8.5 cm). It should be noted that, at the same target-to-detector distance, the detection efficiency for the light fragments is slightly lower in the ^{233}U case (73.7%) compared to ^{230}Ac (75.8%). This can be attributed to the larger total kinetic energy (TKE) released in ^{233}U fission, as shown in Figure 7.10, which results in a wider angular distribution of the light (and heavy) fragments, pushing them further towards the edge of the detector acceptance. This inevitably affects also the expected coincidence efficiency, which is slightly reduced from 66.2% for ^{230}Ac to 65.0%

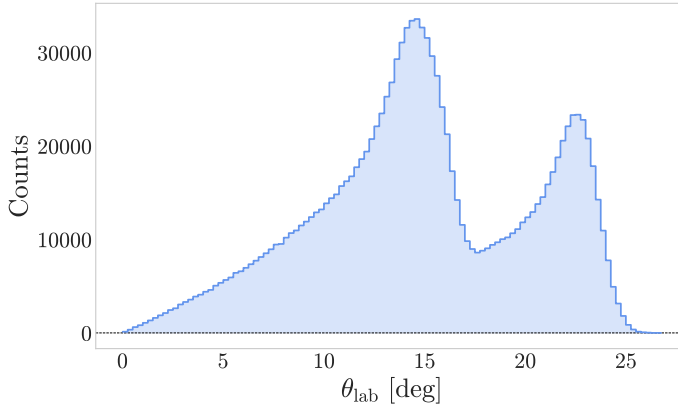


Figure 7.8: Simulated laboratory-frame emission angle θ_{lab} of the light (large angle peak) and heavy (small angle peak) fission fragments from ^{233}U , obtained by boosting the GEF [8] fragment momentum distributions to the laboratory frame at the beam energy of 7.34 MeV/u, using the GGLAND simulation framework.

for ^{233}U .

The full chronology of the run is summarised in Figure 7.11. Beam tuning through HIE-ISOLDE and the ISS beam line was performed on a stable $A/q = 4$ pilot beam while the target group worked on the ^{229}Ac extraction. A practical advantage of ^{232}U emerged once the switch was made: the activity kept effusing from the heated UC_x target even with the protons off, so data taking continued through both interruptions of the proton delivery. The run closed with α - and γ -source calibration measurements for the silicon and CeBr_3 detectors.

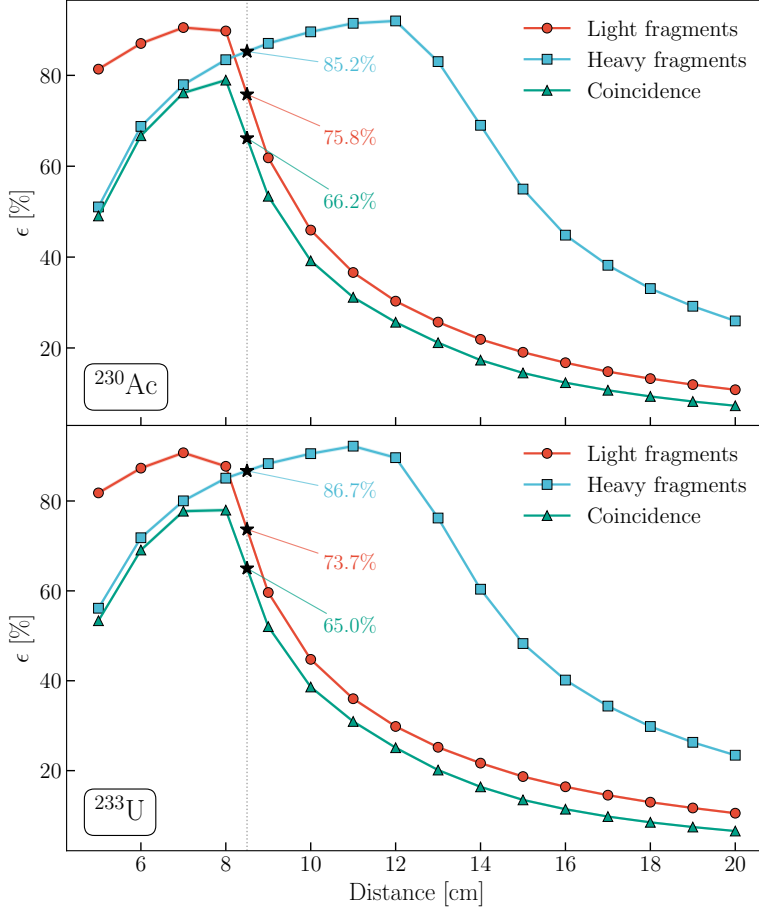


Figure 7.9: Simulated detection efficiency ϵ as a function of target-to-detector distance for light fragments (red circles), heavy fragments (blue squares), and their coincidence (green triangles), for ^{230}Ac (top) and ^{233}U (bottom) fissioning at $E_x = 7$ MeV with a beam energy of 7.34 MeV/u, obtained with GGLAND. The vertical dotted line marks the distance of 8.5 cm adopted during the IS739 experiment, at which the coincidence efficiency amounts to 66.2% and 65.0% for ^{230}Ac and ^{233}U , respectively.

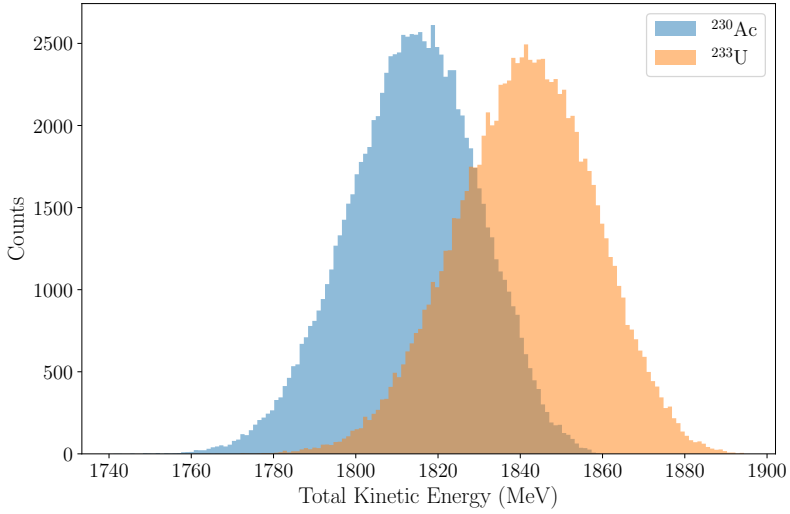


Figure 7.10: Total kinetic energy (TKE) distributions of fission fragments from ^{230}Ac (blue) and ^{233}U (orange) in the laboratory frame, as predicted by GEF [8] at $E_x = 7$ MeV and boosted to the laboratory frame assuming an incoming beam energy of 7.34 MeV/u. The ^{233}U distribution is shifted to higher TKE values with respect to ^{230}Ac , reflecting the mass difference of the two isotopes as well as the larger Coulomb repulsion between the fission fragments of the heavier nucleus.

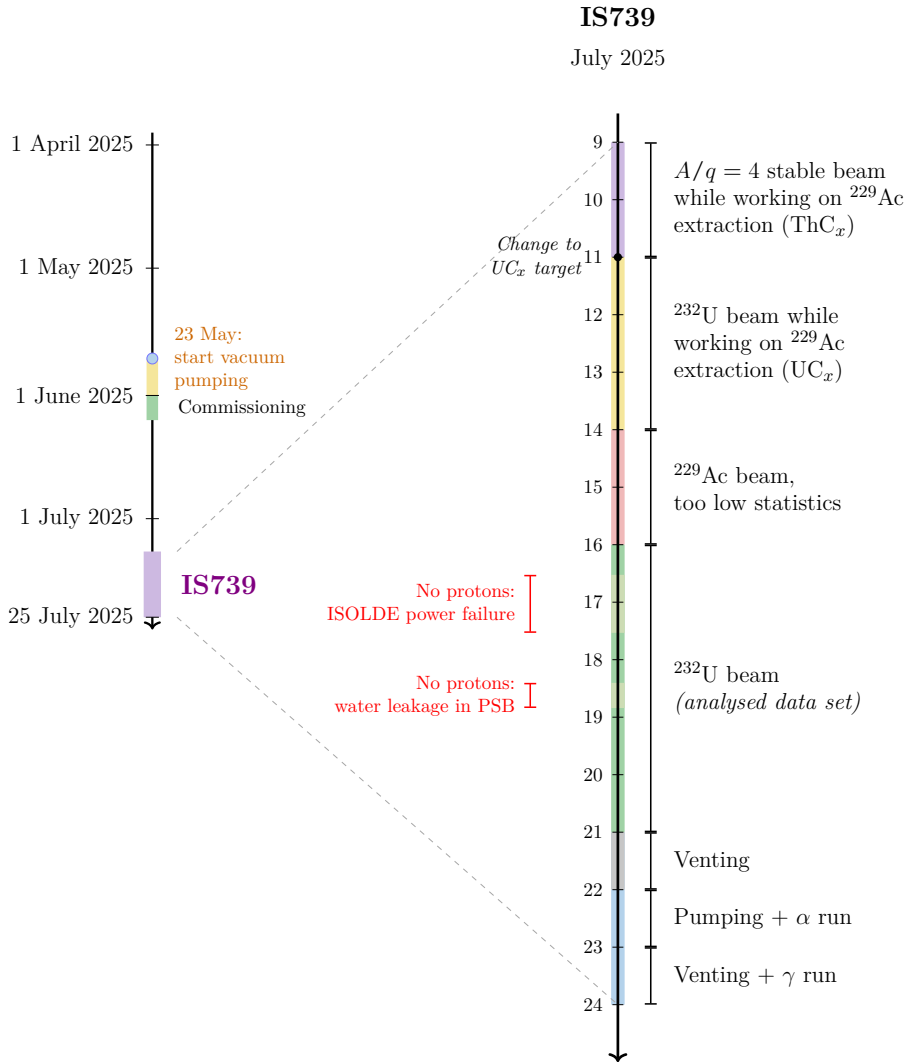


Figure 7.11: Commissioning and IS739 timeline.

Chapter 8

Detector Calibration

BY calibration, we refer to the systematic process through which the raw detector signals are converted into physical quantities of interest by establishing quantitative relationships using reference sources or signals with known characteristics. Figure 8.1 provides an overview of the calibration procedures adopted for the different detection systems. In this chapter, the calibration of the annular fission fragment and the LUME detectors is described. A key software tool used in the calibration of the fission fragment detectors is **Millepede II** [151], which is first described.

8.1 Millepede II

Millepede II¹ is a dedicated software package designed for global fitting and alignment of complex detector systems in high-energy physics experiments [151]. It performs a simultaneous least-squares fit of a large number of parameters, including detector positions, orientations, calibration constants, and, implicitly, all track parameters. This is achieved by exploiting the sparse structure of the problem, making the solution computationally tractable. The underlying mathematical formalism used by **Millepede** is presented in Appendix B. It is widely used in experiments at the LHC at CERN and elsewhere. In the context of this work, its key advantage can be summarised as follows:

¹For simplicity, throughout the remainder of this thesis, **Millepede II** will be referred to as **Millepede**. Although both versions rely on the same underlying principles, **Millepede II** was developed to improve usability and to enable the treatment of significantly larger systems.

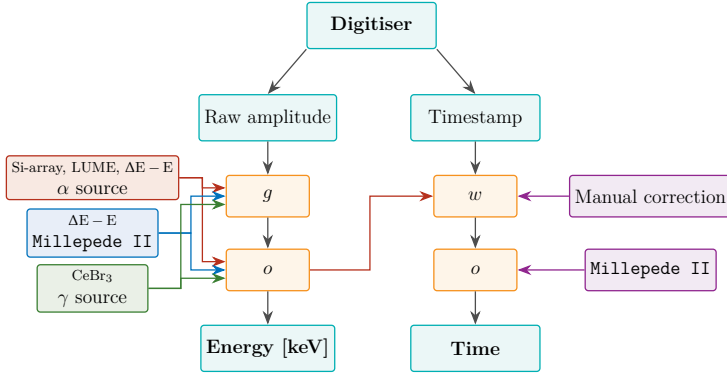


Figure 8.1: Overview of the calibration procedures for all detection systems. The digitiser provides two outputs, raw amplitudes and timestamps, which are processed through two independent calibration chains. In the energy chain, a gain (g) and offset (o) correction for each channel is applied to convert the raw amplitude into calibrated energy in keV; the calibration parameters are determined using α and γ reference sources, with simultaneous optimisation across all detector strips performed via **Millepede II** for the $\Delta E - E$ detector. In the timing chain, a time-walk correction (w) is applied to the timestamp, followed by an offset correction (o) to yield the calibrated time; while the offsets are determined via **Millepede II**, the time-walk corrections are determined semi-manually as an independent procedure.

Rather than calibrating each channel independently, **Millepede** determines the calibration parameters of **all channels** and using all input data **simultaneously** in a single global fit, yielding a statistically optimal and self-consistent solution across the entire detection system.

8.1.1 Typical use case: position alignment

Millepede was originally developed for the alignment of large tracking detectors, such as the CMS silicon tracker, where each particle traverses many detector modules and produces an overdetermined set of measurements. But at the same time, each track is only seen by a very small fraction of the total number of strips or detectors in the entire setup. In this context, the local parameters are the particle track parameters (positions and directions in individual events) and the global parameters are the alignment corrections (translations and rotations) of all detector modules.

This separation allows for efficient processing: the computationally intensive track fitting and data collection (i.e. preparation of **Mille** input data) can be distributed across multiple computing nodes, while the global solution (running

Pede itself) is performed once all data have been collected.

8.1.2 Application to DSSSD gain matching

The same mathematical structure applies to the gain calibration of double-sided silicon strip detectors (DSSSDs). Each detection event produces signals on both the p-side and n-side, which must match to reconstruct the deposited energy.

The key advantage is that **Millepede** treats the calibration problem as if it were fitting all events simultaneously: rather than calibrating each strip independently, it solves for all gain factors and offsets in a single global fit, exploiting the correlations between measurements across the entire dataset. In this gain-matching context, the **Millepede** framework maps as follows:

- **Local parameter:** the true deposited energy $E_{\text{dep},j}$ for event j , valid only for that event.
- **Global parameters:** the gain g_i and offset o_i of each strip (p-side and n-side), shared across all events.
- **Measurements:** the raw ADC signals $S_{p,j}$ and $S_{n,j}$; in case of charge sharing between neighbouring strips on the same side, the gain-corrected signals of adjacent strips are summed before being compared with $E_{\text{dep},j}$.

The model relating measurements to parameters can be expressed as:

$$E_{\text{dep},j} = \underbrace{g_p \cdot S_{p,j} + o_p}_{f_{p,j}} + \varepsilon_p, \quad (8.1)$$

$$E_{\text{dep},j} = \underbrace{g_n \cdot S_{n,j} + o_n}_{f_{n,j}} + \varepsilon_n, \quad (8.2)$$

where ε_p and ε_n represent the measurement uncertainties. In practice, for each event **Mille** records the residuals $r_{p,j} = E_{\text{dep},j} - f_{p,j}$ and $r_{n,j} = E_{\text{dep},j} - f_{n,j}$, together with the derivatives with respect to $E_{\text{dep},j}$ (local) and to g_i, o_i (global). After processing all events, **Pede** constructs and solves the reduced system (derived in Appendix B, Eq. B.15) for the optimal calibration constants of all strips simultaneously. The procedure is iterated until convergence.

Advantages under Sparse Irradiation

Traditional strip-by-strip methods require accumulating sufficient statistics of calibration data for each channel to build reliable energy distributions, which may be unachievable for rarely-hit strips. **Millepede** circumvents this in two ways. First, every event contributes to the global fit regardless of how often a given strip is hit. Second, the p-side and n-side signals share the same local

parameter $E_{\text{dep},j}$: this coupling links the two sides and propagates calibration information globally, constraining strips that would otherwise be underdetermined.

8.2 Fission fragment detectors

Millepede cannot determine the absolute energy scale through detector-internal consistency alone. For that, the classic approach is first used.

8.2.1 Absolute calibration

Typically, detector calibrations are performed using radioactive sources that emit particles at well-defined, known energies. This allows the conversion of the response of the detector, measured in ADC units, into physical energy values. For silicon DSSSDs, α -sources are commonly employed due to their monoenergetic emission lines and their ability to provide a clean calibration signal across the full detector volume. After the IS739 experiment, a dedicated calibration run was performed using an α -source to measure the detector response at known energies under the same experimental conditions. This approach aims at ensuring that the calibration is performed with the same electronic settings, detector operation, and environmental conditions as those present during the actual experiment, providing a direct and reliable energy calibration. The α -source used for this calibration was mounted in the source slot of the target frame (see Section 3.2), positioned at the same location where the target had been during the experiment. In this configuration, the detector geometry and solid-angle coverage matched those of the experimental runs, so the calibration reflects the same conditions. Table 8.1 lists the radionuclides used, along with their half-lives and principal emission energies. Given the energy resolution of the detectors, the α emission spectrum of the source produces four distinct peaks, providing four calibration points. Since the energy resolution of the detectors is not sufficient to resolve the individual α lines emitted by the same radionuclide, the weighted mean of the transition energies, computed using the respective decay intensities as weights, is adopted as the reference energy for each calibration point.

Radionuclide	Half-life (y)	α Energy (keV)
^{148}Gd	86.9	3183 (100%)
^{239}Pu	$2.4 \cdot 10^4$	5105 (12%), 5144 (17%), 5157 (71%)
^{241}Am	432.6	5388 (1.6%), 5443 (13.1%), 5486 (84.8%)
^{244}Cm	18.112	5664 (1%), 5763 (23%), 5805 (76%)

Table 8.1: List of α -emitters within the source used at ISS and their key properties.

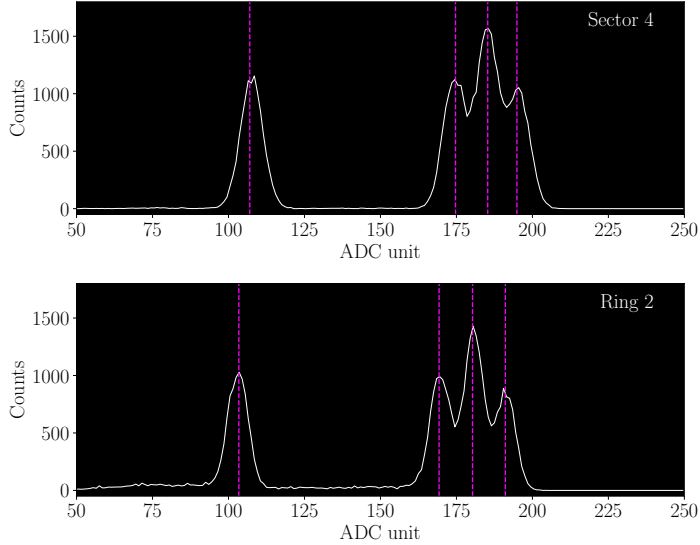


Figure 8.2: Raw α -particle spectra from the four-nuclide α calibration source for Sector 4 (top) and Ring 2 (bottom) of the ΔE layer. The four peaks corresponding to the α emissions are indicated by magenta dashed lines. Each peak was manually fitted using HDTV to extract the centroid position in ADC units for the energy calibration.

ΔE detector

The first step in calibrating the annular fission fragment detectors consisted of manually calibrating every channel of the ΔE layer: 56 channels per side (32 sectors on the p-side and 24 rings on the n-side). This manual calibration was performed using the software *HDTV - Nuclear Spectrum Analysis Tool*, a graphical interface designed for gamma-ray spectroscopy that provides interactive tools for peak selection, fitting, and calibration [152]. HDTV allows the user to visually identify peaks in the spectrum, select the region of interest, and perform automated Gaussian fits to determine the peak centroids with high precision. The software then associates these centroid positions (in ADC units) with the known α -particle energies, generating the calibration parameters for each individual detector channel. Figure 8.2 shows the raw ADC signal from a single sector (Sector 4, p-side) and a single ring (Ring 2, n-side) of the ΔE .

The four peaks from the four-nuclide α -source are clearly visible in both spectra, marked by the vertical magenta dashed lines. Each peak was fitted for all 56 channels on both sides of the detector, yielding a linear calibration of the form

$$E_i = g_i \cdot \text{ADC}_i + o_i, \quad (8.3)$$

where g_i and o_i are the gain and offset of channel i , respectively.

8.2.2 Gain matching

Subsequently, following the initial manual calibration, the gain matching was done using **Millepede**, which performs a simultaneous least-squares fit of all detector channels, taking into account correlations between different strips and optimizing the calibration parameters globally rather than independently for each channel. **Millepede** computes small corrections δg_i and δo_i to the gain and offset of each channel, yielding a refined calibration:

$$E_i = \tilde{g}_i \cdot \text{ADC}_i + \tilde{o}_i \quad (8.4)$$

where

$$\tilde{g}_i = g_i + \delta g_{gm,i} \quad (8.5)$$

$$\tilde{o}_i = o_i + \delta o_{gm,i} \quad (8.6)$$

where $\delta g_{gm,i}$ and $\delta o_{gm,i}$ are the gain and offset corrections determined by the global fit. For this operation, the $A/q = 4$ stable beam data collected during IS739 were used, because of their higher statistics. It should be noted, however, that **Millepede** can work with any data, be it fission data, stable beam data, or alpha source data; it does not require alpha source data specifically. This approach significantly improves the energy resolution by minimizing systematic discrepancies between the two detector sides. Figure 8.3 shows a comparison of the energy resolution of the ΔE detector before and after the gain-matching procedure. The left panel (before) shows the energy difference distribution between the p-side and n-side after the manual calibration only, while the right panel (after) shows the same distribution after applying the corrections calculated by **Millepede**. The FWHM is reduced from 504.85 ± 5.31 keV to 463.67 ± 3.02 keV, representing an improvement in the energy resolution of approximately 8%.

E detector

The calibration of the E layer presented a significant challenge compared to the ΔE . As illustrated schematically in Figure 8.4, the α -particles emitted by the source are not energetic enough to punch through the ΔE layer and therefore do not reach the E detector behind it. Only those particles passing through the aperture in the ΔE detector can reach the E layer. This geometric constraint results in insufficient statistics to perform a manual, channel-by-channel calibration for most E layer strips using the α -source run alone, making the gain-matching procedure indispensable in this case.

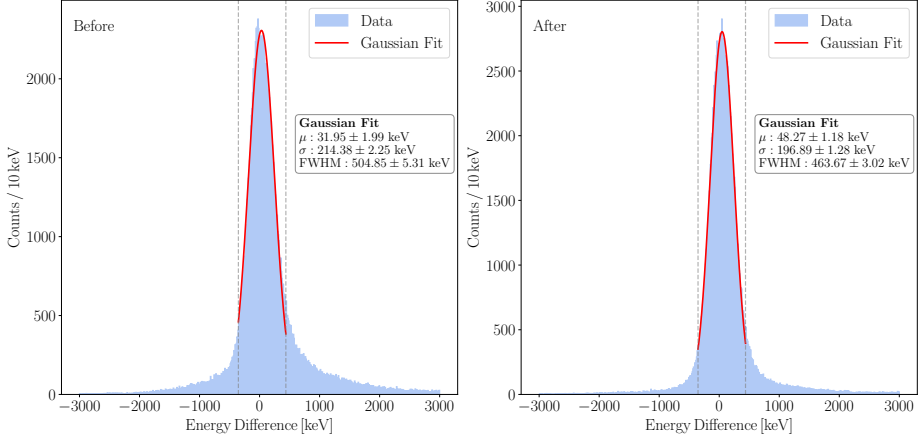


Figure 8.3: Comparison of the energy difference between the p-side and n-side of the ΔE detector before (left) and after (right) gain matching with *Millepede*, for data collected during the IS739 experiment with a $A/q = 4$ stable beam. The blue histogram shows the experimental data, while the red curve represents a Gaussian fit. The improvement in resolution (reduced FWHM) demonstrates the effectiveness of the global calibration approach.

However, the innermost ring (Ring 0) of the E detector collected sufficient statistics for the calibration from the α -particles passing through this opening. This provided an opportunity to establish a reference calibration for at least one channel of the E layer. The calibration of the E layer then proceeded with a two-step strategy:

1. **Gain matching with experimental data:** First, a gain matching procedure was performed between the p-side and n-side of the E detector using the data collected during the IS739 experiment itself. Despite the limited irradiation from the α -source, the experimental runs easily provide sufficient statistics to apply *Millepede* for the gain matching of all channels. This ensures that the relative calibration between the two sides of each E detector channel is consistent, even though the absolute energy scale remains undetermined.
2. **Absolute calibration and scaling:** Using the α -source run, the absolute energy calibration coefficients $g_{r,0}$ and $o_{r,0}$ are determined manually with HDTV for Ring 0, which had accumulated sufficient statistics. For each channel i of the E layer, the final calibration parameters $\tilde{g}_i$ and $\tilde{o}_i$ are then obtained by combining the *Millepede* relative corrections with the absolute scale from Ring 0. The energy is reconstructed according to the same linear relation as in Eq. (8.4), where the calibration parameters

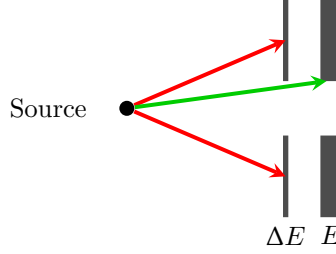


Figure 8.4: Schematic representation of α -particle trajectories through the $\Delta E - E$ telescope detector system. The red arrows indicate α -particles stopped in the ΔE layer, while the green arrow shows particles reaching the E detector by passing through the central aperture.

$\tilde{g}_i$ and $\tilde{o}_i$ are now determined as:

$$\tilde{g}_i = \frac{g_{r,0}}{1 + \delta g_{gm,i}} \quad (8.7)$$

$$\tilde{o}_i = o_{r,0} - g_{r,0} \cdot \frac{\delta o_{gm,i}}{1 + \delta g_{gm,i}} \quad (8.8)$$

A more detailed view of the gain-matching result is provided in Figure 8.5, using data collected during the IS739 experiment with a stable beam with $A/q = 4$. The figure shows the energy difference between the n-side and p-side of the ΔE detector as a function of pixel² ID, for two different pixel indexing schemes: sector major and ring-major. The two indexing schemes allow one to identify whether systematic misalignments are driven by specific sectors or rings. Moving from top to bottom, the figure shows the progressive improvement in the alignment: from the raw ADC differences, to the manually HDTV-calibrated data, to the final *Millepede* gain-matched result. The bottom panel shows the mean and standard deviation of the energy difference per pixel after gain matching, extracted from a Gaussian fit to the per-pixel distribution, providing a direct estimate of the per-pixel energy resolution.

Once the gain-matching parameters are established, it becomes possible to investigate the stability of the calibration throughout the entire IS739 experiment. Figure 8.6 shows the mean and standard deviation of the energy difference between the p-side and n-side, extracted from Gaussian fits, as a function of run number for both the ΔE and E detectors, covering a total data-taking period of approximately five days. The mean remains close to zero across all runs, and the standard deviation stays within approximately ± 250 keV throughout

²A pixel is defined here as the intersection of a sector strip (p-side) and a ring strip (n-side) of the DSSSD, uniquely identified by a sector-ring pair.

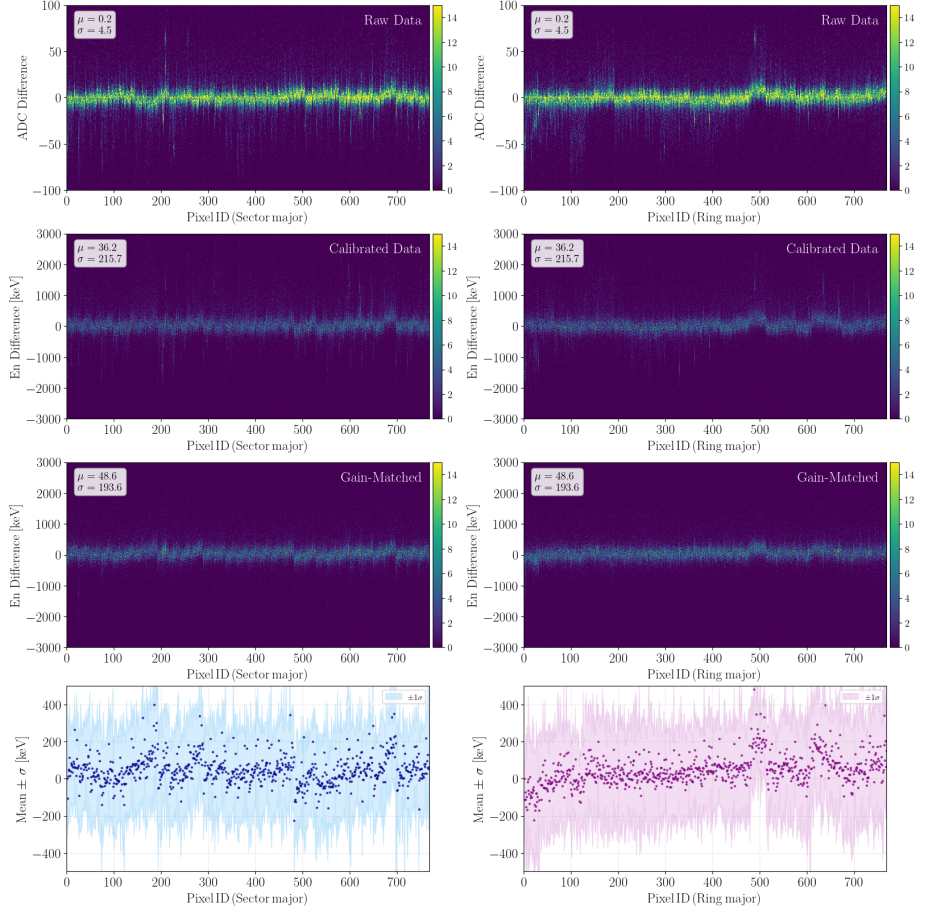


Figure 8.5: Energy difference between the n-side and p-side of the ΔE detector as a function of pixel ID, shown for two different pixel indexing schemes: sector-major (left column) and ring-major (right column). The two indexing schemes allow one to identify whether systematic misalignments are driven by sectors or rings. From top to bottom: (a) raw ADC differences before any calibration; (b) energy differences after applying the manual α -source calibration coefficients only; (c) energy differences after the **Millepede** gain-matching procedure; (d) mean and standard deviation of the energy difference per pixel, illustrating the per-pixel energy resolution after gain matching.

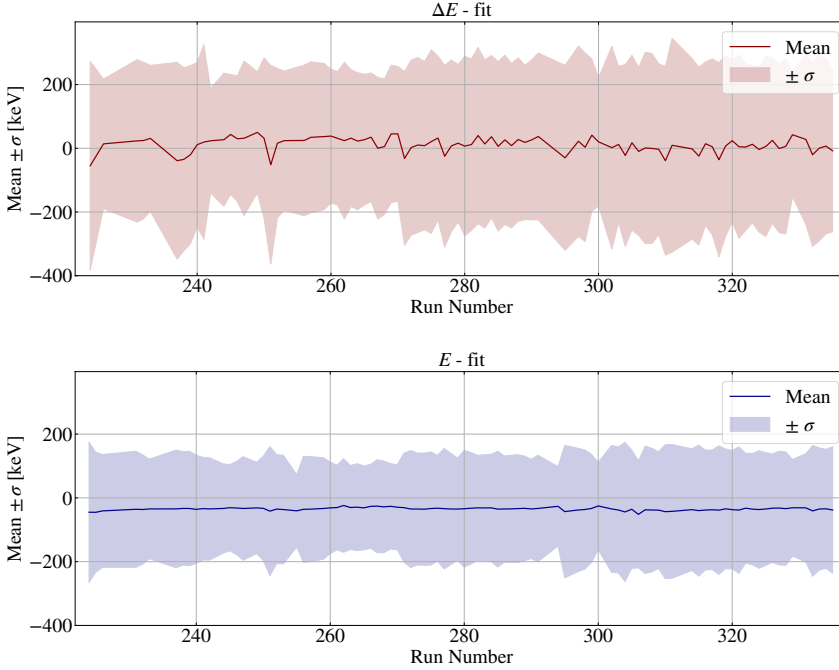


Figure 8.6: Stability of the gain-matching calibration over the course of the IS739 experiment (~ 5 days) for the ΔE (top, red) and E (bottom, blue) detectors of the fission fragment annular telescope. For each run, the mean and standard deviation of the energy difference between the p-side and n-side are shown, extracted from a Gaussian fit to the per-run distribution. The mean remains close to zero, and the spread stays within ± 250 keV throughout the experiment, demonstrating the stability of the relative calibration over time.

the experiment, confirming that the relative calibration between the two sides is stable over time and does not exhibit any significant run-dependent drift.

8.2.3 Calibration cross-check

To conclude this section, a cross-check of the calibration procedure was performed by investigating the effect of using calibration coefficients derived from runs acquired at different times during the experiment. Under realistic experimental conditions, the electronic configuration of the detector system may drift over time or be inadvertently modified between runs. A calibration that is not contemporaneous (or close in time) with the data may therefore fail to correctly

account for such variations, resulting in a degraded alignment between the two detector sides, or in channel-dependent misalignment.

Two scenarios are considered here. In the first scenario, the absolute calibration scale was extracted from the α -source run R349, acquired immediately after the IS739 experiment, and subsequently refined by applying the gain-matching routine to the combined runs R322 and R323, among the last runs of the experiment. The resulting coefficients were then used to sort the same α -source run R349. Figure 8.7 shows the resulting energy spectra for all sectors and rings of the ΔE detector. The well-aligned horizontal bands in the 2D correlation plot and the consistent peak positions across all channels in the waterfall plot confirm that calibration coefficients derived from contemporaneous runs yield a uniform and consistent channel-by-channel alignment across the full detector.

For illustrative purposes, a second scenario is presented to highlight the importance of using contemporaneous calibration runs. In this case, the manual absolute calibration was again performed on the α -source run R349, but the relative gain-matching was performed on run R190, acquired in the middle of the experiment prior to a change in the preamplifier settings of the ΔE detector. As a consequence, the calibration coefficients derived from R190 do not correctly reflect the detector response at the time of R349, and when the α -source run is sorted with these coefficients, the individual channels are not well aligned, as shown in Figure 8.8.

8.3 LUME detectors

Out of the four charge-resistive silicon detectors operating as luminosity monitors, only one survived till the end of the IS739 experiment, namely LUME-#1 (0-based index). This detector is therefore the only one for which calibration data are available, collected during dedicated α -source runs performed after the conclusion of the experiment, using the same source employed for the calibration of the annular fission-fragment silicon telescope. As described in the TextBox on page 69, the detector produces three signals: the *near* and *far* signals, collected from the two opposite ends of the resistive layer, and the *back* signal, collected from the back contact, which provides a direct measurement of the total deposited energy.

The first step of the calibration procedure consists of the energy calibration of the *back* signal. The raw E_{back} spectrum, shown in the upper-left panel of Figure 8.9, displays four well-resolved peaks corresponding to the α -lines of known energy emitted by the source introduced in Table 8.1. Each peak is fitted with a Gaussian function in order to extract the centroid position in ADC channels. The resulting channel-to-energy correspondence is then used to perform a linear fit, shown in the upper-right panel, yielding a calibration

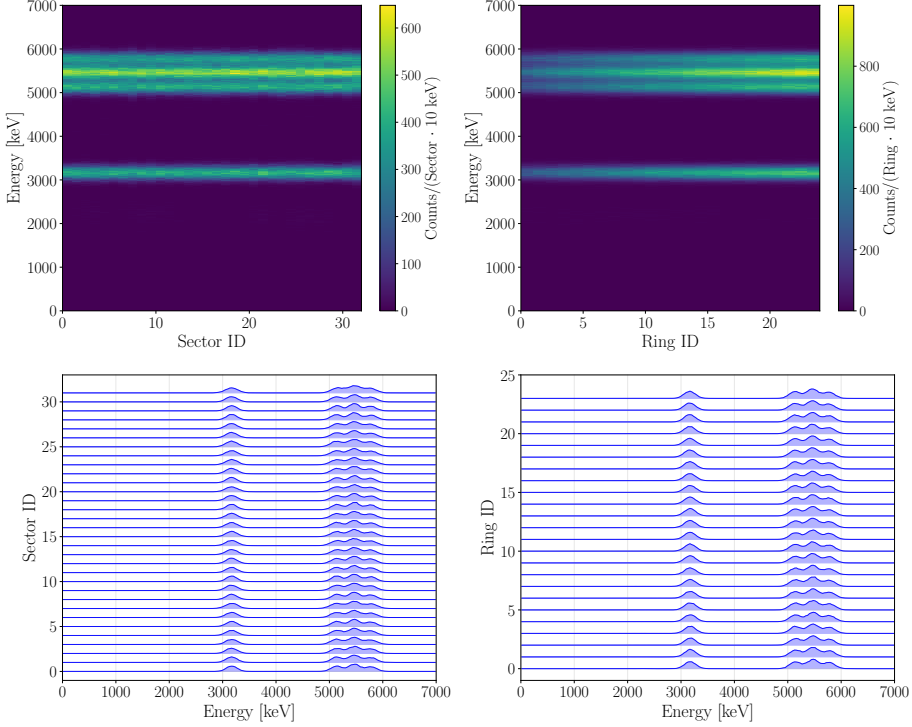


Figure 8.7: *Upper panels:* two-dimensional correlation between energy and strip ID for the p-side (left, sectors) and n-side (right, rings) of the ΔE detector, obtained by sorting the α -source run R349 with calibrated coefficients derived from a manual absolute scale calibration on R349 itself and gain matching on runs R322–R323. The four α -source peaks appear as sharp, uniform horizontal bands across all strips, demonstrating a consistent channel-by-channel alignment. *Lower panels:* Waterfall plot of the α -particle energy spectra for each sector (left) and ring (right) of the ΔE detector, obtained by sorting the α -source run R349 with calibration coefficients derived from the manual calibration on R349 itself and gain matching on runs R322–R323. The four α peaks are well resolved and consistently positioned across all channels.

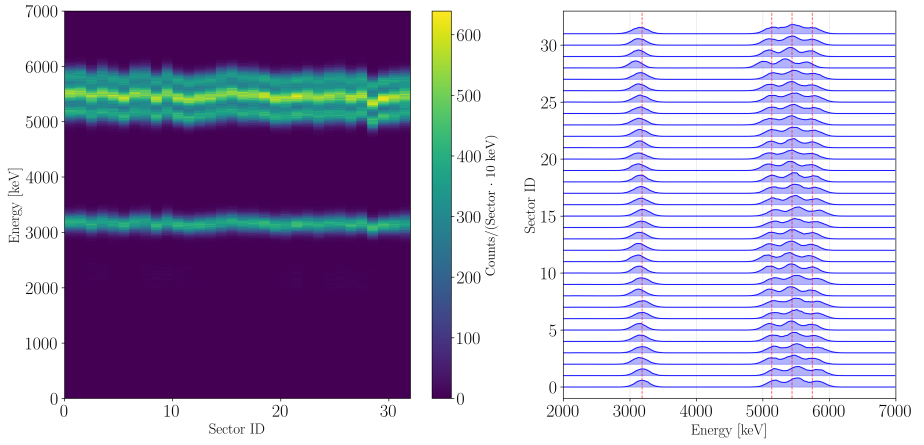


Figure 8.8: Two-dimensional correlation between energy and sector ID (left) and waterfall plot of the α -particle energy spectra per sector (right) of the ΔE detector, obtained by sorting the α -source run R349 with calibration coefficients derived from the manual calibration on R349 and gain matched with run R190. Only the p-side (sectors) is shown; the n-side exhibits analogous behaviour. The broadening of the peaks in the 2D plot and the channel-dependent misalignment visible in the waterfall plot demonstrate the degradation in calibration quality when non-contemporaneous runs are used for the calibration procedure.

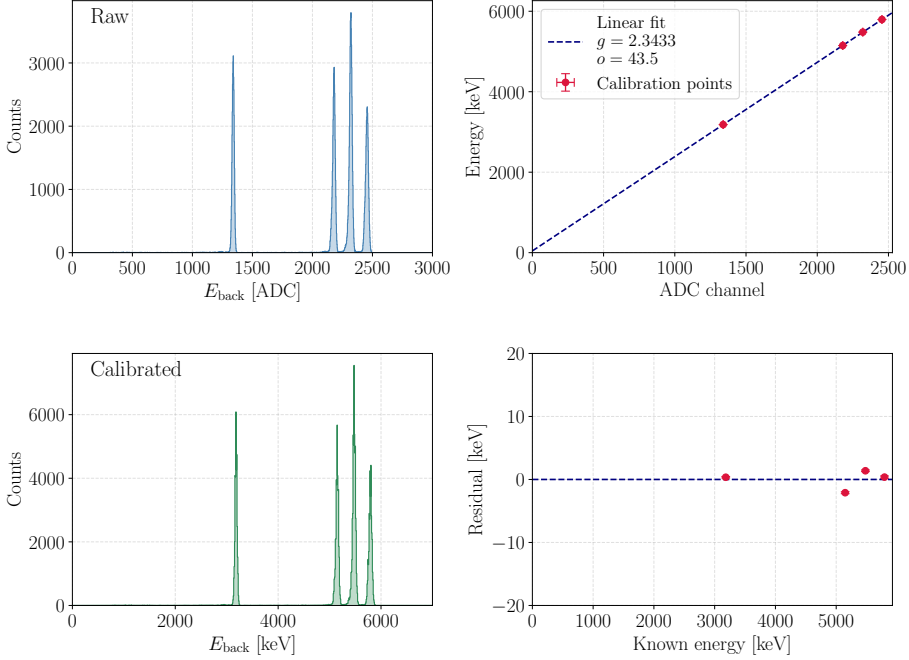


Figure 8.9: Energy calibration of the *back* signal of LUME-#1. *Upper left:* raw E_{back} spectrum showing the four α -lines from the calibration source. *Upper right:* linear fit to the centroid positions extracted from Gaussian fits to each peak, yielding a gain $g = 2.3$ keV/channel and an offset $o = 43.5$ keV. *Lower left:* calibrated E_{back} spectrum, with the peaks now correctly positioned at the known α -source energies. *Lower right:* residuals between the fitted and known α -source energies. The error bars resulting from the fitting procedure of each peak are smaller than the marker size.

function of the form

$$E_{\text{back}} = g \cdot \text{ADC} + o, \quad (8.9)$$

where $g = 2.3$ keV/channel is the gain and $o = 43.5$ keV is the offset. Applying this calibration to the raw spectrum produces the calibrated E_{back} spectrum shown in the lower panel of Figure 8.9, where the peaks are now correctly positioned at the known α -source energies.

Once the *back* signal is calibrated, the individual energy signals from the two resistive ends, *near* and *far*, must be calibrated independently. This is possible for up to three of the four gain and offset parameter combinations using the energy deposits. The fourth parameter combination requires the use of known positions. The energies E_{near} and E_{far} extracted from the two ends of the resistive layer are assumed to be linearly proportional to their respective

ADC amplitudes:

$$E_n = g_n \cdot \text{ADC}_{\text{near}} + o_n, \quad (8.10)$$

$$E_f = g_f \cdot \text{ADC}_{\text{far}} + o_f, \quad (8.11)$$

where g_n , g_f are the gains and o_n , o_f are the offsets of the two channels, respectively. The total deposited energy and the relative hit position η along the resistive layer are defined as

$$E_{\text{tot}} = E_{\text{near}} + E_{\text{far}}, \quad (8.12)$$

$$\eta = \frac{E_{\text{near}} - E_{\text{far}}}{E_{\text{near}} + E_{\text{far}}}, \quad (8.13)$$

with $\eta \in [-1, 1]$.

Since the α source illuminates the entire active area of the detector, each α line appears as a diagonal band in the E_{near} vs E_{far} matrix, as shown in Figure 8.10a. The anti-correlation between the two signals is a direct consequence of charge sharing along the resistive layer. At fixed total energy E , the relation between the two signals reads

$$E_{\text{near, ADC}} = -\frac{g_f}{g_n} \cdot E_{\text{far, ADC}} + \text{const}, \quad (8.14)$$

so each α band appears as a straight line with slope $k_0 = -g_f/g_n$.

To extract the four calibration constants, a graphical cut (TCutG) is applied to each of the four α bands, following the charge-division calibration strategy of Sun et al. [153]. For each band, a profile histogram³ is built along the E_{Far} axis and fitted with a linear function $E_{\text{near, ADC}} = p_0^{(\alpha_i)} + p_1^{(\alpha_i)} \cdot E_{\text{far, ADC}}$, as shown in Figure 8.10a. The gain ratio is then obtained by averaging the slopes over the four lines:

$$R \equiv \frac{g_f}{g_n} = -\langle p_1^{(\alpha_i)} \rangle, \quad (8.15)$$

The gain g_n is determined from the intercepts $p_0^{(\alpha_i)}$ of the four fits, which at fixed η scale linearly with the true α energy E_i . Specifically, taking the two extreme α lines,

$$g_n = \frac{E_{\alpha_4} - E_{\alpha_1}}{p_0^{(\alpha_4)} - p_0^{(\alpha_1)}}, \quad (8.16)$$

and the gain of the *far* channel follows from the ratio:

$$g_f = R \cdot g_n. \quad (8.17)$$

³A profile histogram slices the data along one axis and, for each slice, computes the mean of the distribution along the other axis (with its standard deviation). Slicing along the abscissa profiles y versus x ; the transpose is equally valid.

The common offset $o_n + o_f$ is obtained by requiring that the calibrated total energy matches the known α energies on average over all four lines, and is, for convenience, equally split between the two channels:

$$o_n = o_f = \frac{1}{2} \cdot \frac{1}{4} \sum_{i=1}^4 \left(E_{\alpha_i} - g_n \cdot p_0^{(\alpha_i)} \right). \quad (8.18)$$

Determining the actual split between o_n and o_f (or the difference) requires using known positions (η) along the detector. The resulting calibration constants are applied event-by-event, producing the calibrated E_{near} vs E_{far} matrix shown in Figure 8.10b, where the diagonal bands are now correctly positioned at the known α -source energies. As a consistency check of the calibration procedure, Figure 8.11 shows the correlation between E_{back} and $E_{\text{near}} + E_{\text{far}}$ after applying the calibration to all three channels. The two independent energy measurements are in excellent agreement, lying along the diagonal $E_{\text{back}} = E_{\text{near}} + E_{\text{far}}$, which confirms the self-consistency of the calibration and validates the assumption that the total charge collected by the resistive layer is equal to that collected by the back contact. The four hot spots along the diagonal correspond to the α lines of the calibration source.

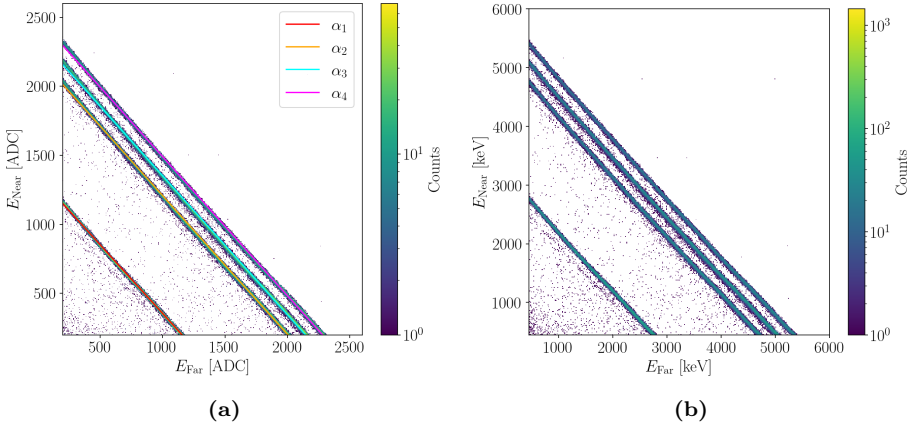


Figure 8.10: E_{Near} vs E_{Far} correlation matrix for LUME-#1. Panel (a) shows the raw ADC signals, where the four α lines from the calibration source appear as anti-diagonal bands. The overlaid lines show the linear fits to the profile histograms of each band, used to extract the gain ratio $R = g_f/g_n$ and the individual calibration constants g_n , g_f , o_n and o_f as described in the text. Panel (b) shows the same matrix after applying the energy calibration, with the α bands now correctly positioned at the known source energies.

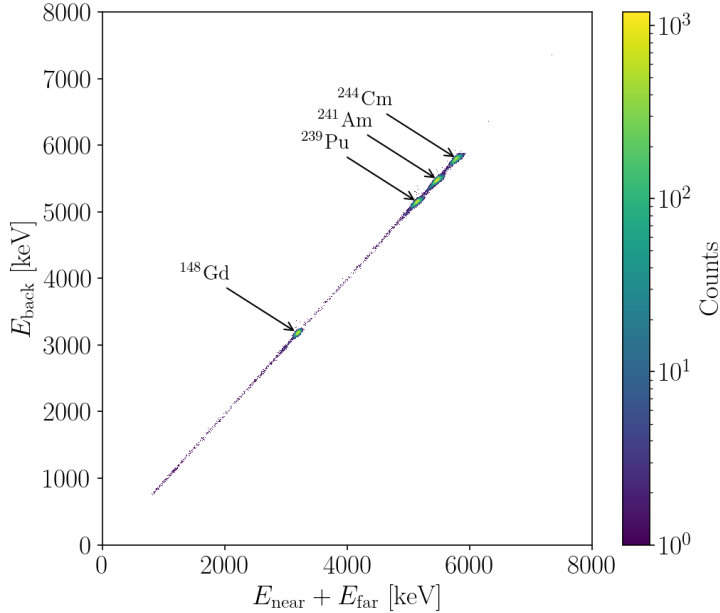


Figure 8.11: Correlation between E_{back} and $E_{\text{near}} + E_{\text{far}}$ after calibration of all three channels of LUME-#1. The four α lines from the calibration source cluster along the diagonal, confirming the consistency between the two independent energy measurements.

8.3.1 Position dependence

The energy calibration of the *back* signal alone is, however, not sufficient to achieve a flat position-independent energy response. While E_{back} and $E_{\text{far}} + E_{\text{near}}$ agree eventwise, there might exist a position dependence in the measured energy deposit. As shown in Figure 8.12, the calibrated E_{back} signal exhibits a residual dependence on the relative hit position η : events occurring near the centre of the detector ($|\eta| \approx 0$) appear at systematically lower energies than those hitting closer to the ends ($|\eta| \approx 1$). This well-known phenomenon, referred to in the literature as the *ballistic deficit* [153, 154], arises from two concurring mechanisms. The first is the finite shaping time of the charge-sensitive preamplifier combined with the position-dependent rise time of the collected charge pulse: events deposited at the centre of the resistive layer take longer to drift to the collection electrode, resulting in incomplete charge integration by the shaping amplifier and a consequent systematic underestimation of the deposited energy. The second contribution comes from the attenuation of the signal pulse during its propagation along the dispersive electrode, which introduces an additional

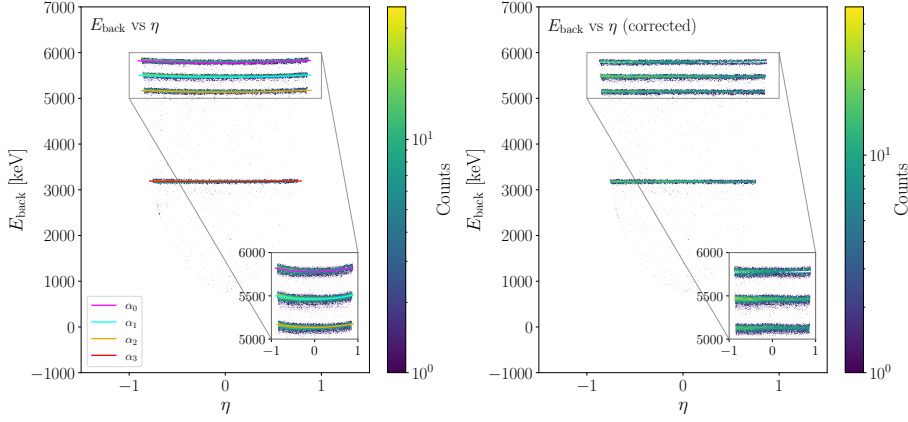


Figure 8.12: Calibrated E_{back} as a function of the relative hit position η for LUME-#1, before (left) and after (right) the ballistic deficit correction. The four α lines from the calibration source are visible as horizontal bands; the effect and its correction are best seen in the insets, which magnify the three highest-energy lines. *Left panel:* the residual curvature reflects the ballistic deficit, i.e. events deposited near the centre of the resistive layer ($\eta \approx 0$) suffer from incomplete charge integration, resulting in a systematic underestimation of the deposited energy; the overlaid lines show the second-order polynomial fits used to correct for this effect. *Right panel:* after applying the position-dependent correction, the four α lines appear as flat horizontal bands, demonstrating that the position dependence of the energy response has been successfully removed.

position-dependent loss. These two effects are largest at $\eta \approx 0$ and vanish towards the strip ends, where the drift path is shortest, producing the characteristic curvature visible in Figure 8.12.

In order to correct for this position-dependent bias, four graphical cuts are applied to isolate each of the four α lines in the E_{back} vs η matrix. For each selected band, a profile histogram is built along the η axis and fitted with a second-order polynomial $f_i(\eta) = A_i + B_i\eta + C_i\eta^2$, whose result is overlaid in the left panel of Figure 8.12. These four parabolas, anchored at the known α energies at $\eta = 0$, are then used to interpolate a position-dependent correction factor for every event, which is applied to flatten the E_{back} response across the full active area of the detector. The result of the ballistic deficit correction is shown in the right panel of Figure 8.12. After applying the position-dependent correction factor interpolated from the four parabolic fits, the E_{back} signal is now uniform across the full range of η : the four α lines appear as flat horizontal bands, with no residual dependence on the hit position.

The four parabolic fits yield one set of coefficients (A_i, B_i, C_i) per α line, i.e. one correction curve per energy. To extend the correction to arbitrary energies

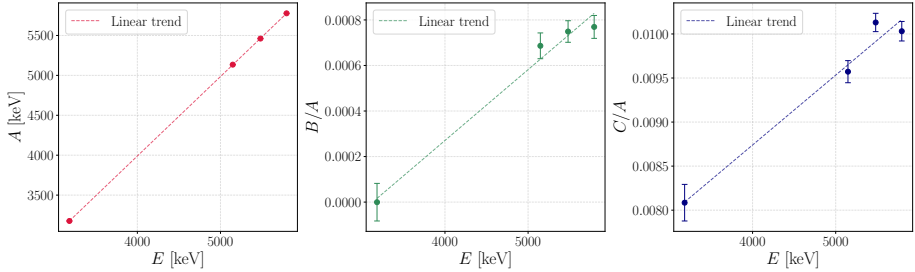


Figure 8.13: Energy dependence of the parabola coefficients obtained from the second-order polynomial fits $f_i(\eta) = 1 + \frac{B_i}{A_i}\eta + \frac{C_i}{A_i}\eta^2$ of Figure 8.12. *Left:* the overall scale A ; *centre and right:* the normalised linear and quadratic coefficients B/A and C/A . Each quantity is plotted against the corresponding α energy E , with the error bars from the fit; the dashed lines show the linear trends used to interpolate the coefficients at arbitrary energy. The clear linear behaviour of all three parameters justifies parametrising the position-dependent correction as a continuous function of energy, $E_{\text{back}}(\eta, E)$. The ratios $\frac{B}{A}$ are $\ll \frac{C}{A}$, as expected for a symmetric parabola on the interval $\eta \in [-1, 1]$.

rather than only the four calibration lines, the energy dependence of the fit parameters is considered. It is convenient to work with the normalised shape coefficients B_i/A_i and C_i/A_i , which describe the curvature independently of the overall scale A_i . As shown in Figure 8.13, the amplitude A and both normalised coefficients B/A and C/A vary linearly with E over the calibration range, so each is fitted with a first-order polynomial: $A(E)$, $(B/A)(E)$ and $(C/A)(E)$. Substituting these into

$$f(\eta, E) = A(E) \left[1 + \frac{B}{A}(E) \eta + \frac{C}{A}(E) \eta^2 \right] \quad (8.19)$$

promotes the four discrete parabolas to a continuous, energy-dependent correction surface $E_{\text{back}}(\eta, E)$, allowing the ballistic deficit correction to be applied consistently to every event regardless of its reconstructed energy.

With this energy-dependent correction applied event by event, the flattened E_{back} distribution is projected onto the energy axis and, for each α line, the resulting peak is fitted with a Crystal Ball function [155]. This choice is motivated by the intrinsic low-energy tail of the α peaks: energy deposited in non-ionizing processes in the silicon (nuclear recoils and the associated pulse-height defect), together with residual energy loss in the source and dead layers, produces a systematic asymmetry towards lower energies that a symmetric Gaussian cannot reproduce [156]. The Crystal Ball function, a Gaussian core with a power-law low-energy tail, captures this asymmetry, as illustrated in Figure 8.14, where it is compared to a plain Gaussian fit for the four calibration lines. The FWHM

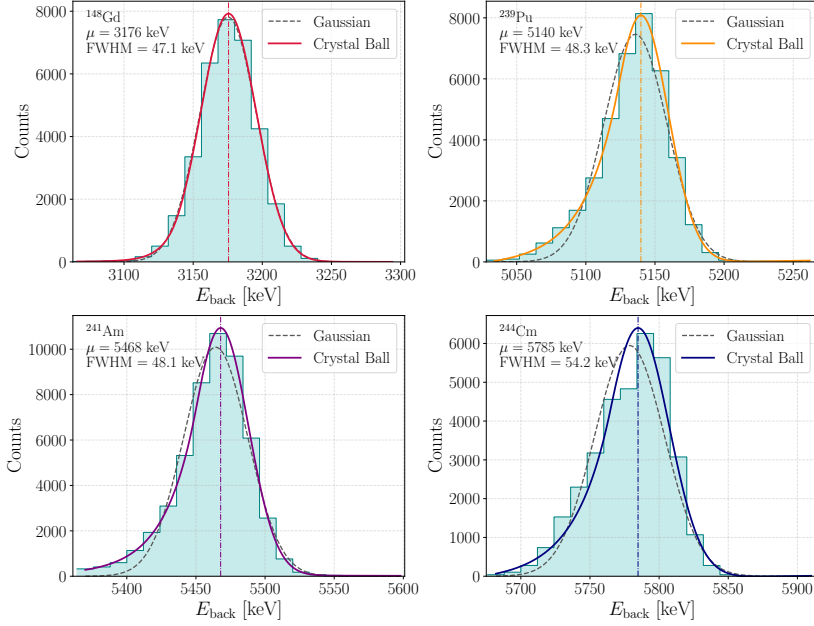


Figure 8.14: Projected E_{back} spectra for the four calibration α lines (^{148}Gd , ^{239}Pu , ^{241}Am , ^{244}Cm), fitted with a Crystal Ball function (solid) and, for comparison, with a Gaussian (dashed). The low-energy tails of the α peaks are well reproduced by the Crystal Ball function, whereas the Gaussian fails to describe the asymmetry. The extracted centroid μ and FWHM are reported in each panel.

extracted from the Crystal Ball fit is then taken as a measure of the energy resolution of the detector. To quantify the improvement brought by the correction, the same Crystal Ball fit is also applied to the uncorrected (raw) spectrum, and the two sets of resolutions are compared in Figure 8.15 and Table 8.2. The correction improves the resolution of the three high-energy lines from about 58 to 48 keV, while the lowest-energy ^{148}Gd line, which is only weakly affected by the η dependence, remains essentially unchanged. Since the correction only redistributes events in energy while conserving their total number, the sharpened peaks are correspondingly taller, as shown in the inset of Figure 8.15.

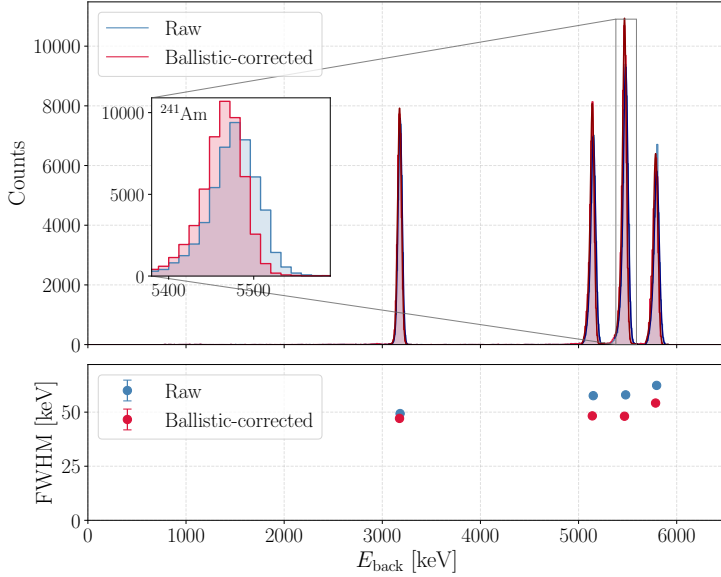


Figure 8.15: Effect of the ballistic-deficit (η -dependence) correction on the back-signal energy resolution of LUME-#1. *Top panel:* projected E_{back} spectrum before (raw, blue) and after (red) the correction, with an inset zooming on the ^{241}Am peak, where the narrowing is directly visible. *Bottom panel:* FWHM of each α line as a function of energy, from the Crystal Ball fits, for the raw (blue) and corrected (red) spectra.

Line	E_{α} [keV]	FWHM_{raw} [keV]	$\text{FWHM}_{\text{corr}}$ [keV]
^{148}Gd	3182.7	49.3 ± 0.2	47.1 ± 0.2
^{239}Pu	5147.6	57.6 ± 0.4	48.3 ± 0.4
^{241}Am	5480.9	58.0 ± 0.4	48.1 ± 0.3
^{244}Cm	5794.9	62.4 ± 0.5	54.2 ± 0.4

Table 8.2: FWHM of the four α calibration lines, from Crystal Ball fits to the back-signal spectrum, before (raw) and after the ballistic-deficit correction.

8.4 Calibration of the upstream Si array

Similarly to the annular DSSSDs, the Liverpool Si proton recoil array was energy calibrated using the source combination listed in Table 8.1. At ISS, the array calibration proceeds via an *autocalibration* routine implemented in the `ISSSort` code. In this routine, the four α peaks are first identified in the raw ADC spectra and associated with their known energies. Based on the centroid of these peaks in ADC units, a linear calibration function (gain and offset) is determined. Each p-side and n-side strip of the array is calibrated individually to account for channel-to-channel variations in response, also taking dead layer and angle-of-incidence into account. In the case of failure in fitting some channels, a manual calibration is performed.

For the IS739 experiment, this calibration was carried out by A. Kawęcka, a fellow PhD student in the group. A detailed description of the procedure can be found in Ref. [102]. The energy resolution achieved by this procedure is quantified by the FWHM of the fitted α peaks for every calibrated channel; the channel-by-channel distributions for the three modules are reported in Figures 3.47–3.49 of Ref. [102]. The p-side strips reach a typical resolution of ~ 100 keV FWHM, degrading to ~ 200 keV for the channels read out by the ASIC located farthest from the calibration source, where the α particles impinge at the most grazing angles and therefore suffer the largest energy loss and straggling in the entrance dead layer. The n-side strips are appreciably worse, with a broad distribution centred around ~ 150 keV FWHM and a tail extending beyond 400 keV. For this reason, the event-wise energies are reconstructed from the p-side readout only, while the n-side is used solely for the azimuthal position and for the p–n coincidence condition.

The time walk correction procedure described in the remainder of this section was developed and implemented by E. A. M. Jensen, a postdoctoral researcher within the group. The method and results are presented here for completeness, as they constitute an integral part of the data analysis chain.

8.4.1 Time-walk correction

Time walk is an effect in which the leading-edge threshold-crossing time used to define a detector hit deviates from the physical hit time by an amplitude-dependent amount. The effect is particularly pronounced when using shaped signals, which typically have a slower rise time compared to the fast-rising unshaped output of a preamplifier. With shaped signals, the time at which the threshold is crossed depends on the signal amplitude: lower-amplitude signals reach the threshold later than higher-amplitude ones, causing the recorded timestamp to shift. As a result, time walk increases as the signal amplitude decreases. Figure 8.16 illustrates this behaviour for a set of signals with identical shape but different amplitudes crossing the same trigger threshold.

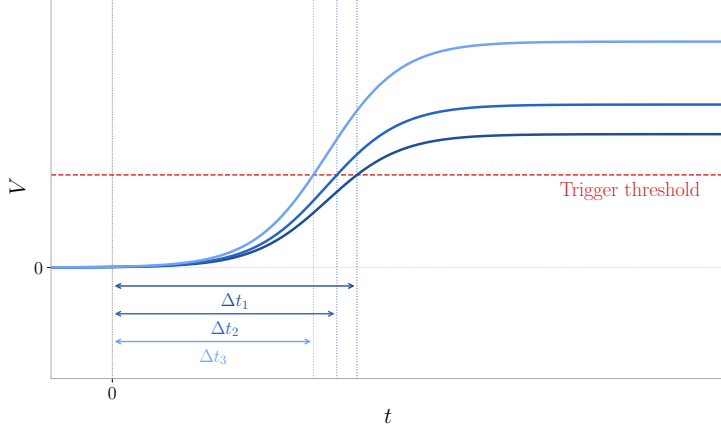


Figure 8.16: Illustration of the time walk effect for three signals of identical shape and rise time but different amplitudes. The time at which each signal crosses the trigger threshold (measured from the signal origin at $t = 0$) depends on the amplitude V : lower-amplitude signals cross the threshold later, resulting in larger values of Δt .

Since time walk depends on signal amplitude, and therefore on the energy deposited in the detector, it can be corrected empirically by studying the timing difference between strips of the upstream Si array and a reference detector as a function of energy deposited in the Si array. The CeBr₃ detectors are used as the timing reference for this purpose. Their use is motivated by two factors: first, they provide high statistics due to the large number of detected γ -ray coincidences; second, the time walk of the CeBr₃ detectors is negligible compared to that of the Si array, so their contribution to the variation of the measured timing difference can be disregarded.

For each event in the data, reconstructed after the event-building and re-sorting stages, the quantity $t_p - t_\gamma$ is computed, where t_p is the timestamp of a p-side hit on the upstream Si array and t_γ is the timestamp of a coincident signal in one of the CeBr₃ crystals. This time difference is then plotted as a function of the energy deposited on the p-side of the Si array. The resulting distribution, shown in the upper panel of Figure 8.17, displays the characteristic time walk curve: at low energies the time difference changes more and is positive ($\sim 2 \mu\text{s}$), decreasing monotonically as the energy increases and asymptotically approaching a constant offset at high energies ($\sim -500 \text{ ns}$). To better visualise and parametrise the time walk curve, the energy axis is plotted on a logarithmic scale in the lower panel of Figure 8.17. This transformation is motivated by the approximately exponential dependence of the time walk on energy at the lowest amplitudes: taking the logarithm linearises this behaviour

considerably, preventing the curve from diverging sharply at low energies and making it easier to define a stable graphical selection. A graphical cut is drawn around the time walk region, as shown by the red contour in the lower panel, in order to isolate events associated with the time walk curve from the random coincidence background.

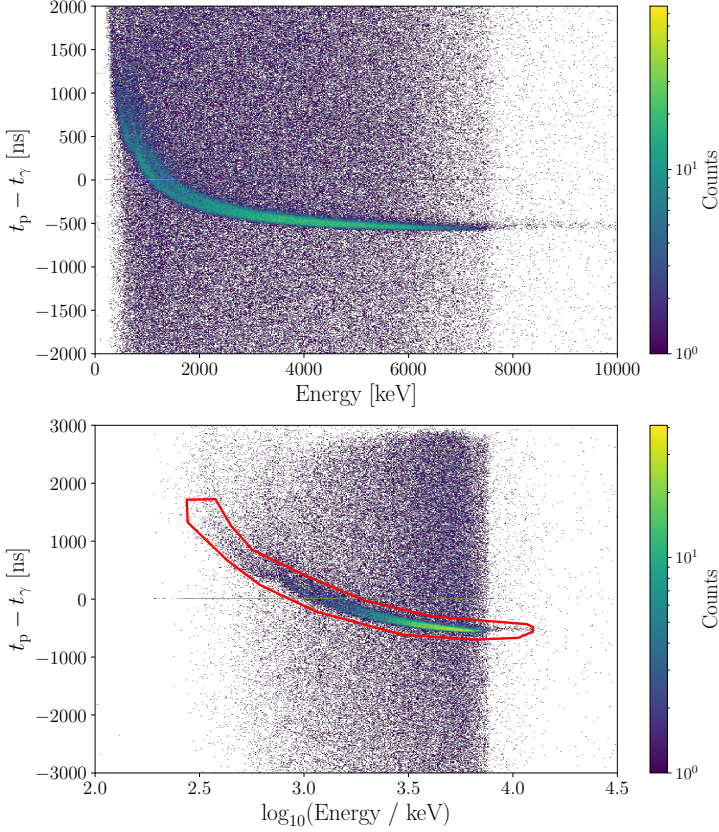


Figure 8.17: *Upper panel:* The time difference $t_p - t_\gamma$ between p-side hits on the upstream Si array and coincident signals in the CeBr₃ detectors, plotted as a function of the energy deposited on the p-side, with no time walk correction applied. The data include all p-side ASICs of the array. The time walk curve is clearly visible as the high-statistics locus curving from large positive values of $t_p - t_\gamma$ at low energies towards a constant offset at high energies. *Lower panel:* The same data plotted against $\log_{10}(\text{Energy}/\text{keV})$, which to a large extent linearises the exponential behaviour of the time walk at low energies. The red contour defines the graphical selection used to isolate the time walk locus for the subsequent per-module correction.

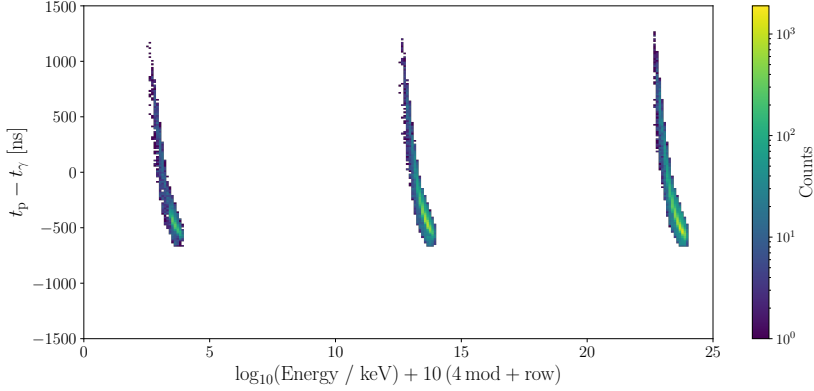


Figure 8.18: Time difference $t_p - t_\gamma$ as a function of $\log_{10}(\text{Energy}/\text{keV})$ for three p-side ASICs of Module 0 (ASICs 1, 2, and 3), shown after applying the graphical selection. The curves are artificially offset along the horizontal axis in units of 10 to allow all three ASICs to be displayed in a single plot. The time walk locus is clearly resolved for each ASIC individually.

Since the time walk characteristics can vary from module to module due to differences in threshold settings and shaping parameters, the correction is applied independently for each p-side ASIC of the array. Figure 8.18 shows, as an example, the timing difference $t_p - t_\gamma$ as a function of $\log_{10}(\text{Energy}/\text{keV})$ for ASICs 1, 2, and 3 of Module 0, after applying the graphical cut described above.

For each ASIC, the time walk curve is extracted by computing the profile of the $t_p - t_\gamma$ distribution along the energy axis within the graphical cut. The resulting data points are then interpolated to obtain a smooth correction function, as shown in Figure 8.19 for ASIC 3 of Module 0. The interpolated curve is subsequently used to correct the timestamp of every hit recorded by that ASIC, shifting t_p by the value of the correction function evaluated at the corresponding hit energy. The result of applying the time walk correction to all p-side ASICs is shown in Figure 8.20. After correction, the timing difference $t_p - t_\gamma$ is flat across the full energy range, demonstrating that the amplitude-dependent timing shift has been successfully removed. An analogous procedure was applied to correct the time walk of the n-side ASICs of the array. The residual width of the $t_p - t_\gamma$ distribution after correction provides a measure of the achieved time resolution: a Gaussian fit to the time projection gives a FWHM of 25.1 ± 0.2 ns in the 5–6 MeV range, degrading to ≈ 270 ns below 1 MeV, where the reduced signal-to-noise ratio dominates the timing performance.

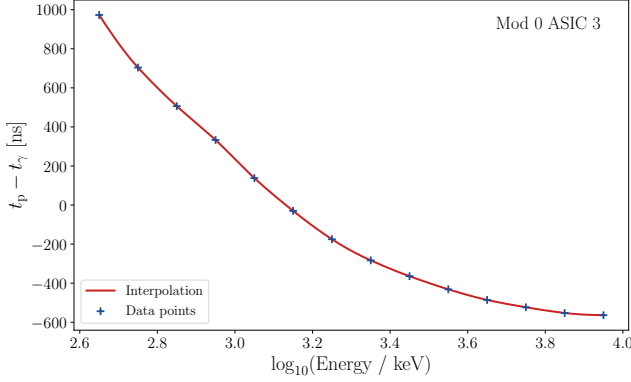


Figure 8.19: Time walk correction curve for ASIC 3 of Module 0. The data points (blue crosses) are obtained from the profile of the $t_p - t_\gamma$ distribution within the graphical cut, and the red curve shows the interpolation used to correct the timestamps. The curve spans the full energy range covered by the graphical selection.

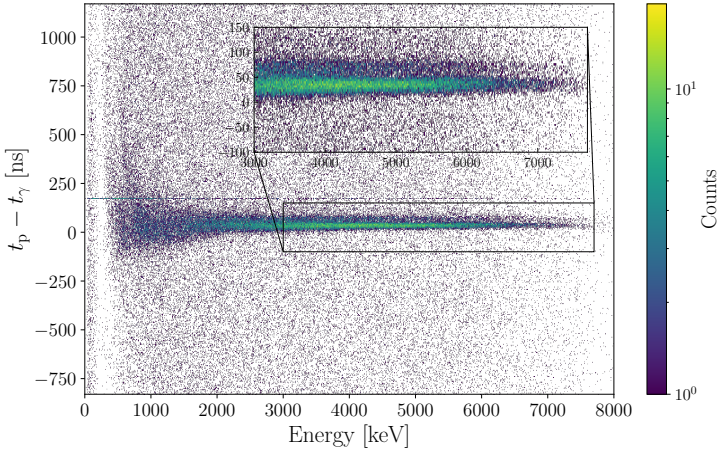


Figure 8.20: Time difference $t_p - t_\gamma$ as a function of energy after applying the time walk correction to all p-side ASICs of the upstream Si array. The distribution is now flat across the full energy range, confirming that the time walk effect has been successfully corrected. The inset shows a zoom on the region $3000 < E < 7700$ keV, $-100 < t_p - t_\gamma < 150$ ns, where a second, fainter band is visible about 35 ns above the main one, most likely due to α particles (see SubSection 3.3.1 and Figure 3.6; double-turn protons were physically removed during the experiment by the passive support of the array).

Chapter 9

IS739 Data analysis

FOLLOWING the successful commissioning of the experimental setup, data were collected during the IS739 experiment beamtime from July 10th to 20th, 2025. Before describing the analysis procedure in detail, a summary of the raw spectra recorded by the various detector systems is presented, in order to provide a general picture of the data quality and the main features observed during the data-taking.

9.1 Data overview

A first overview of the collected data can be obtained by examining the correlation between the energy deposited by particles detected in the upstream silicon array and their hit position z along the spectrometer axis, relative to the target position, shown in Figure 9.1. No software thresholds are applied. A number of noisy or non-functioning strips are visible as vertical features, while an accumulation of counts at low energy reflects the detector noise pedestals. When comparing the CD₂ and C target datasets, a clear kinematic signature is visible in the CD₂ data, manifesting as characteristic sloped band structures in the E - z plane. No such structures are observed in the C target dataset, confirming that these structures originate from reactions with deuterons, ruling out carbon-induced background reactions.

As discussed in Section 2.4.1, the energy and hit position of the detected proton, combined with the known beam energy and reaction kinematics, allows for the reconstruction of the excitation energy of the recoiling compound nucleus on an event-by-event basis. Figure 9.2 presents the resulting excitation energy spectra for module 0 of the Si array, for the CD₂ target (top panel) and the C target (bottom panel). The CD₂ spectrum exhibits a peak near $E_x \approx 0$ keV, corresponding to the ground state of ²³³U populated via the ²³²U(d, p) reaction, followed by additional structures around 1500–2000 keV and

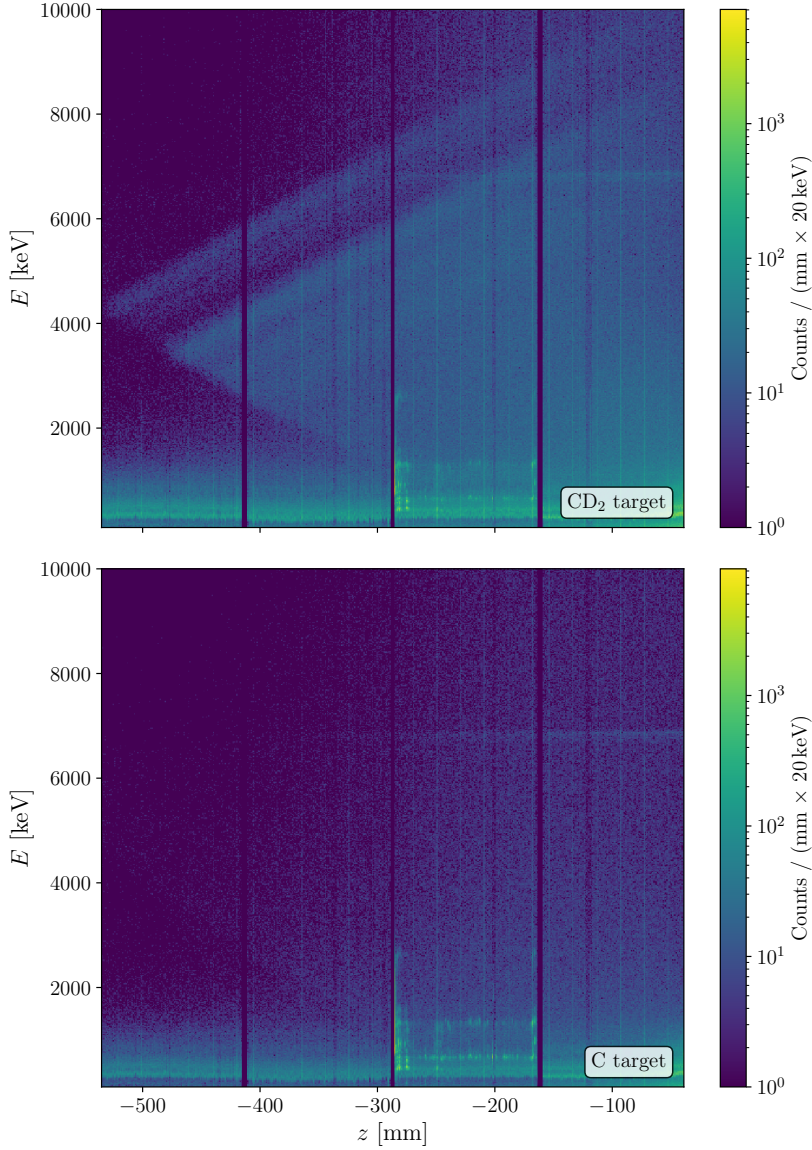


Figure 9.1: Energy deposited in the upstream silicon array versus hit position z along the spectrometer axis, for the CD₂ target (top) and the C target (bottom). No software thresholds are applied. Noisy and non-functioning strips appear as vertical features. The curved kinematic structures visible in the CD₂ dataset are consistent with (d, p) reactions populating single-particle excited states in the recoiling compound nucleus, and are absent in the C target data.

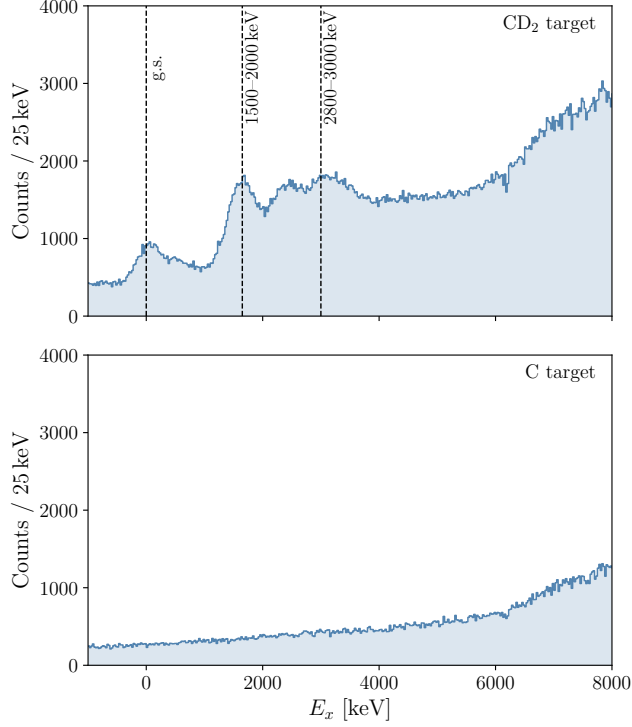


Figure 9.2: Excitation energy spectra of ^{233}U reconstructed via the missing mass method, for module 0 of the Si array, for the CD_2 target (top) and the C target (bottom), integrated over the full experiment. The ground-state peak and excited-state structures visible in the CD_2 data are absent in the C target dataset.

2800–3500 keV, associated with the population of excited states. In contrast, the C target spectrum shows no similar structures, only a smooth, monotonically increasing spectrum.

9.1.1 Luminosity monitor

The luminosity monitor detector exhibits clear kinematic structures, consistent with what was already observed during the stable beam commissioning experiment discussed in Chapter 6. These features are already distinguishable after only ~ 2 hours of data taking, demonstrating the sensitivity of the detector. In the CD_2 target dataset, kinematic lines corresponding to elastically scattered deuterons, identified by their punch-through signature, and protons are clearly visible, together with a higher-energy line consistent with elastically scattered

^{12}C from the target (Figure 9.3, top). In the C target dataset, the deuteron line is absent as expected, while an additional kinematic line appearing above the carbon line is attributed to elastically scattered ^{16}O , likely originating from water contamination in the C target (Figure 9.3, bottom). Both lines are resolved owing to the strong Coulomb repulsion of the heavy ions, which scatter ^{12}C target nuclei and ^{16}O contaminants alike into the angular range covered by the luminosity monitor, in contrast to the lighter ^{22}Ne beam used during commissioning, where these two kinematic lines are not visible in Figures 6.9 and 6.10.

9.1.2 Fission fragment telescope

When it comes to the $\Delta E - E$ silicon telescope, the upper panel of Figure 9.4 shows the correlation between the energy loss ΔE in the thin detector and the total energy E , for the CD_2 target. The energy resolution of the telescope separates distinct bands, associated with different nuclear charges Z . This broad, banded distribution at high energies ($\Delta E \sim 400 - 900$ MeV) is attributed to fission fragments. In addition, a thin and distinct kinematic line is visible at lower energies ($\Delta E \sim 50$ MeV), consistent with elastically scattered ^{12}C from the target, as already observed in the LUME1 spectra; the inset, obtained by zooming into the low-energy region, more clearly reveals this sharp line.

The bottom panel shows the correlation between the energy losses measured in two segments of the ΔE detector in coincidence, ΔE_1 and ΔE_2 , corresponding to two complementary fragments emitted in the same fission event. The main antidiagonal (indicated by a dashed line) reflects the approximately constant maximum total kinetic energy (TKE) for a given fissioning nucleus shared between the two fragments. Figure 9.5 shows the same correlations but for the C target. No obvious differences are observed between the CD_2 and C target datasets.

Diamond structures

The origin of the diamond-shaped structures within the $\Delta E_1 - \Delta E_2$ correlation can be understood by separating two effects. Both ΔE_1 and ΔE_2 are energy losses of the two complementary fragments recorded in the same segmented ΔE detector. In a binary fission event, the two fragments are emitted back-to-back in the center-of-mass frame. In case of asymmetric fission, by momentum conservation, the lighter fragment carries the larger velocity, so heavier and lighter partners are emitted with correlated but distinct opening angles in the laboratory, as shown in Figure 7.8 of Chapter 7. Since the energy loss scales as Z^2/v^2 , the heavier, higher- Z fragment deposits more energy than its lighter partner in the thin detector: ΔE_1 and ΔE_2 are therefore anti-correlated, forming the main antidiagonal, which is itself a signature that the detected particles are

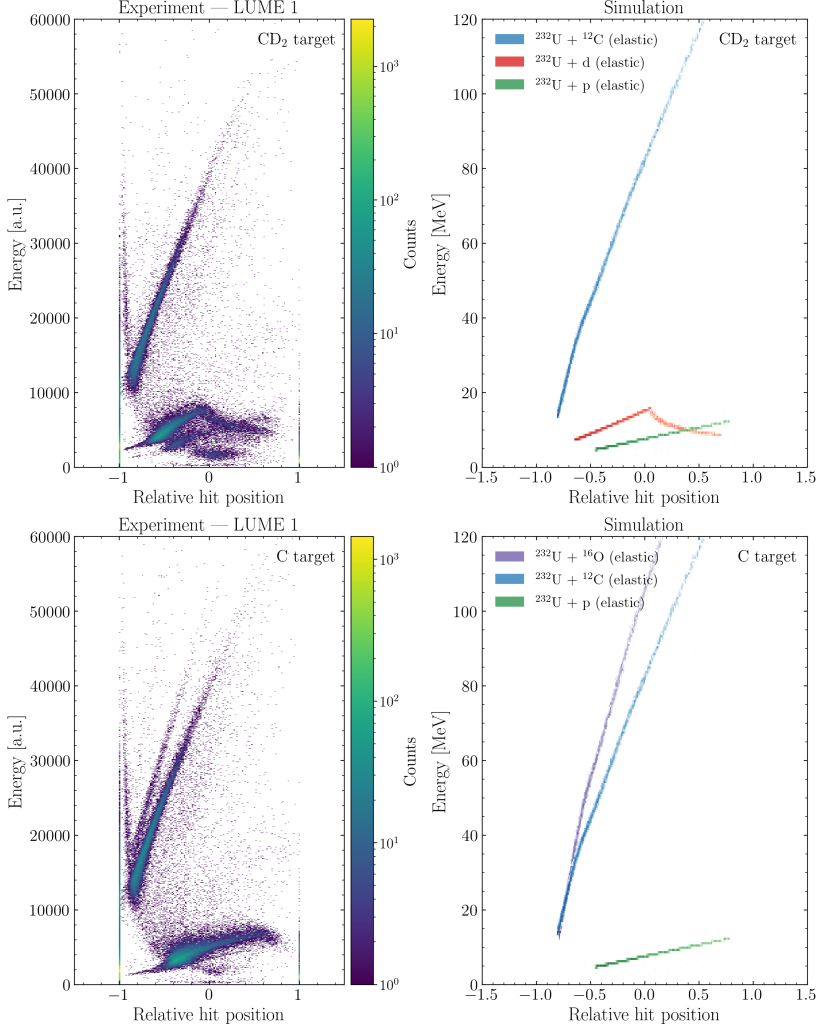


Figure 9.3: Energy (in arbitrary units) versus hit position measured by the luminosity monitor detector (here LUME1), for the CD_2 target (top) and the C target (bottom), after approximately 2 hours of data taking. In each row, the left panel shows the experimental data and the right panel the simulated kinematics for elastic scattering of the ^{232}U beam off the target constituents, with detection of the latter. For the CD_2 target, kinematic lines corresponding to elastically scattered deuterons (identified by their punch-through signature), protons, and ^{12}C are visible; for the C target, the deuteron line is absent as expected, while an additional line above the carbon locus is attributed to elastically scattered ^{16}O from water contamination.

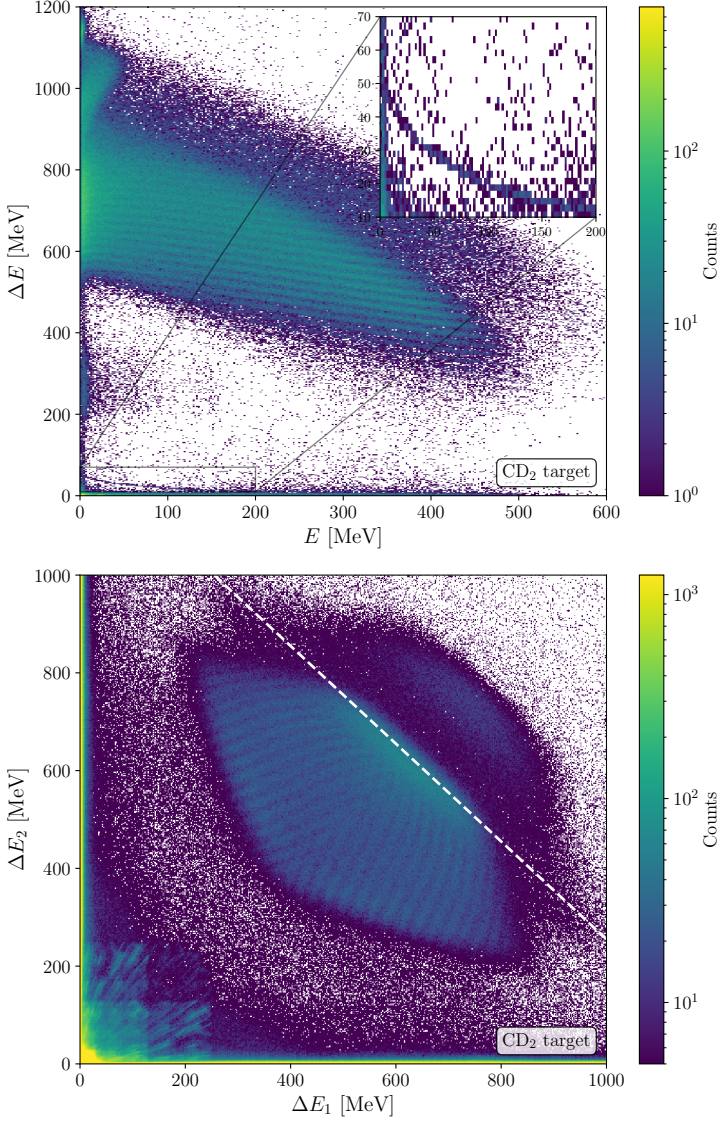


Figure 9.4: $\Delta E - E$ (top) and $\Delta E_1 - \Delta E_2$ (bottom) correlations measured for the CD_2 targets over the full experiment. In the top panel, the banded structure corresponds to fission fragments of different charge Z , while the inset reveals a thin kinematic line due to elastically scattered ^{12}C . In the bottom panel, the diamond-shaped locus reflects the fission kinematics, with the internal ridges corresponding to complementary fragment charge pairs, their extent determined by the fission kinematics. The white dashed line marks the main antidiagonal, the signature of two complementary fragments from a single fission event.

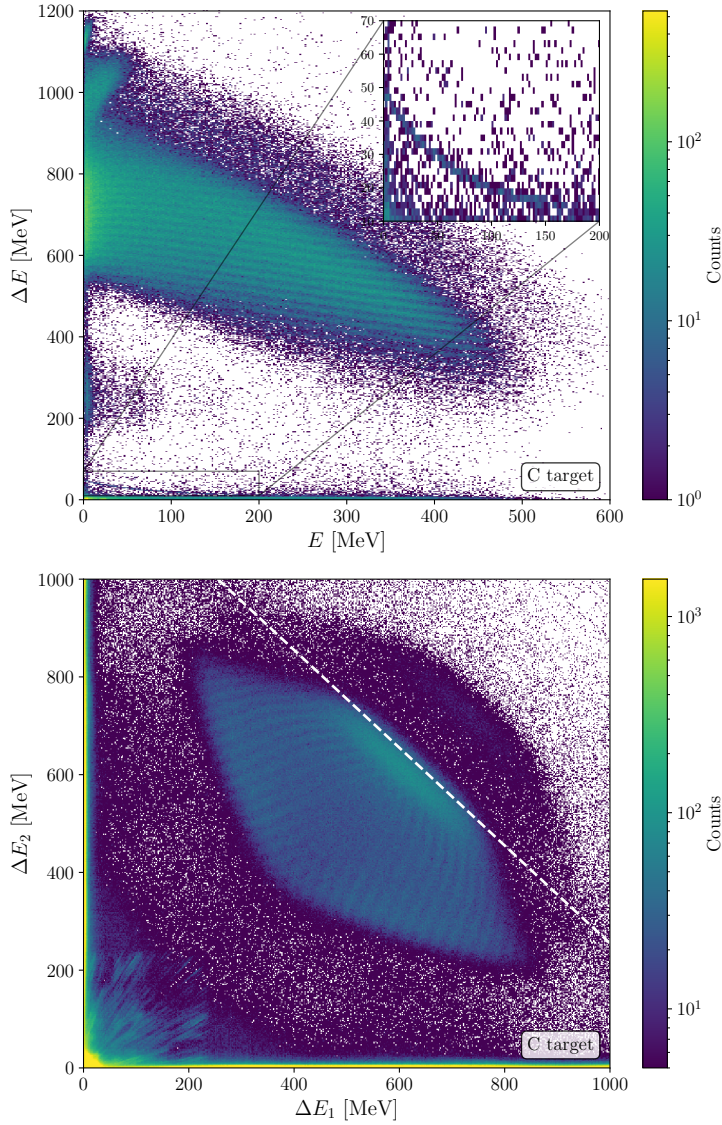


Figure 9.5: Same as Figure 9.4, but for the data collected with carbon targets. No significant differences are observed with respect to the CD_2 case.

the two fragments of a single fission event. The discrete ridges superimposed on this antidiagonal arise from the quantised nuclear charge: since $Z_1 + Z_2$ is approximately fixed by the fissioning system, each ridge corresponds to a specific complementary charge pair (Z_1, Z_2) , while its extent reflects the spread in fragment energy along that pair.

The overall “diamond” envelope is given by the fragment velocity distribution and the geometric acceptance.

This velocity distribution can be understood by considering the two relevant reference frames. In the center-of-mass frame of the fissioning system, the two fragments are emitted back-to-back with a distribution that is, to first approximation, isotropic (the validity of this assumption is discussed in Section 9.2). In the laboratory frame, the kinematic boost along the beam direction turns this sphere into an elongated, ellipsoidal distribution centered around the velocity vector, so that a given emission angle in the center-of-mass frame maps onto a specific velocity, and hence energy, in the laboratory. This is illustrated in Figure 9.6. The angular dependence therefore determines the energies along each charge ridge and, together with the geometric acceptance, shapes the overall diamond envelope. The annular geometry of the silicon telescope, with its central hole for the passage of the unreacted beam, further shapes the observed distribution. The angular acceptance of the ΔE detector is limited both by the central aperture and by its finite outer radius. Fragments emitted close to the beam axis are not detected, which is also the case for fragments missing the outer radius of the detector. The loss due to the inner aperture becomes more severe as the fragment velocity increases relative to the kinematic boost of the fissioning system, since a wider range of center-of-mass emission angles is then mapped onto laboratory angles falling outside the acceptance. The lightest fragments, having the highest velocities, are the most affected, which accounts for the cut-off in the region of largest charge asymmetry between the two fragments. A magnified view of the central region of the ΔE_1 – ΔE_2 correlation, with the antidiagonal and the cut-off region annotated, is shown in Figure 9.7.

9.1.3 Second beam component

A further feature to be noted in the $\Delta E_1 - \Delta E_2$ correlation, seen in Figures 9.4, 9.5 and 9.7, is the second diamond structure. This correlates with the 1.4 GeV proton pulses delivered by the PS Booster to the primary ISOLDE target. Since a radioactive beam can be extracted both with and without protons impinging on the target, the runs can be separated into these two conditions. As shown in Figure 9.8, the second, fainter elliptical structure (black contour, labelled *b*) lies just outside the main diamond-shaped fission structure (red contour, labelled *a*), at larger $\Delta E_1 + \Delta E_2$. It is present only in the runs taken with protons hitting the production target, and essentially disappears when no protons are delivered from the PSB.

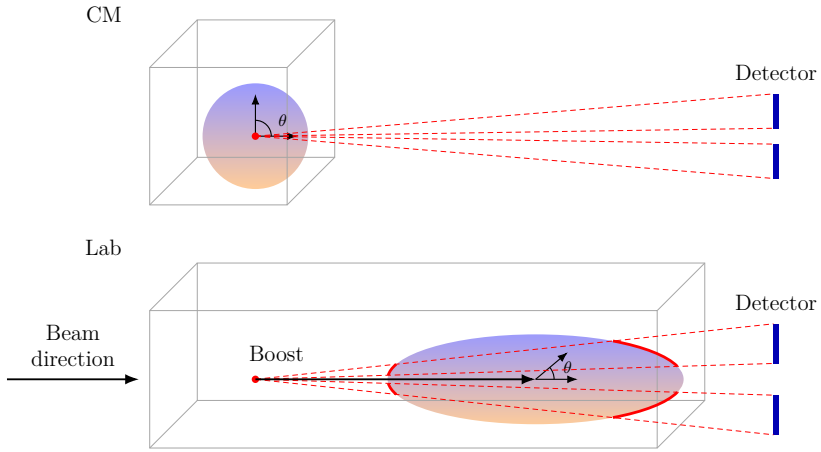


Figure 9.6: Schematic figure of the velocity-distribution boost from the center-of-mass to the laboratory frame. *Top:* in the center-of-mass frame, the fragment velocity distribution is, to a good approximation, isotropic (represented by a sphere), with θ the fragment emission angle. *Bottom:* the velocity distribution in the laboratory frame, elongated along the beam axis by the kinematic boost. A given emission angle θ in the center-of-mass frame therefore results in a different pair of fragment energies, in the laboratory frame. The dotted lines indicate the limited angular acceptance of the annular silicon telescope: fragments emitted at angles too close to the beam axis pass through the central aperture, while those emitted at too large angles are beyond the geometric coverage of the telescope, and in both cases are not detected.

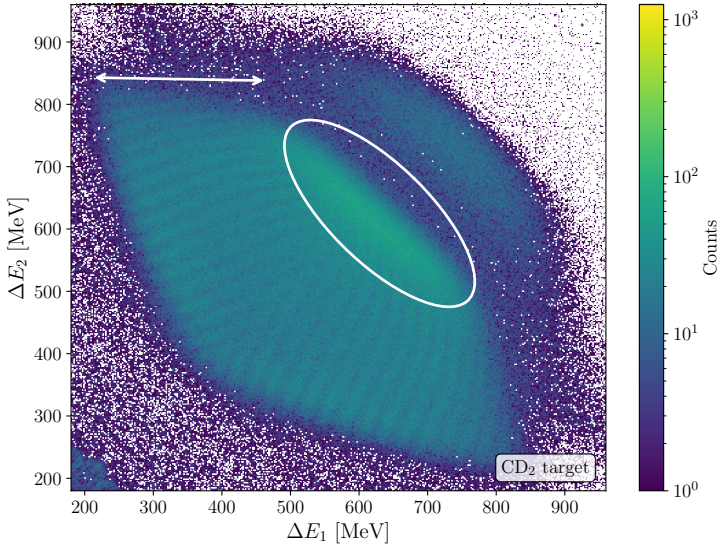


Figure 9.7: Magnified view of the central region of the $\Delta E_1 - \Delta E_2$ correlation for the CD_2 target. The white ellipse marks the main antidiagonal; a signature of the two complementary fragments of a single fission event. The double arrow marks the sharp cut-off at the largest charge asymmetry, where the lightest, fastest fragments fall outside the angular acceptance of the annular telescope, producing the abrupt drop in yield past the marked boundary.

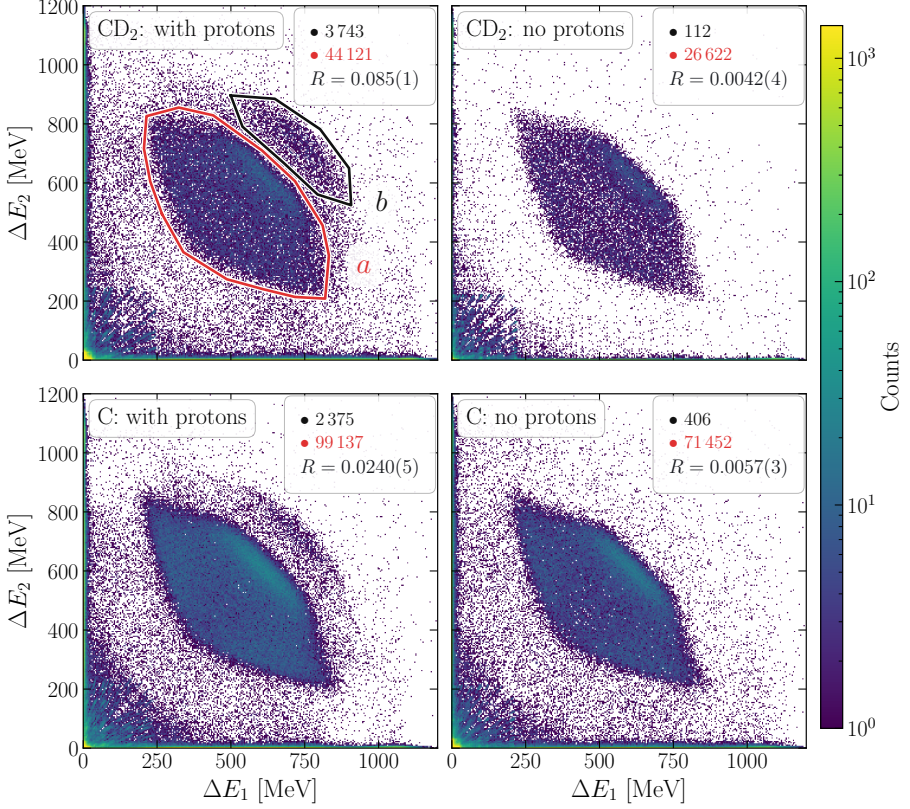


Figure 9.8: ΔE_1 – ΔE_2 correlations sorted by the active irradiation of the ISOLDE production target by protons from the PS Booster, for the CD_2 (top) and C (bottom) experimental targets, with protons on target (left) and without (right). The red contour marks the main fission locus and the black contour the second structure. The ratio R between the counts in the two contours, given in each panel, quantifies the absence of the second locus when no protons are delivered. Each data set corresponds to approximately two hours of data taking.

Table 9.1: Counts inside the graphical cuts on the $\Delta E_1 - \Delta E_2$ pair matrix of Figure 9.8. N_a is the main pair island and N_b the second structure, the subscripts following the labels beside the two outlines on the figure; with ratio $R = N_b/N_a$. Both yields can be normalised to the scattered ^{12}C yield ($N_{12\text{C}}$) in the luminosity monitor, see Figure 9.9. Uncertainties are Poissonian and quoted in units of the last digit.

Target	Protons	N_a	N_b	R	$N_{12\text{C}}$	$N_a/N_{12\text{C}}$	$N_b/N_{12\text{C}}$
CD ₂	yes	44 121	3 743	0.085(1)	3 944	11.2(2)	0.95(2)
CD ₂	no	26 622	112	0.0042(4)	2 598	10.2(2)	0.043(4)
C	yes	99 137	2 375	0.0240(5)	6 137	16.2(2)	0.387(9)
C	no	71 452	406	0.0057(3)	3 644	19.6(3)	0.111(6)

This correlation is quantified by the ratio $R = N_b/N_a$ between the counts in the second structure and those in the main one. For both targets, R drops sharply between the proton-on and proton-off conditions, from 0.085(1) to 0.0042(4) for CD₂ and from 0.0240(5) to 0.0057(3) for C, see Table 9.1. That is by factors 20(2) and 4.2(2) respectively. The clear correlation of the second structure with the presence of protons on the primary target suggests that it originates from a second beam component produced under proton irradiation. The proton-induced nature of the structure b can be verified further by normalising the counts in each structure to the beam luminosity measurements. The scattered ^{12}C kinematic line identified in the luminosity monitor (Figure 9.3) provides a convenient normalisation reference, since it originates from elastic scattering of the beam off the target and is present in all four datasets, independent of the proton condition. Its yield therefore tracks the beam luminosity on the experimental (secondary) target for each subset. A graphical cut is applied around this line (red contour in Figure 9.9) and the enclosed counts $N_{12\text{C}}$ are used as a “luminosity” estimator.

Table 9.1 lists, for each dataset, the counts in the two structures, their ratio R , the ^{12}C line yield used for normalisation and the two normalised yields. The normalised main-structure fission yield $N_a/N_{12\text{C}}$ is comparable in the two proton conditions, 11.2(2) against 10.2(2) for CD₂ and 16.2(2) against 19.6(3) for C, as expected if it scales with the delivered luminosity. The second structure behaves very differently: after normalisation $N_b/N_{12\text{C}}$ is still strongly enhanced in the runs with protons on target. Its production therefore scales with proton irradiation rather than merely with the accumulated beam luminosity.

The origin of this second structure is still under investigation, and we are in contact with ISOLDE beam experts regarding this issue.

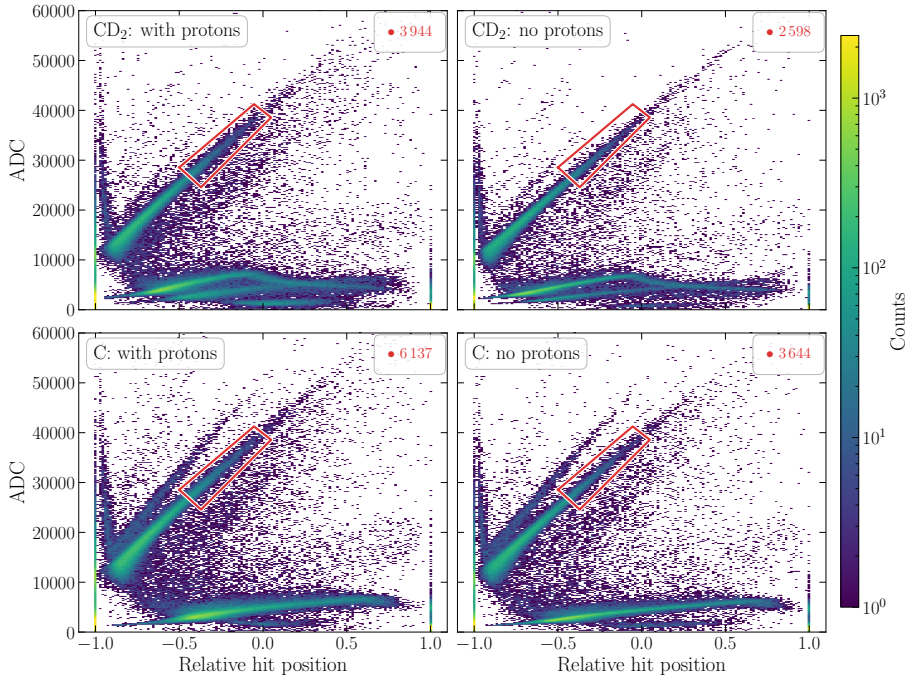


Figure 9.9: Energy (ADC) versus hit position in the luminosity monitor (LUME 2), sorted by the presence of PS Booster protons impinging on the primary ISOLDE target, for the CD₂ (top) and C (bottom) targets, with protons (left) and without (right). The red contour marks the scattered ¹²C line used as a luminosity reference; the enclosed counts are quoted in each panel.

9.2 Reactions with carbon in the target

At beam energies around the Coulomb barrier, the collision of a heavy actinide with a light C nucleus opens several competing reaction channels. In the present work, the signal of interest is the transfer reaction $^{232}\text{U}(\text{d}, \text{p})^{233}\text{U}$ using the deuterons of the CD_2 target, followed by fission of the moderately excited ^{233}U ; every other process producing fission fragments which reach the silicon telescope constitutes a background. The two dominant such contributions both originate from reactions on the C nuclei of the target: multinucleon transfer, which accounts for only a small fraction of the total reaction cross section, and complete fusion followed by fission, which dominates [157].

9.2.1 Multi-nucleon transfer

In multinucleon-transfer-induced fission, nucleons are exchanged between the two partners, producing a range of neutron-rich actinides that are left with enough excitation energy to fission. This mechanism was characterised in detail for the analogous $^{238}\text{U} + ^{12}\text{C}$ reaction studied in inverse kinematics by Rodríguez-Tajes *et al.* [99], where up to nine transfer channels were identified, populating actinides from U to Cm over a range of excitation energies below ~ 30 MeV. The corresponding target-like reaction products, from ^{16}O down to ^4He , were resolved in the identification matrix reproduced in Figure 9.10.

Since a similar entrance-channel dynamics is expected to govern the present $^{232}\text{U} + ^{12}\text{C}$ system, an equivalent set of transfer channels is expected to contribute here, each producing a fissioning actinide with its own excitation energy and fragment distribution. Because this carbon-induced component carries no fission-barrier information, an accurate determination of $B_f(^{233}\text{U})$ hinges on the carbon subtraction, which removes precisely this yield.

9.2.2 Fusion-fission

In fusion-fission, the complete fusion of ^{232}U and ^{12}C forms the compound nucleus ^{244}Cf at high excitation energy and angular momentum. Two features make it an especially efficient fission source. First, its fission barrier is intrinsically low: for such a heavy compound nucleus the ground-state barrier is almost entirely of ground-state shell-correction origin, and at the excitation energies reached here these shell effects are largely washed out, so that the relevant quantity is the macroscopic barrier. GEF [8] gives $B_f(^{244}\text{Cf}) \approx 6$ MeV, while the finite-range rotating-nucleus model of Sierk [158] places the $L = 0$ macroscopic barrier of a $Z = 98$ system already below ~ 2 MeV. Second, this barrier is further lowered by the large angular momentum brought in by complete fusion: the barrier decreases with L and, for heavy systems, vanishes above a critical spin [158], a trend reproduced by the four-dimensional Langevin treatment of

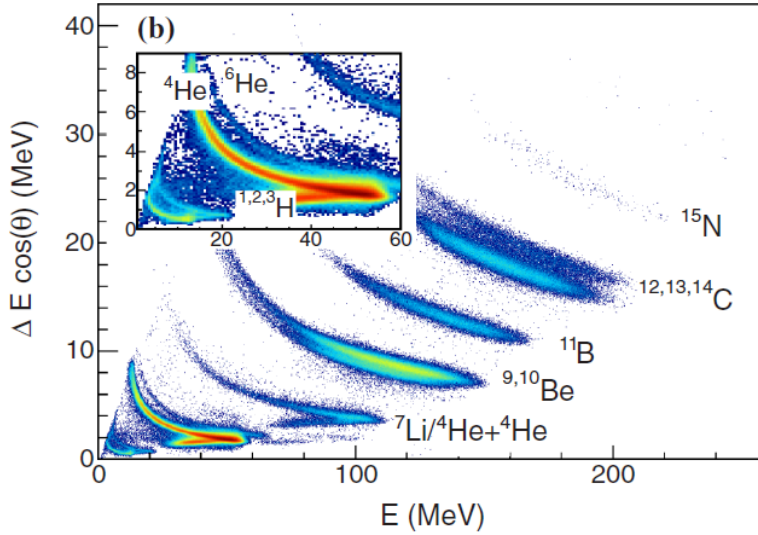


Figure 9.10: Identification of target-like nuclei from the $^{238}\text{U} + ^{12}\text{C}$ reaction, measured with SPIDER, the annular double-sided silicon ΔE - E telescope used to detect the target-like recoils in [99]. The spectrum is shown in coincidence with the detection of a fission fragment in the VAMOS spectrometer. The energy loss in the ΔE detector is plotted against the total kinetic energy E ; the factor $\cos(\theta)$ accounts for the different effective thickness crossed by target-like nuclei emitted at different angles θ . Each band corresponds to a transfer exit channel, from ^{16}O down to ^4He , and hence to a neutron-rich actinide from U to Cm produced in the collision. Reprinted figure with permission from M. Caamaño *et al.*, Phys. Rev. C **89**, 024614 (2014) [99]. Copyright 2014 by the American Physical Society.

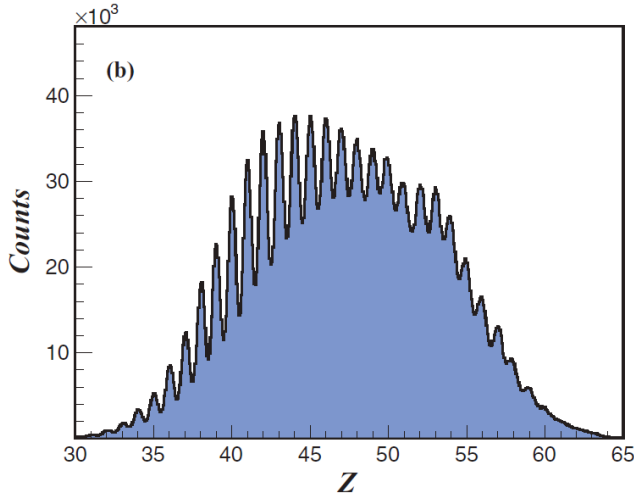


Figure 9.11: Atomic-number (Z) distribution of the fission fragments produced in the fusion–fission of $^{238}\text{U} + ^{12}\text{C}$, which forms the compound nucleus ^{250}Cf at ~ 45 MeV of excitation energy. The spectrum is obtained from the fragment ΔE – E_{tot} identification in the VAMOS spectrometer. It spans $Z \sim 30$ – 64 in a single broad distribution, reflecting fission at high excitation energy where the asymmetric structure of low-energy Cf fission is largely smeared out. Reprinted figure with permission from M. Caamaño *et al.*, Phys. Rev. C **88**, 024605 (2013) [98]. Copyright 2013 by the American Physical Society.

neighbouring nuclei in the Cf region [159]. At the spins populated here (see below), the effective barrier of ^{244}Cf is therefore close to zero, so that fission competes overwhelmingly with all other decay channels and $P_f \approx 1$ over the whole excitation-energy range.

A statistical-model calculation with PACE4 [103] gives $E_x = 57$ MeV for an incoming beam energy of 7.34 MeV/u and an angular-momentum distribution extending up to $50\hbar$, peaked around $30\hbar$. For the reaction of a stable ^{238}U beam on a ^{12}C target, fission has been measured to account for roughly 90 % of the reaction cross section, with the compound nucleus ^{250}Cf produced at ~ 45 MeV of excitation energy [98]. The fission of such a highly excited, heavy compound nucleus yields fragments spanning a broad range in charge and mass. The measured characteristic broad charge distribution is reproduced in Figure 9.11.

9.2.3 Fission signatures

The two channels populate fissioning systems that differ in charge and mass, but above all in excitation energy and angular momentum, and this difference propagates to every fission fragment observable. Figure 9.12 compares GEF calculations of the fission of the two systems: that of ^{233}U at $E_x = 7$ MeV and $0 \hbar$, corresponding to the transfer-induced signal, and that of ^{244}Cf at $E_x = 57$ MeV and $20 \hbar$, a value constrained by the limitations of GEF at high angular momenta¹, corresponding to background from fusion-fission.

Total kinetic energy The top row shows the post-neutron total kinetic energy. At 7 MeV of excitation energy, the fission of ^{233}U takes place well below the energy at which shell effects are washed out, and it is markedly asymmetric: the fragment charges cluster in a light group around $Z \sim 30\text{--}43$ and in the complementary heavy group around $Z \sim 50\text{--}62$, while the symmetric split at $Z \approx 46$ is strongly suppressed. The total kinetic energy follows the same structure, with two maxima of about 177 MeV at the centres of the two groups and a pronounced minimum of about 157 MeV at symmetry. Symmetric splits, in contrast, proceed in general through elongated scission configurations in which a larger share of the energy is stored as deformation energy of the nascent fragments, and are associated with a lower total kinetic energy.

For ^{244}Cf at $E_x = 57$ MeV the situation is different. The shell effects that drive asymmetric fission are largely washed out. As a consequence, the charge distribution becomes a single broad distribution centred at symmetry, and the total kinetic energy is a smooth, nearly parabolic function of Z with a maximum of about 183 MeV at $Z \approx 49$ and no minimum at symmetry. The absolute scale is also higher, as expected from the larger Coulomb repulsion of the fissioning system: the systematics of Viola *et al.* [160], using $\text{TKE} = 0.1189 Z^2/A^{1/3} + 7.3$ MeV, gives 171 MeV for ^{233}U and 190 MeV for ^{244}Cf . The simulated values lie somewhat below the latter, consistent with the higher excitation energy and angular momentum. Plotted are total kinetic energy distributions after prompt-neutron emission, which is the quantity influencing the experiment. Since neutron emission removes mass but not charge, the fragment Z is unaffected. The large angular momentum brought in by complete fusion contributes further to the width of the TKE distribution.

Single-fragment energy The middle row shows how this total energy is shared between the two partners. In the center of mass frame, the two fragments are emitted with equal and opposite momenta; the heavier partner there-

¹Even though PACE4 predicts a maximum partial cross section at $\ell = 30\hbar$, GEF fails to run this reaction at such high spin. The expected impact on the total kinetic energy would be a reduction, while the expected charge or mass distributions of the fission fragments would be wider. The general trend observed, however, would not change.

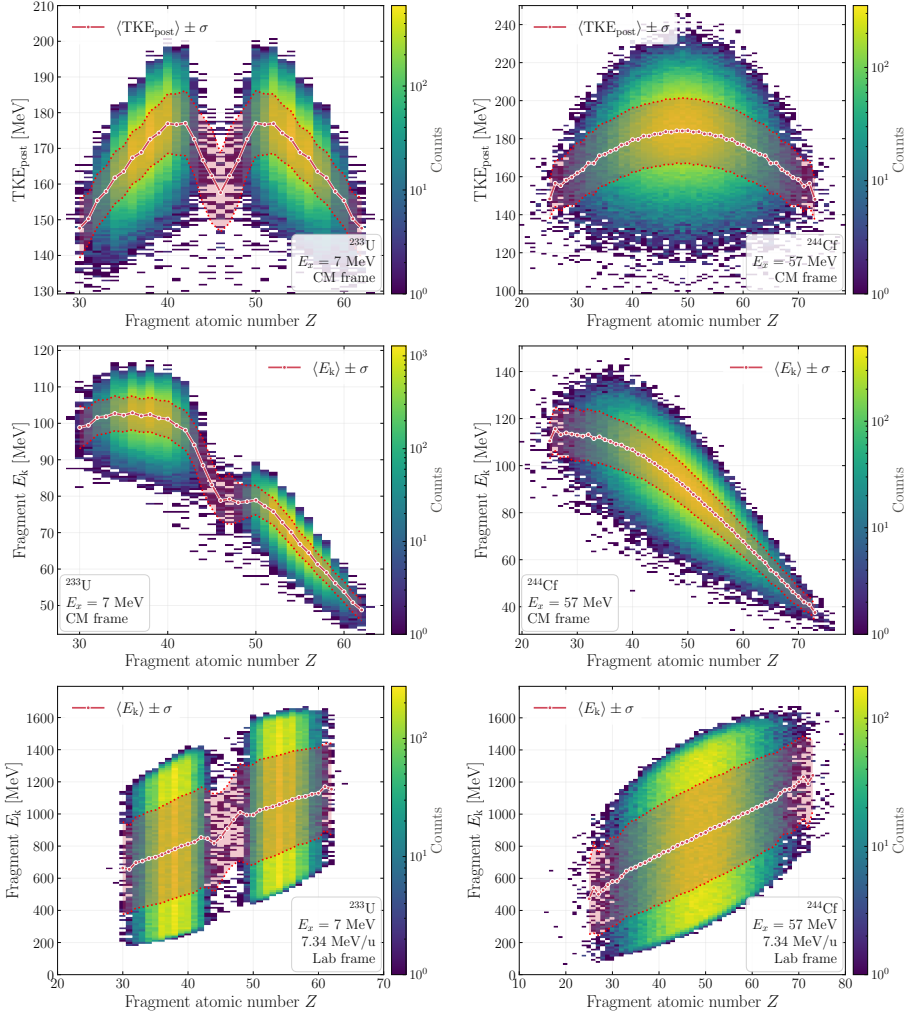


Figure 9.12: Fission-fragment kinetic-energy observables as a function of the fragment atomic number Z , calculated with GEF [8] for two fissioning systems relevant to the present work. *Left column:* ^{233}U at $E_x = 7$ MeV, as populated by the $^{232}\text{U}(\text{d}, \text{p})$ transfer reaction. *Right column:* ^{244}Cf at $E_x = 57$ MeV, as formed by the complete fusion of ^{232}U and ^{12}C . *Top row:* post-neutron total kinetic energy TKE_{post} in the centre-of-mass frame. *Middle row:* kinetic energy of the individual fragments, E_k , in the same frame. *Bottom row:* the same fragment kinetic energy in the laboratory frame, i.e. including the boost of the 7.34 MeV/u beam illustrated in Figure 9.6. The dash-dotted line indicates the mean value with its standard deviation.

fore carries the lower velocity and, consequently, the smaller kinetic energy. Expressed in terms of the total kinetic energy, the single-fragment energy is $E_k = \text{TKE} (A_{\text{CN}} - A) / A_{\text{CN}}$, and since the fragment mass grows with its charge, E_k decreases as Z increases. For ^{233}U , the two fission modes appear as two separate branches: a plateau near 100 MeV for the light group, $Z \sim 30\text{--}43$, and a lower, steeply falling branch for the complementary heavy fragments, $Z \sim 50\text{--}62$, separated by a sharp drop at $Z \approx 44\text{--}46$ that mirrors the minimum of the total kinetic energy at symmetry and the low yield of symmetric splits. For ^{244}Cf the same quantity forms a single continuous band, decreasing from about 113 MeV to about 40 MeV over the full charge range.

Effects on measured distributions The bottom row shows the same fragment energy in the laboratory frame, after the Lorentz transformation sketched in Figure 9.6. The transformation adds a momentum corresponding to an energy of $A \times 7.34$ MeV parallel to the beam direction over the relevant mass range, and therefore reverses the ordering with respect to the charge: the laboratory energy increases almost linearly with the fragment charge, from a few hundred MeV up to about 1600 MeV. The width of each band, of the order of several hundred MeV, is dominated by the interference term $2 \cos \theta_{\text{cm}} \sqrt{E_k E_{\text{beam}}}$, that is, by the centre-of-mass emission angle, which is the origin of the extension of the $\Delta E - E$ and $\Delta E_1 - \Delta E_2$ loci discussed above in Section 9.1.2. In the laboratory frame, the two distributions overlap over nearly the whole sensitive range, so that neither the total kinetic energy nor the single-fragment energy allows an event-by-event separation, and a coincidence requirement with the (d, p) proton remains the only clean handle. The residual difference is nevertheless of diagnostic value: the signal is expected to populate two distinct branches separated by a depleted region around $Z \approx 46$, whereas the fusion-fission background forms a single continuous band. A coincidence requirement with the (d, p) proton is the key handle for disentangling these contributions. Crucially, the excitation energy is reconstructed from the proton kinematics alone: even though fusion-fission of ^{244}Cf produces fission fragments that reach the silicon telescope, it emits no proton² and therefore does not contribute to the excitation-energy spectrum.

The fragment angular distribution provides a further handle to separate the two mechanisms. Following the $^{232}\text{U}(\text{d}, \text{p})$ transfer reaction, ^{233}U is formed with little angular momentum, so the angular distribution of the fission fragments is close to isotropic in the center-of-mass frame. Fusion-fission, in contrast, proceeds through a compound nucleus formed with high angular momentum aligned perpendicular to the beam axis, and its fragments are emitted anisotropically, preferentially along the beam direction [99, 161].

²Proton emission is very unlikely due to the high Coulomb barrier.

9.2.4 Nature of the second structure

The second, proton-induced structure introduced in Section 9.1.3 can now be revisited in light of the fission kinematics discussed above. Its displacement towards higher $\Delta E_1 + \Delta E_2$ was tentatively ascribed to a second beam component; it should be stressed, however, that even if this is the case, the shift cannot be attributed to a real difference in the TKE released in fission. Two arguments support this: first, the TKE released in the centre-of-mass frame varies only slowly between neighbouring fissioning systems, following the Viola systematics, so that fission of a different actinide contaminant would release a comparable TKE, differing by at most a few MeV. Second, and more importantly, the energies recorded in the ΔE telescope are largely set by the inverse-kinematic boost: each fragment carries most of the beam momentum, so that the detected energy reflects primarily the energy of the beam rather than the intrinsic fission TKE. The observed shift of the second locus towards larger ΔE_1 and ΔE_2 is therefore consistent with a contaminant transmitted through HIE-ISOLDE at a slightly different energy – a beam effect – and not with a genuinely different fission process.

9.3 Charge identification of fission fragments

To obtain a cleaner identification of the fissioning nucleus, the fact that the fission fragment detectors can resolve individual charges is exploited. This requires two steps:

- identifying which $\Delta E - E$ band corresponds to which charge;
- finding events where both fission fragments are identified, so that their charge sum, and hence the fissioning system, can be reconstructed.

Starting from the energy-loss discrimination provided by the $\Delta E - E$ telescopes, an analysis is carried out in an attempt to identify the atomic number Z of the fission fragments. For the sake of visualization, Figure 9.13 shows a zoomed-in view of the total $\Delta E - E$ (with $\text{CD}_2 + \text{C}$ data combined). In the right panel, the ridges of the distribution have been highlighted to mark the presence of charge bands. Note that these ridges are not used in the analysis and are shown for illustrative purposes only.

9.3.1 SRIM or ATIMA?

The idea was to use energy-loss curves calculated from range tables obtained with SRIM [126], a code for computing the energy loss of ions in matter. The calculated $\Delta E - E$ curves corresponding to the silicon telescope configuration

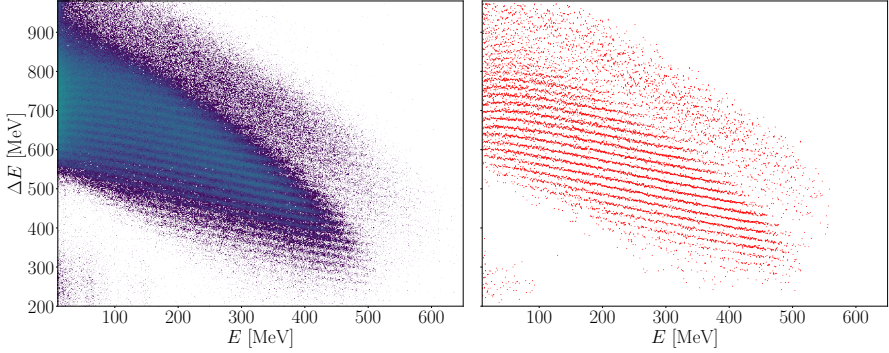


Figure 9.13: Zoomed-in view of the total $\Delta E - E$ correlation (combined $\text{CD}_2 + \text{C}$ data), shown as measured (left) and as the extracted ridges of the distribution (right). The ridges trace the charge bands and are shown for illustrative purposes only.

would be used as a reference for the experimental data, in order to check whether the observed bands correspond to the predicted curves.

The current state-of-the-art code for stopping-power and range calculations is generally assumed to be SRIM. SRIM was in fact the first choice for this analysis; however, it was found to produce anomalous energy-loss curves for a few isotopes (notably Kr and Nb) in the low-energy region, where the fragments barely punch through the ΔE layer. In this regime, the SRIM-based $\Delta E - E$ curves depart from the smooth trend followed by the neighbouring elements, in contrast with the behaviour of the measured data. Hence, the same calculations based on ATIMA [162] range curves were performed.

Figure 9.14 compares the $\Delta E - E$ curves obtained with SRIM and ATIMA for the same detector configuration: the anomaly is visible in the SRIM zoom inset for Kr and Nb, while ATIMA follows a regular, monotonic trend across all isotopes. The origin of this behaviour appears related to the SRIM tabulated stopping-power curves for Kr and Nb being both broader and lower at the Bragg peak than those of their neighbours, breaking the regular Z ordering, as illustrated in Figure 9.15. ATIMA, which below 10 MeV/u actually relies on a Ziegler³ scaling formula from the 1990s, does not exhibit the anomaly. For this reason, ATIMA was adopted for the energy-loss calculations in the following analysis.

³J. F. Ziegler (1935–2024) was also the principal author of SRIM.

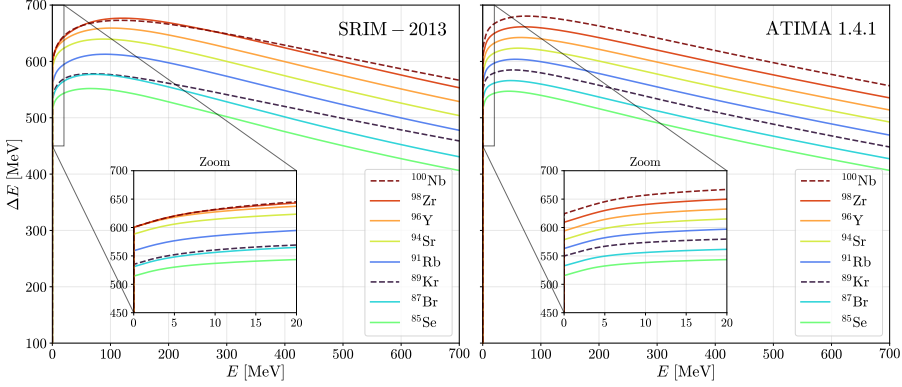


Figure 9.14: Comparison of $\Delta E - E$ energy-loss curves computed with SRIM (left) and ATIMA (right) range tables for the same silicon telescope geometry (Ring 0, $\Delta E = 65 \mu\text{m}$, $E = 1000 \mu\text{m}$), for a set of representative fission-fragment isotopes. The zoom insets show the low-energy region where the fragments barely traverse the ΔE layer: the SRIM-based curves for Kr and Nb deviate from the smooth trend of the neighbouring elements, whereas the ATIMA-based curves remain regular.

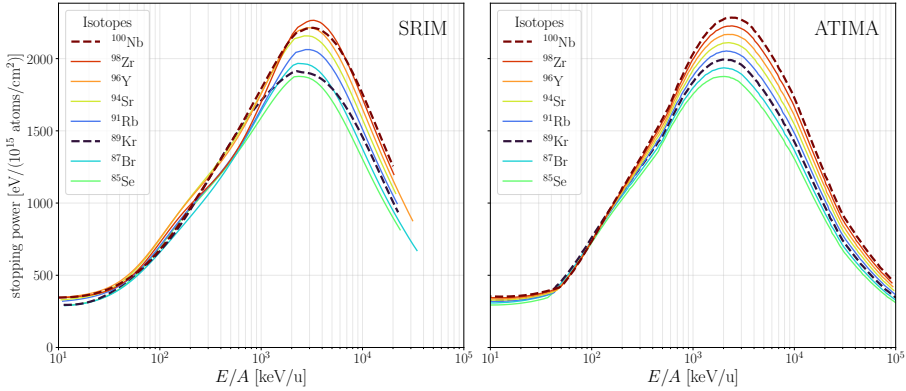


Figure 9.15: Stopping power in Si as a function of energy per nucleon E/A for the representative fission-fragment isotopes, computed with SRIM (left) and ATIMA (right). For most isotopes, both codes reproduce the expected gradual ordering, with the stopping power increasing smoothly with Z . In the SRIM tabulations, however, the ^{89}Kr and ^{100}Nb curves (dashed) are anomalous: they are broader than those of the neighbouring elements and their Bragg peak is lower, so they cross and fall out of the monotonic Z ordering around the maximum. ATIMA, which is based on an earlier Ziegler scaling formula, shows no such anomaly, with all projectile isotopes following a regular, well-ordered trend.

9.3.2 Reference isotope masses

In addition, it was necessary to decide which isotopes to use as references for the calculation of the reference energy-loss curves, since, as illustrated in Eq. 6.1, the ion mass also affects the stopping power in a given material. Moreover, during the nuclear fission process, fission fragments tend to be produced with a neutron excess. Therefore, in order to guide the choice of which isotopes to consider, a GEF simulation of the fission of ^{233}U at an excitation energy of 7 MeV was used, and the resulting mass and charge distribution of the fragments was inspected. Figure 9.16 shows the resulting Z vs A distribution obtained from the GEF simulation, together with the weighted average mass number $\langle A \rangle$ as a function of Z (red curve). For each value of Z , the corresponding $\langle A \rangle$ was used to select the reference isotope for the calculation of the energy-loss curves, thus taking into account the neutron excess characteristic of the fission fragments. Once the reference isotopes were selected, the corresponding energy-loss curves were superimposed on the experimental $\Delta E - E$ correlation, obtained by selecting pairs of adjacent rings, which improves the statistics in each plot and makes the correlation clearer, as shown in Figure 9.17.

The entrance angle of fission fragments with respect to the detector surface affects the deposited energy, due to the varying effective thickness of the ΔE detector and dead layers. As a consequence, one would expect that considering

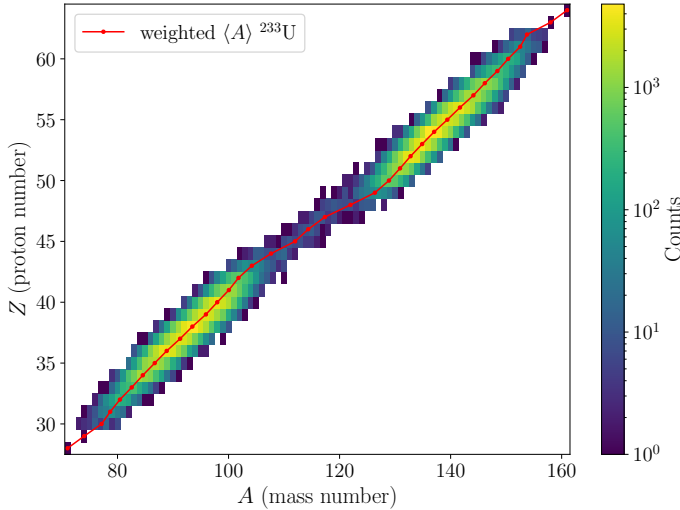


Figure 9.16: Distribution of proton number Z versus mass number A for fission fragments obtained from a GEF simulation of ^{233}U fission at 7 MeV excitation energy. The red curve shows the weighted average mass number $\langle A \rangle$ as a function of Z .

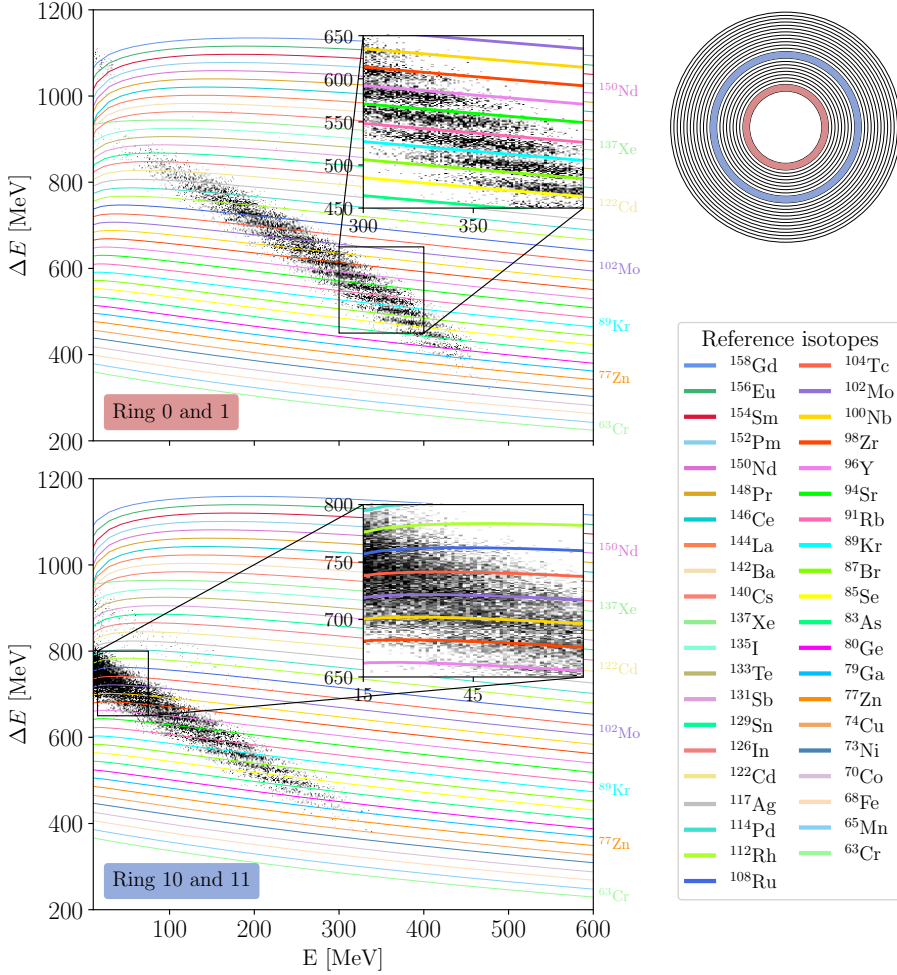


Figure 9.17: Experimental $\Delta E - E$ correlations for two representative ring pairs (Ring 0+1, top, and Ring 10+11, bottom), superimposed with ATIMA-based energy-loss curves calculated for the reference isotopes selected as described in the text. The calculated isotopes are listed in the legend in the same order as the corresponding curves (from top to bottom). Note that rings are paired here only for illustrative purposes, and were treated individually in the actual analysis. The energy loss curves are corrected for the entrance angles, assumed to be the angles subtended by the center of each ring; for each pair shown here, the angle-corrected energy loss curves are calculated separately for the two rings, and their average is then shown. The schematic on the top right shows the ring structure of the detector, with the selected ring pair highlighted. The ATIMA curves are found to reproduce, overall, the trend of the experimental data. The inset in the bottom panel shows a zoomed-in view highlighting the individual charge bands.

the detector as a whole (i.e., all 24 rings together) would result in a smearing of the charge bands, thus worsening the achievable resolution. Surprisingly, the resolution is found to be sufficient to distinguish the charge bands even when the full detector is considered. This can be explained by noting that, if the data are gated on individual ring pairs, the $\Delta E - E$ correlation populates different regions depending on the ring ID, as shown in Figure C.1 in Appendix C. In other words, different rings, corresponding to different entrance angles, do not simply broaden a single band, but instead populate progressively shifted regions of the $\Delta E - E$ plane, moving towards lower deposited energy as the ring number increases. This spatial separation avoids angular smearing, thus preserving a good separation of the charge bands even when the detector data plot is considered as a whole.

9.3.3 Interpolation to integer charges

The next step consists of interpolating the experimental data with the charge values associated with each ATIMA energy-loss curve, thus assigning to each event a non-integer, interpolated charge value Z_{interp} . This procedure is performed independently for each individual ring. Subsequently, for each ring, the peaks of the Z_{interp} distribution are identified and fitted, and a charge increment calibration is carried out by attempting to associate a preliminary integer charge value Z' to each fitted peak. Figure 9.18 shows this procedure for three representative rings (Ring 0, Ring 8, and Ring 16), while the complete set of rings is reported in Figures C.2 and C.3 in Appendix C. The left panels show the Z_{interp} distributions, with the identified peaks and the corresponding integer charge assignments; the right panels show the resulting linear calibration between the fitted peak positions μ and the assigned integer charges Z' . As the ring ID increases, the range of resolved charges progressively narrows, and the peaks become less clearly separated. This behavior is consistent with a worsening of the energy resolution at larger ring ID, likely due to the increasing effective thickness of the dead layer traversed at larger entrance angles. The procedure described above, i.e. the linear calibration between the fitted peak positions μ and the assigned integer charge Z' , was repeated independently for each ring. Figure 9.19 shows the resulting gain and offset parameters of the calibration as a function of the ring ID. Their smooth evolution across rings ensures that the assigned Z' does not jump discontinuously between adjacent rings, confirming the consistency of the per-ring calibration.

Once the gain and offset have been determined for each ring, the resulting calibration is applied to the whole dataset, obtaining an aligned charge distribution across all rings. Figure 9.20 shows a comparison between the interpolated charge distribution before (left) and after (right) the ring-by-ring calibration, for the first 20 rings. After calibration, the peaks are well aligned across all rings, confirming the consistency of the calibration procedure. In cases where

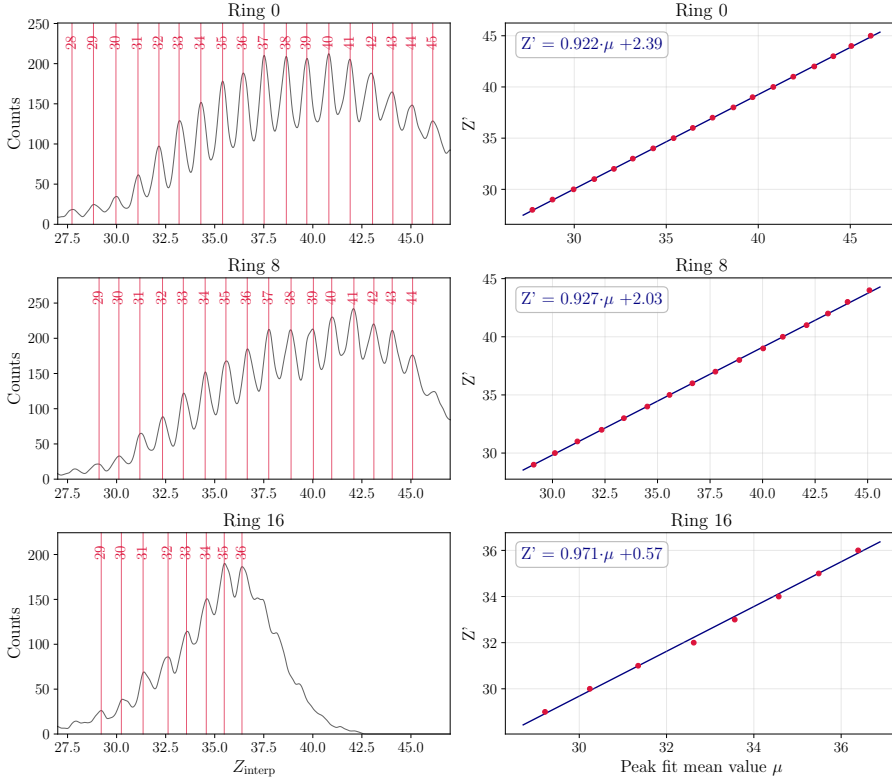


Figure 9.18: Charge calibration procedure for three representative rings (Ring 0, top; Ring 8, middle; Ring 16, bottom). *Left:* distribution of the interpolated charge Z_{interp} , with the identified peaks labeled by the corresponding integer charge value; peaks marked in grey were excluded from the calibration fit. *Right:* linear calibration based on the fitted peak positions μ and the assigned integer charge Z' , together with the resulting calibration function. As the ring ID increases, the range of resolved charges decreases, consistent with a worsening of the charge resolution due to the increasing effective dead-layer thickness at larger entrance angles.

the reduced charge resolution limits the range over which the increment calibration can be reliably determined, the transformation is extrapolated beyond the fitted range. The extrapolated region is highlighted in red in the right panel.

Once all rings are aligned, a global one-dimensional Z' distribution can be reconstructed by summing the contributions of the individual rings, as shown in Figure 9.21. In this representation, each colored band corresponds to the statistics contributed by a single ring, allowing the relative weight of each ring to the total distribution to be visualized directly. The varying width and intensity

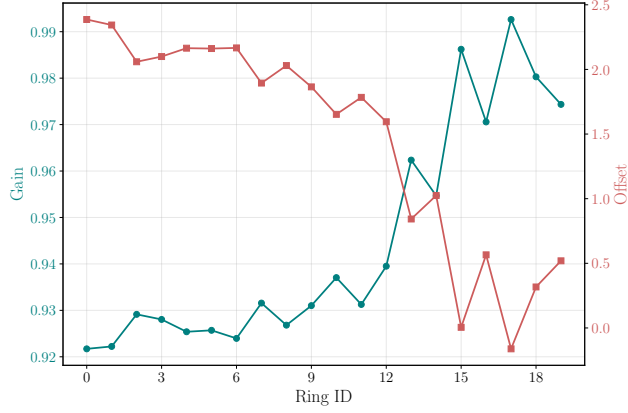


Figure 9.19: Gain (left axis, blue) and offset (right axis, red) of the linear charge increment calibration $Z' = \text{gain} \cdot \mu + \text{offset}$, as a function of the ring ID.

of the bands across the Z' range reflect the fact that the charge resolution is not uniform across rings: rings with better resolution contribute narrower, more sharply peaked distributions, while rings with degraded resolution, particularly at higher ring ID, as discussed above, produce broader contributions that are less well localized in Z' . The dashed red line marks the boundary beyond which the calibration was extrapolated, and the shaded region highlights the range affected by this extrapolation.

It is important to stress that Z' is a “pseudo-charge”, defined as $Z' = Z_{\text{true}} + \text{offset}$, rather than the true atomic number of the fragments. As shown in the inset of the upper panel of Figures 9.4 and 9.5, the scattered carbon line is clearly identifiable in the $\Delta E - E$ plot. However, a large gap separates this line from the region where fission fragments start to populate the $\Delta E - E$ matrix, as the statistics for intermediate-mass ions are too low to define well-resolved calibration lines. This gap prevents a direct extrapolation of the absolute charge simply by counting the individual bands from the carbon line up to the fission fragment region. Moreover, the spacing between the resolved bands is not constant across the whole range, so a naive extrapolation could easily lead to a mismatch between the assigned pseudo-charge and the true atomic number. For this reason, the possibility of an offset between Z' and Z_{true} must be explicitly taken into account.

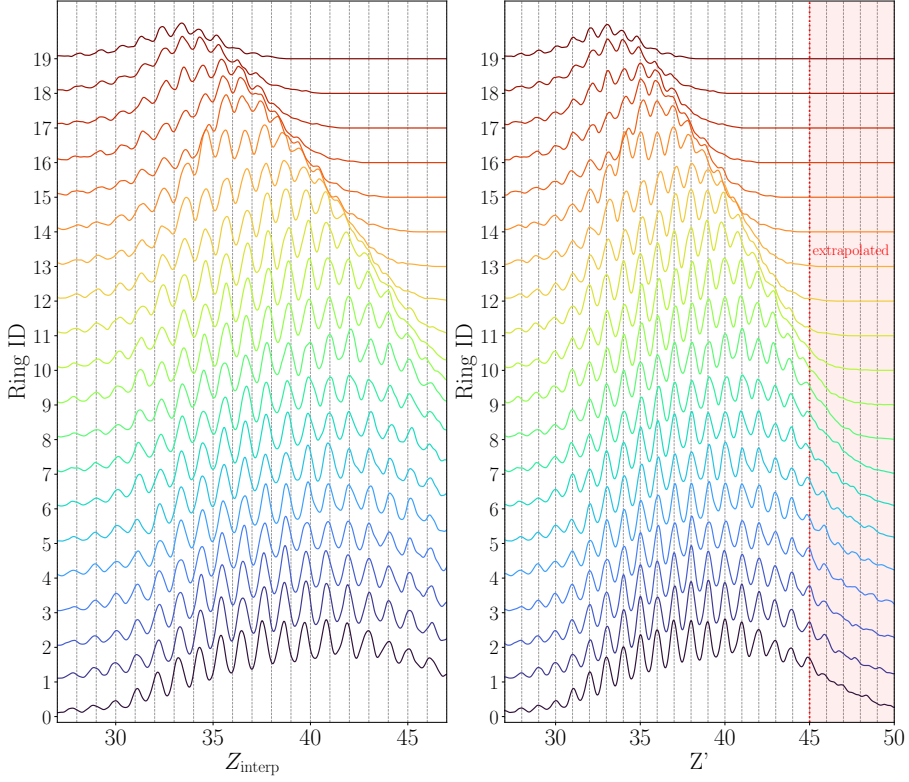


Figure 9.20: Comparison between the interpolated charge distributions before (left, Z_{interp}) and after (right, Z') the ring-by-ring charge increment calibration, for all rings. The shaded red region in the right panel indicates the range over which the calibration was extrapolated beyond the fitted peaks.

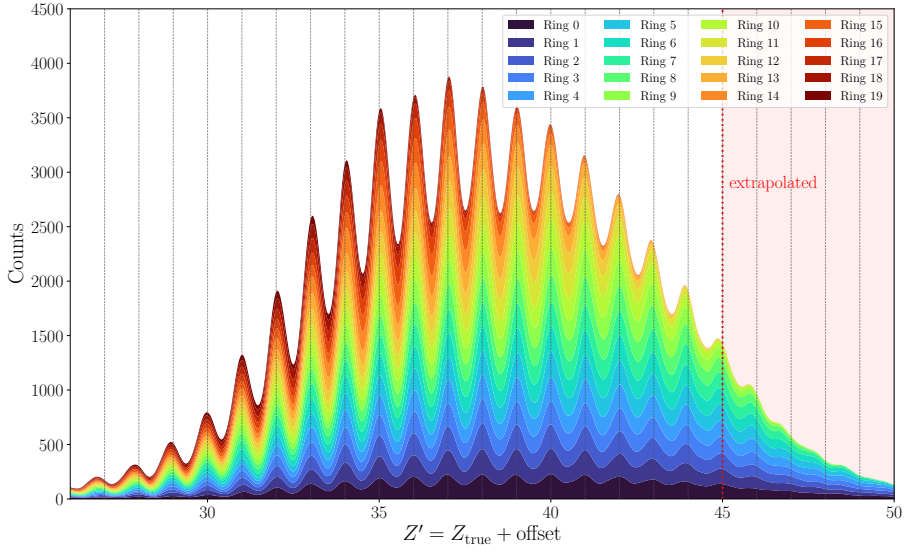


Figure 9.21: Global Z' distribution obtained by summing the aligned contributions of all rings. Each colored band represents the statistics contributed by an individual ring (Ring 0 to Ring 19), illustrating how the charge resolution varies across rings and across the Z' range. The shaded red region indicates the extrapolated calibration range.

9.4 Absolute charge assignment

In some events, both fission fragments are detected in coincidence with complete $\Delta E - E$ measurements. In this case, having an assigned pseudo-charge for each fragment proves particularly useful, as it allows the correlation between the two fragment charges, Z'_1 and Z'_2 , to be investigated on an event-by-event basis. Figure 9.22 shows the resulting Z'_1 vs Z'_2 correlation for the CD_2 target (left) and for the carbon target (right). For the CD_2 target, a clear anti-diagonal band is visible, corresponding to a nearly constant value of $Z'_1 + Z'_2$, as expected from the total charge being shared by the two fission fragments alone. In contrast, for the carbon target the distribution appears considerably more smeared, with no dominant correlation between Z'_1 and Z'_2 . To further investigate the offset between Z' and Z_{true} , the anti-diagonal band observed for the CD_2 target can be used to estimate the total charge of the fissioning system. As shown in the left panel of Figure 9.24, a diagonal line corresponding to $Z'_1 + Z'_2 = 88$ can be drawn through the centroid of the correlation. If no offset is assumed ($Z' = Z_{\text{true}}$), this sum would correspond to a fissioning system with $Z = 88$, i.e. Ra. However, this identification is not entirely consistent with the expected fissioning system, which, given the incoming ^{232}U beam, should result in $Z_{\text{sum}} = 92$. Assuming instead an offset of $+2$ for each fragment (i.e. $Z_{\text{true}} = Z' + 2$), the total charge becomes $88 + 2 + 2 = 92$, correctly matching uranium as the fissioning system. Such an offset is reasonable, since the pseudo-charge bands were originally identified via comparison with ATIMA energy-loss curves, a procedure which is not expected to yield an absolute charge calibration

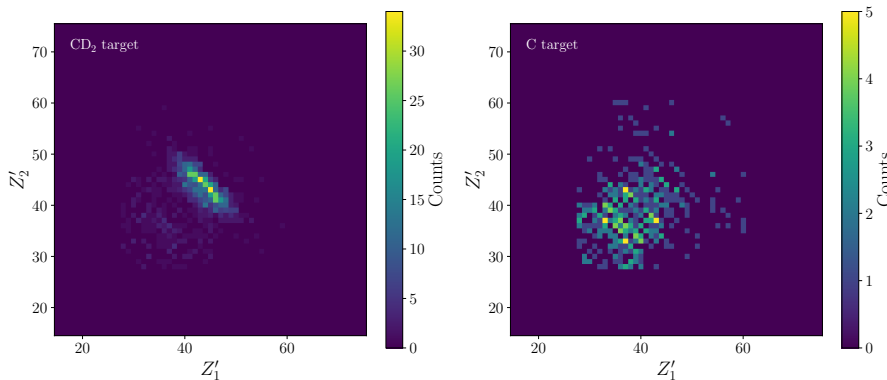


Figure 9.22: Correlation between the pseudo-charges of the two coincident fission fragments, Z'_1 vs Z'_2 , for the CD_2 target (left) and for the C target (right). The CD_2 target shows a clear anti-diagonal band, reflecting the approximate conservation of the total charge $Z'_1 + Z'_2$ in the fission process, while the carbon target shows a smeared distribution. Note the different scales.

with better than a few units of precision. While this identification cannot be regarded as conclusive, it appears plausible: no comparably well-defined anti-diagonal structure is observed for the carbon target (Figure 9.22, right), where the absence of deuterium prevents the (d, p) transfer reaction that selectively populates the fissioning uranium system. Although other reaction channels, such as fusion-fission or multi-nucleon transfer, may still occur, they are not expected to produce the same well-defined charge-correlated fragment distribution. This supports the interpretation that the anti-diagonal band seen for the CD₂ target reflects a genuine physical correlation between coincident fission fragments, rather than an artifact of the analysis, and that an offset of 2 units between Z' and Z_{true} is a reasonable choice, at least in the charge region relevant for this measurement. It should be noted that, while the absolute offset might be different, the fissioning system has an even charge since any offset moves $Z'_1 + Z'_2$ in steps of two.

The presence of a well-defined total charge for the CD₂ target, as opposed to the smeared distribution observed for the carbon target, can be seen more directly by projecting the Z'_1 vs. Z'_2 correlation onto the $Z'_1 + Z'_2$ axis. Figure 9.23 shows the distributions for the two targets, with the carbon-target data scaled for direct comparison (the scaling procedure is described in detail later in this chapter). A narrow, well-defined peak is clearly visible for the CD₂ target, consistent with the anti-diagonal band observed in Figures 9.22 and 9.24, and with the approximate conservation of the total charge in fission at low excitation energies. A Gaussian fit to this peak yields a centroid of $\mu = 87.9 \pm 0.2$. In contrast, the carbon-target distribution is broad and featureless, spanning a wide range of $Z'_1 + Z'_2$ values with no comparable peak.

9.4.1 Comparison with simulations

This interpretation is further supported by comparison with a GEF simulation of the Z_1 vs. Z_2 correlation for ²³³U fissioning at 7 MeV of excitation energy, shown in the right panel of Fig. 9.24. The simulated distribution exhibits the characteristic asymmetric fission pattern, with the dominant yield concentrated at either high or low nuclear charges of the fragments, and a comparatively small contribution in the symmetric region (the “valley” of the mass/charge distribution). The red ellipse, based on the data on the left panel of Figure 9.24, highlights the charge region in which the annular silicon telescope is efficient at detecting *and* identifying both fission fragments in coincidence via $\Delta E - E$: this region overlaps almost entirely with the symmetric valley of the GEF distribution, rather than with the asymmetric peaks where GEF predicts the largest statistical yield. This is consistent with the experimental data of Figure 9.22, where the reconstructed Z'_1 – Z'_2 correlation appears concentrated near the symmetric region. The origin of this bias is mainly kinematic and related to the detector acceptance. In asymmetric fission, the two fragments

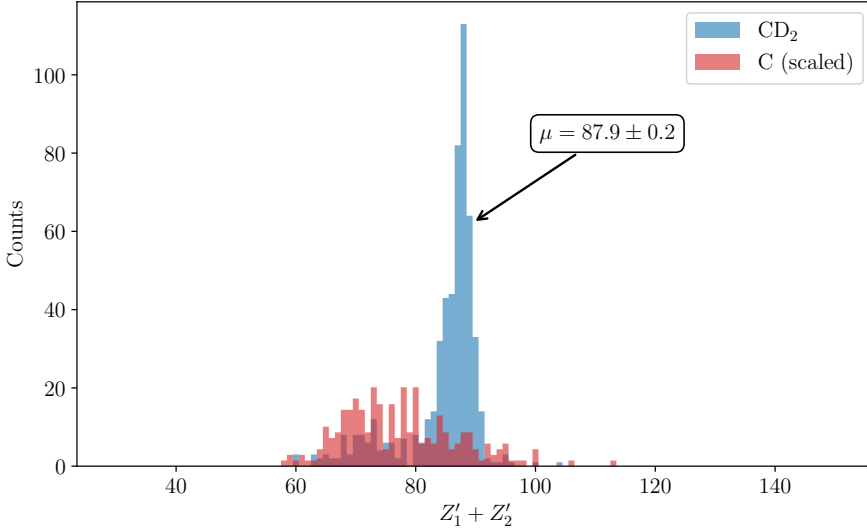


Figure 9.23: Distribution of the summed pseudo-charge $Z'_1 + Z'_2$ for coincident fragment pairs, for the CD_2 target (blue) and the carbon target (red, scaled). The CD_2 target shows a narrow peak centered at $\mu = 87.9 \pm 0.2$ (Gaussian fit), reflecting the approximate conservation of the total charge in the fission process, while the carbon target displays a broad, structureless distribution, consistent with the absence of a specific fissioning system.

have different probabilities of being fully detected. The light fragment, due to its larger velocity and consequently broader angular distribution, is more likely to escape the geometrical acceptance of the telescope. On the other hand, the heavy fragment has a shorter range in silicon and is more likely to be stopped entirely within the ΔE detector, preventing the identification through a complete $\Delta E-E$ signal. Therefore, the identification of both coincident fragments is more efficient for near-symmetric fission events, while asymmetric events, although predicted by GEF to dominate the fission yield, are less represented in the fully Z-identified sample.

This acceptance bias might have a useful counterpart. As shown in Figure 9.12, the near-symmetric region that the telescope samples most efficiently is also the one in which the two fissioning systems differ most in total kinetic energy: about 157 MeV for ^{233}U , where symmetric splits proceed through elongated scission configurations, against about 183 MeV for ^{244}Cf , where the damping of shell effects places the maximum of the distribution at symmetry. Provided the fragment energies can be reconstructed with sufficient accuracy, i.e. after correcting for the pulse-height defect and for the energy lost in the dead

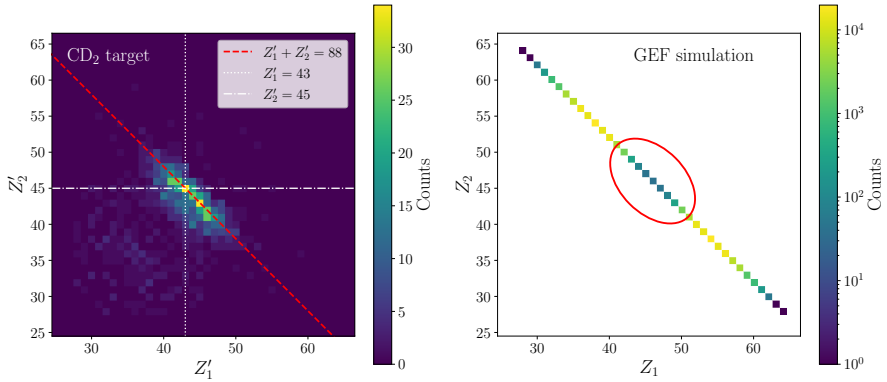


Figure 9.24: *Left:* Z_1' vs Z_2' correlation for the CD₂ target, with the anti-diagonal line $Z_1' + Z_2' = 88$ (red dashed) drawn through the centroid of the distribution, together with the projections $Z_1' = 43$ and $Z_2' = 45$ (white dotted lines). Assuming a pseudo-charge offset of -2 per fragment, consistent with the precision of the ATIMA-based pseudo-charge identification, this total would correspond to a fissioning system with $Z = 92$, matching the ^{233}U incoming beam, although this identification remains tentative. *Right:* GEF simulation of the Z_1 vs. Z_2 charge correlation for ^{233}U fissioning at 7 MeV excitation energy, showing the characteristic asymmetric fission pattern. The red ellipse indicates the charge region corresponding to the region populated in the left panel, thereby probably reflecting the detection efficiency of the annular silicon telescope for Z-identified fragment pairs, which overlaps with the symmetric valley of the distribution rather than with the dominant asymmetric peaks.

layers, a determination of the total kinetic energy in this region could therefore provide a statistical discriminant between the transfer-induced signal and the fusion–fission background.

9.5 Fission barrier

As mentioned already, the solenoidal-spectrometer technique has already been applied to transfer-induced fission to extract a fission-barrier height: the B_f of ^{239}U was determined through the $^{238}\text{U}(\text{d}, \text{p}f)$ reaction in inverse kinematics at HELIOS (ANL) [10]. A stable ^{238}U beam at 8.6 MeV/nucleon impinged on a CD₂ target inside the 2.5 T solenoid; the protons emitted backwards from the (d, p) reaction were detected by an upstream silicon array, while the forward-focused fission fragments were detected by four downstream Multi-Wire Proportional Chambers (MWPCs) + Bragg detector arms. The layout is shown in Figure 9.25. This measurement is the direct precedent for the analysis presented here, and its method is summarised below before being adapted to IS739.

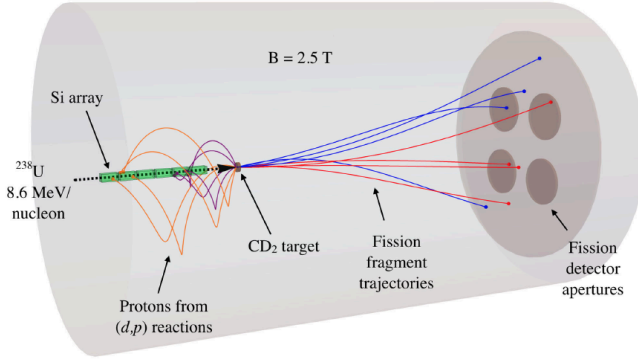


Figure 9.25: Detection setup of the $^{238}\text{U}(d, pf)$ experiment at HELIOS. Example proton trajectories (orange, purple) and fission-fragment trajectories (blue, red) are shown. Reproduced from Ref. [10].

The fission-barrier height was obtained by constructing the fission probability as a function of the excitation energy E_x of the compound nucleus, as reported in Eq. 3.1. Because the CD_2 target also contains carbon, both the singles and fission-gated spectra carry a smooth, featureless background, attributed to multinucleon transfer-induced fission on carbon in which light ejectiles reach the Si array. It was characterised from data taken with a pure C target: the C spectrum was scaled to the CD_2 spectrum in a region of matching shape and subtracted. The scaling can be fixed at negative E_x , where no genuine deuteron-induced reaction can contribute, so any yield there must come from carbon. The procedure is illustrated in Figure 9.26. From the carbon-subtracted spectra, the fission probability $P_f(E_x)$ was built and the barrier height read off from its rise around $E_x \approx B_f$, yielding $B_f = 6.42(12)$ MeV, consistent with the evaluated value of 6.46 MeV. The same strategy is adopted in the following subsection to extract the fission-barrier height of ^{233}U from the $^{232}\text{U}(d, pf)$ reaction measured in IS739.

9.5.1 Fission-Barrier extraction for $^{232}\text{U}(d, pf)$

To extract the fission barrier of ^{233}U , the excitation-energy spectra must be examined gated on the detection of one, or preferably two, fission fragments in coincidence. The first step towards this is the validation of the hits recorded in the upstream Si array.

As a first selection, only events with a single hit in the upstream Si array are retained, removing noise, scattering, and pile-up background and leaving the interaction point and energy unambiguously defined. Each DSSSD delivers

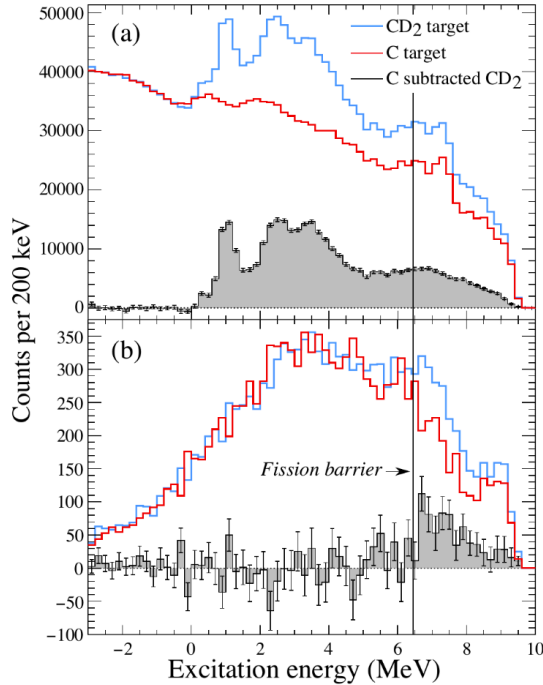


Figure 9.26: (a) Excitation-energy spectra for all Si-array events, measured with CD₂ and C targets, with the C data scaled onto the CD₂ data and the resulting carbon-subtracted CD₂ spectrum. (b) Same, but for events with ≥ 1 detected fission fragment. The vertical line marks the known fission-barrier height. Figure from Ref. [10].

an independent measurement of the interaction on its junction (p) and ohmic (n) sides. A genuine proton hit therefore deposits consistent signals on both sides, whereas random or noise-induced signals generally do not. Hits were validated by comparing the p - and n -side signals in both energy and time: for a real interaction, the two sides register the same energy and are correlated in time, so the distributions of $E_p - E_n$ and $t_p - t_n$ peak around a common value with a finite spread set by the detector resolution (Figure 9.27, top).

The time correlation, however, is not uniform in energy. The read-out ASICs of the silicon array switch the way the timestamp is derived at a fixed threshold of ~ 6 MeV: below this threshold the time is extracted from the energy branch, above it from the dedicated time branch. This is directly visible in the bottom panel of Figure 9.27, where the $t_p - t_n$ distribution is markedly broader below $E_p \approx 6$ MeV and sharpens abruptly above it, as the time branch takes over. The low-energy protons are precisely the ones of interest here, since they populate the higher excitation-energy states of ^{233}U ; imposing a tight coincidence window

on $t_p - t_n$ would preferentially reject them. For this reason, while a clean p - n match is required in energy, the tolerance on the time difference is deliberately relaxed, so as to retain the low-energy protons at the cost of a looser timing condition. A further feature of the bottom panel is that the centroid of the $t_p - t_n$ distribution drifts with energy, i.e. the timing carries a residual time-walk. The per-ASIC time-walk correction presented in Section 8.4.1 is therefore not sufficient; the correction has to be determined and applied for each individual strip.

This procedure also yields, as a by-product, cleaner E vs z and excitation-energy spectra. This is illustrated in Figure 9.28 (to be compared with Figure 9.2), which shows the E vs z distribution alongside the corresponding excitation-energy spectrum after the elliptical gate (Figure 9.27). The noise pedestal is thus suppressed together with the noisy strips discussed at the beginning of this chapter, so that a software threshold on the p -side energy is no longer required. The lower panel shows the E_x spectrum reconstructed from the cleaned E vs z matrix. The C-target contribution is subtracted after scaling, with the scaling factor computed as the ratio of counts in the $[-7.5, -2.5]$ MeV window of E_x , the unphysical negative-energy region where only background contributes. The subtraction is consistent with zero throughout the negative-energy region, confirming that the background is correctly normalised. Beyond the low-lying structures near $E_x \approx 0$ and ≈ 2 MeV, the spectrum may hint at an onset of fission above ~ 6 MeV.

To apply a fission requirement in the E_x spectra, coincidences between the good candidate hits in the Si array and hits in the ΔE layer of the fission-fragment telescope are requested, with the condition that the detected energy exceeds 150 MeV in the latter. The corresponding time difference is shown in Figure 9.29. The shaded band spanning -75 to 75 ns marks an additional coincidence gate applied to select prompt events; hits outside this time window are due to random coincidence background.

Figure 9.30 shows the resulting E_x spectra: the left panel includes all coincidences passing the p - n cut with $\Delta E > 150$ MeV, while the right panel additionally requires the prompt time gate $t_{\text{array}} - t_{\Delta E} \in [-75, 75]$ ns. The scaling factor is fixed as before, by matching the respective counts in the $[-7.5, -2.5]$ MeV range of E_x where only background is expected. Other approaches to determine this scaling factor could be used, for instance through the luminosity monitor instead.

In both cases, no statistically significant fission barrier is observed when gating on the ΔE detector. Possible explanations include:

- losses in the proton array, in particular the requirement of a p - n energy and time matching, with remaining time-walk;
- most of the statistics is actually due to carbon-induced background from a second, lighter beam component in addition to ^{232}U .

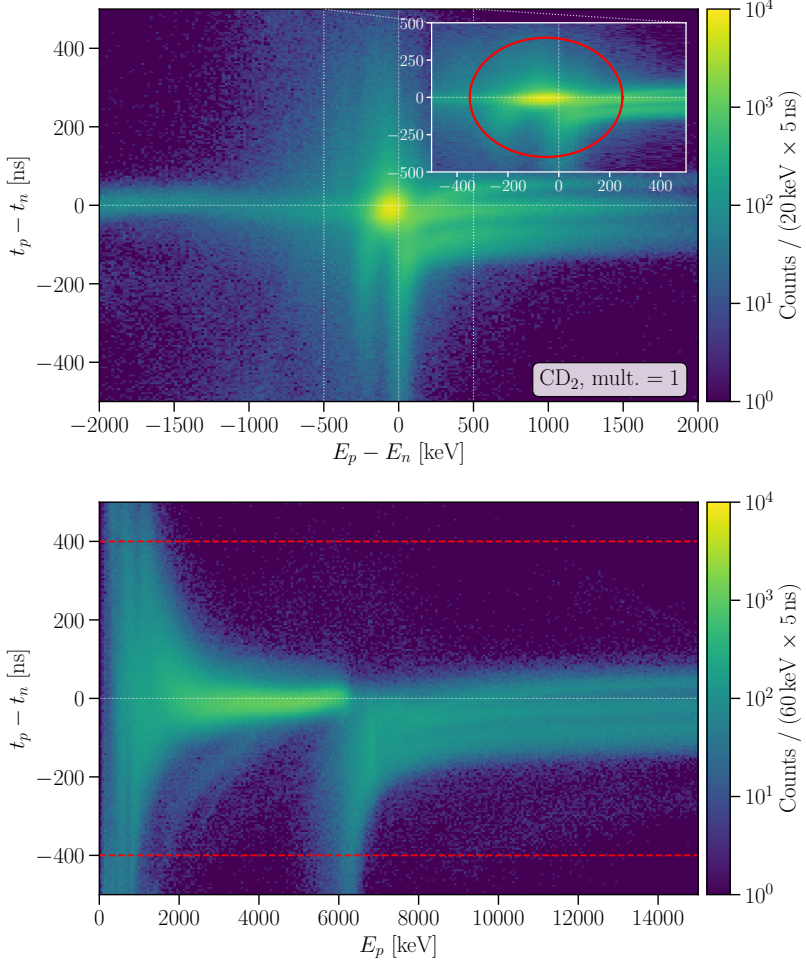


Figure 9.27: Matching of the p - and n -side signals for single-hit events in the upstream Si array (CD₂ target, multiplicity 1). *Top:* time difference $t_p - t_n$ versus energy difference $E_p - E_n$. Genuine hits form the intense spot around (0,0), while the horizontal and vertical ridges correspond to hits matched in only one observable and the diffuse background to uncorrelated random coincidences; the inset shows a magnified view of the central region, with the red circle marking the selected region. *Bottom:* $t_p - t_n$ versus p -side energy E_p . The time resolution degrades below $E_p \approx 6$ MeV, where the ASIC derives the timestamp from the energy branch rather than from the time branch, broadening the distribution; the dashed red lines indicate the time window retained. The energy dependence of the centroid reflects a residual time-walk that must be corrected strip by strip (not done in this analysis).

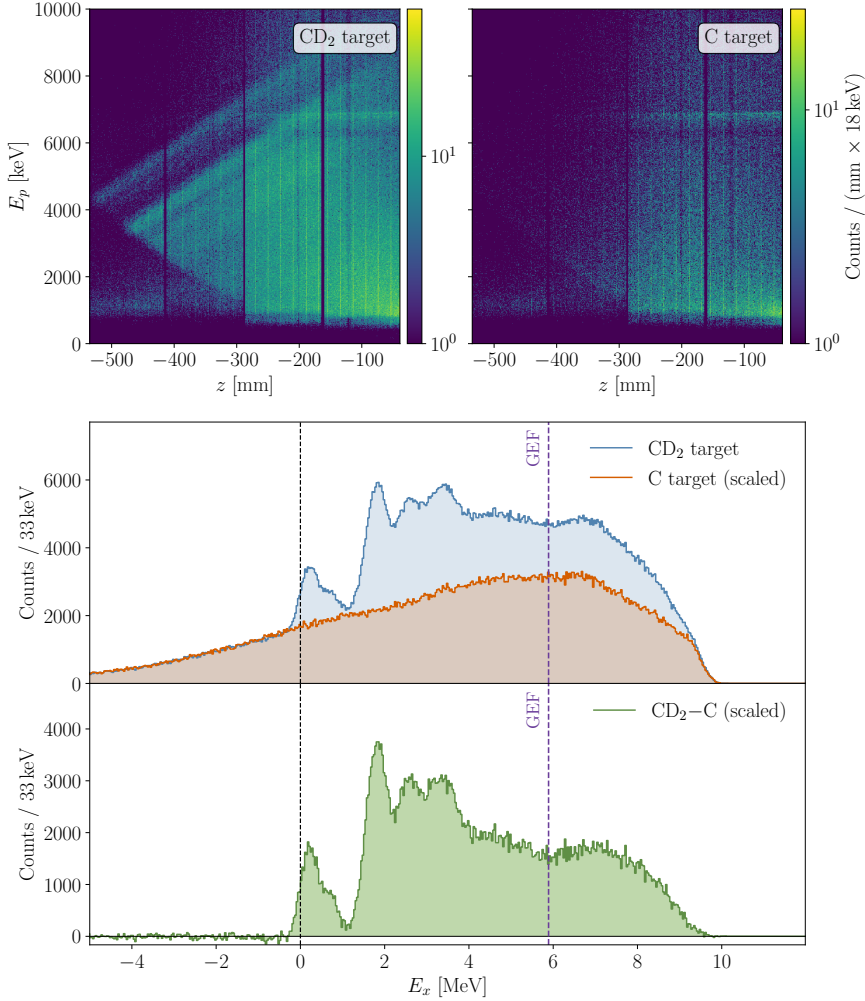


Figure 9.28: *Top:* E_p vs. z distributions for the CD_2 (left) and C (right) targets after the elliptical gate, with the noise pedestal and noisy strips thus suppressed. *Middle:* reconstructed E_x spectra for the CD_2 target (blue) and the scaled C target (orange). *Bottom:* the background-subtracted $\text{CD}_2 - \text{C}$ spectrum (green), obtained by subtracting the scaled C-target contribution. The scaling factor is fixed by matching the counts in the $[-7.5, -2.5]$ MeV window of E_x , where only background contributes; the subtraction is consistent with zero in this region. The black dashed line marks $E_x = 0$, and the purple dashed line indicates the fission-barrier value predicted by the GEF model.

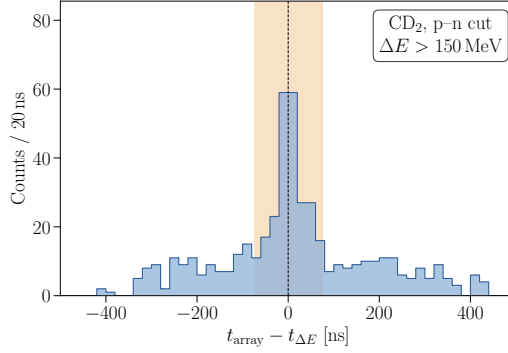


Figure 9.29: Time difference $t_{\text{array}} - t_{\Delta E}$ between good candidate hits in the Si array and hits in the ΔE layer of the fission-fragment telescope with detected energy above 150 MeV, for the CD_2 target (Figure 9.30, left). The shaded band (± 75 ns) indicates the gate applied for Figure 9.30, right.

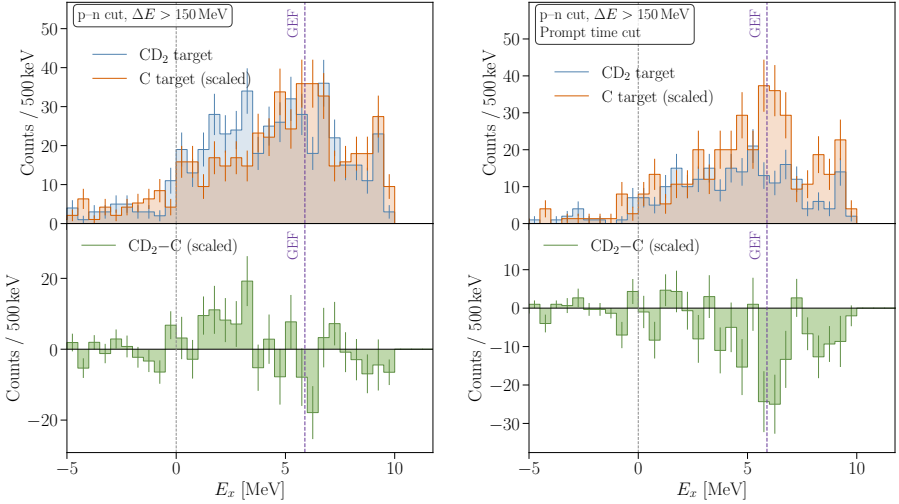


Figure 9.30: Excitation-energy spectra of Figure 9.28 after the p-n elliptical cut and $\Delta E > 150$ MeV condition. *Left:* all coincidences; *right:* same, additionally requiring the prompt time gate $t_{\text{array}} - t_{\Delta E} \in [-75, 75]$ ns. *Top:* CD_2 target (blue) and scaled C target (orange). *Bottom:* background-subtracted CD_2 -C spectrum (green). Requiring the tighter time coincidence removes the excess around 2 MeV in the left subtracted spectrum, leaving no significant structure above background.

Disentangling these two effects requires a dedicated study of the array response at low proton energies, together with a quantitative characterisation of the beam composition and its second component; both are beyond the scope of the present analysis. The determination of $P_f(E_x)$ and of the barrier height itself depends on the subtraction of the carbon component of the target and on the unambiguous selection of fission events, both of which are still in progress.

Chapter 10

Conclusions and outlook

THIS thesis set out to establish a new experimental route to the fission barriers of neutron-rich actinides, in a region of the nuclear chart that conventional fission measurements cannot reach because they require the fissioning species itself as a target. The strategy developed here combines three ingredients. The first is a heavy radioactive ion beam from the ISOLDE facility. The second is the (d, pf) transfer reaction, which populates the fissioning nucleus above its barrier while tagging the event through a single backward-emitted proton. The third is a solenoidal spectrometer, whose field allows for reconstructing the proton energy and interaction point with a resolution that mitigates the kinematic compression and shift limiting ordinary inverse-kinematics measurements. The distinctive feature of the approach is the sharp, event-by-event excitation-energy tag provided by the ejected proton of a clean two-body reaction: unlike Coulomb-excitation or multinucleon-transfer techniques, which populate a distribution of E_x or reconstruct it from multi-body kinematics, the (d, pf) channel fixes the excitation energy of a directly selected fissioning system. IS739 constitutes the first application of this technique to the $^{232}\text{U}(d, p)$ and $^{232}\text{U}(d, pf)$ reactions, extending to an ISOL radioactive-beam facility the proof of principle carried out with a stable beam at HELIOS.

The analysis presented in the preceding chapters is still ongoing, and the results reported here reflect the current understanding of the data rather than a final interpretation. The analysis has proven considerably more complex than anticipated on the basis of the analogous HELIOS experiment [10]. The following should therefore be read as the present status of the project, with several aspects still open to refinement.

Two main results have been reached. First, the fission fragments detected in the annular silicon telescope can be resolved in nuclear charge. Starting from the ΔE – E energy-loss correlation and using ATIMA-based reference curves, a per-ring calibration assigns each fragment a pseudo-charge Z' , and the aligned

distribution reproduces the charge bands consistently across the detector. In coincidence events, where both complementary fragments are identified, the sum $Z'_1 + Z'_2$ forms a narrow peak for the CD_2 target, absent for the pure carbon target, confirming that a genuine charge correlation between the two fragments of a single fission event is being observed. What is not yet available is an *absolute* charge identification: the large gap between the scattered-carbon line and the fission-fragment region, together with the tight band spacing, prevents a direct counting of the bands, so the offset between Z' and the true atomic number can only be inferred indirectly. A comparison of the measured $Z'_1 + Z'_2$ centroid with the expected uranium fissioning system favours an offset of two charge units, but this assignment remains tentative.

Second, the missing-mass reconstruction yields clean excitation-energy spectra once the upstream silicon hits are validated through their $p - n$ energy and time correlation. The determination of $P_f(E_x)$ and of the barrier height itself depends on the subtraction of the carbon component of the target, and on the unambiguous selection of fission events, both of which are work in progress. The role of a second component in the beam, currently not identified and possibly dominating the spectra, has complicated the analysis. Nevertheless, the present spectra already show a hint of the rise in fission probability expected around the barrier, motivating a continuation of the analysis.

10.1 Outlook

The analysis opened by this thesis can be advanced along several lines, some consolidating the present results and other exploring alternative handles that the data have only begun to reveal.

- **Detector-level improvements.** A per-strip time-walk calibration of the upstream silicon array and a refined time alignment of the fission fragment telescope would allow to tighten the coincidence gates and remove more random coincidences, which currently limit the cleanliness of the fission-gated excitation-energy spectra.
- **Background identification and subtraction.** A more accurate characterisation of the carbon-induced background, and of the scaling factor used to subtract the C-target spectrum from the CD_2 data, is central to the barrier extraction. Alternative estimates of the scaling factor, for instance through the luminosity monitor instead of anchored to the region of negative reconstructed E_x .
- **Simulation of the detector response.** A full simulation of the telescope response to fission fragments based on GEF could allow the measured energies to be converted into total kinetic energies and the acceptance bias towards near-symmetric splits to be modelled quantitatively.

- **Total kinetic energy as a discriminant.** Because the annular telescope samples most efficiently the near-symmetric region, where the transfer signal and the fusion–fission background differ most in TKE, a reconstruction of the TKE in this region could provide an independent, statistical discriminant between the two contributions.
- **Coincident two-fragment gating.** Building the excitation-energy spectrum gated on the coincident detection of both fission fragments, rather than a single one, could further suppress the background.
- **The γ -ray channel.** The CeBr₃ signals recorded in coincidence open the possibility of extracting the fission barrier with a tag on the γ -ray multiplicity. The multiplicity is an observable sensitive to the onset of fission that is complementary to the fragment-based determination.
- **Absolute charge calibration.** Establishing the offset between the pseudo-charge Z' and the true atomic number on a firmer basis, beyond the tentative two-unit shift inferred.
- **Identification of the beam contaminant(s).** A likely beam contaminant, or contaminants, remains to be identified. The significant difference in TKE visible in Figures 9.4, 9.5 and 9.7 is at present a puzzle and needs to be understood before future experiments.
- **Detection efficiencies.** The detection efficiencies for protons, for fission fragments, and for their coincidence still need to be determined. Given the strong effect of the gates on the excitation-energy spectra, this could prove to be a crucial ingredient of the analysis.
- **Absolute cross sections.** Deuteron breakup has to be taken into account in order to convert the measured yields into absolute cross sections.

Taken together, these directions indicate that the data recorded in IS739 carry more information than the present analysis has yet extracted. The method has been shown to work end to end, from a radioactive-beam-adjacent species to charge-resolved fission fragments tagged by a sharp excitation energy; turning this into a quantitative fission barrier, and ultimately extending the technique towards the genuinely neutron-rich actinides relevant to the r-process, is the natural continuation of the work begun here.

This is not the end — it is only the beginning...

Appendix A

Scaling factor and beam rates

Beam rates required to probe the fission barrier of ^{230}Ac were estimated based on data from a previous experiment conducted at ANL. In that experiment, a stable ^{238}U beam with an energy of 8.6 MeV/u and an average intensity of 10^6 particles per second (pps) was employed over seven days [10]. This empirical approach to estimating beam rates was adopted because theoretical methods, such as DWBA calculations, rely on assumptions that are less reliable due to the limited knowledge of the structure of ^{230}Ac at the excitation energies of interest. To reach the same significance level, determining the fission barrier height of ^{230}Ac requires obtaining 100 counts above the barrier per energy bin of 0.2 MeV (see Fig. 2 in Ref. [10]). However, whereas the fission probability P_f is 20% for ^{239}U , the predicted value drops to 3% for ^{230}Ac [8]. Therefore, beam rate estimates for ^{230}Ac were accordingly scaled by weighting the beam intensity of the previous experiment with the relative fission probabilities.

Compared to the previous experiment, a gain of a factor of 16 per incident ion is expected due to the following improvements:

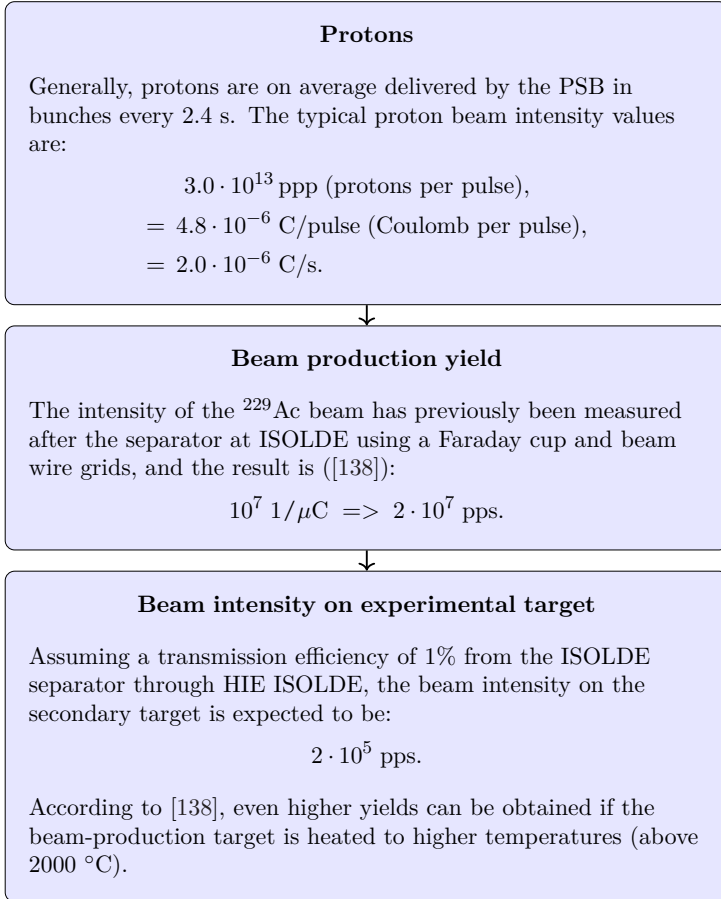
- Detection system: Replacing the gaseous fission fragment detectors, consisting of four detection arms, each combining a position-sensitive MWPC and a Bragg (FIFI) detector for fragment identification, with annular-shaped DSSSDs (see Section 3.4). This provides a factor of 8 gain due to the larger angular coverage of the DSSSDs.
- Target thickness: Using a CD_2 target twice as thick (1 mg/cm^2 instead of $500 \text{ } \mu\text{g/cm}^2$). This contributes an additional factor of 2 gain.

Table A.1 presents the estimated beam intensities required to unambiguously determine the fission barrier heights for both isotopes under these improved conditions. Finally, the flow diagram below summarizes the scaling used to estimate the beam intensity required to measure the fission barrier height of

Setting	Isotope	P_f (%)	Target ($\mu\text{g}/\text{cm}^2$)	Est. req. beam int. (pps)
ANL	^{239}U	20	500	10^6
ISS (scaled)	^{239}U	20	1000	$1/16 \cdot 10^6 = 6.3 \cdot 10^4$
ISS (scaled)	^{229}Ac	3	1000	$20/3 \cdot 1/16 \cdot 10^6 = 4.2 \cdot 10^5$

Table A.1: Estimated beam intensity on the experimental target required to determine the fission barrier heights of ^{239}U and ^{229}Ac , comparing the setup at ISS with the reference experiment performed at ANL.

^{230}Ac with a radioactive beam produced at ISOLDE for the same one-week data-taking period.



Appendix B

Least-Squares formalism of the Millepede II algorithm

The foundation of **Millepede II** lies in the linear least-squares method applied to problems with a special parameter structure. What follows is based on the **Millepede II** draft manual [163].

Consider a set of measurements y_i with associated uncertainties σ_i . Each measurement can be described by a model function that depends on both local parameters $\mathbf{q}$ and global parameters $\mathbf{p}$:

$$y_i = f(x_i, \mathbf{q}, \mathbf{p}) + \varepsilon_i, \quad (\text{B.1})$$

where x_i is the coordinate of the measurement, ε_i is the measurement error with standard deviation σ_i , $\mathbf{q}$ represents the local parameters (valid only for a specific subset of measurements), and $\mathbf{p}$ represents the global parameters (appearing in all measurements). In the context of detector calibration, $\mathbf{p}$ corresponds to the sought calibration parameters, and $\mathbf{q}$ are event-wise reconstruction parameters that are needed to mimic enough reconstruction to make the connections between measured values through the model f .

We show how the input required by **Millepede** arises by considering the typical use case, where the sought global parameters are detector locations and the (per-event) local parameters are track parameters. The least squares objective function to be minimized is:

$$\chi^2 = \sum_i \frac{(y_i - f(x_i, \mathbf{q}, \mathbf{p}))^2}{\sigma_i^2}. \quad (\text{B.2})$$

For a linear or linearized problem, consider the residual, i.e. the difference between a measured value and the expected value given the local track parameters, $r_i = y_i - f(x_i, \mathbf{q}, \mathbf{p})$. In terms of corrections $\Delta\mathbf{q}$ and $\Delta\mathbf{p}$ to the initial parameter values, the residual can be expressed as:

$$r_i = \sum_{j=1}^{\nu} \frac{\partial f_i}{\partial q_j} \Delta q_j + \sum_{\ell=1}^n \frac{\partial f_i}{\partial p_\ell} \Delta p_\ell, \quad (\text{B.3})$$

where ν is the number of local parameters and n is the number of global parameters.

In fact, the input to **Millepede II** is numerical only: the residuals and estimated uncertainties r_i , σ_i , as well as the derivatives describing how the model function varies with respect to the local and global parameters, $\frac{\partial f_i}{\partial q_j}$ and $\frac{\partial f_i}{\partial p_\ell}$.

B.1 Normal Equations for Local Parameters

For a single local fit object (e.g., a track) with ν local parameters $\mathbf{q} = (q_1, \dots, q_\nu)^T$, ignoring global parameters momentarily, the χ^2 stationarity conditions and their linearisation give

$$\frac{\partial \chi^2}{\partial q_j} = 0 \quad \forall j \Rightarrow \sum_i \frac{1}{\sigma_i^2} \frac{\partial f_i}{\partial q_j} r_i = 0 \Rightarrow \sum_k \underbrace{\sum_i \frac{1}{\sigma_i^2} \frac{\partial f_i}{\partial q_j} \frac{\partial f_i}{\partial q_k} \Delta q_k}_{(\Gamma)_{jk}} = \underbrace{\sum_i \frac{1}{\sigma_i^2} \frac{\partial f_i}{\partial q_j} r_i}_{\beta_j}, \quad (\text{B.4})$$

where i runs over the measurements and $j, k = 1, \dots, \nu$ index the local parameters. In matrix form it reads

$$\mathbf{\Gamma} \Delta \mathbf{q} = \boldsymbol{\beta}, \quad \mathbf{\Gamma} \in \mathbb{R}^{\nu \times \nu}, \quad \boldsymbol{\beta} \in \mathbb{R}^\nu. \quad (\text{B.5})$$

B.2 Coupled System with Global Parameters

Let there be N local fit objects (tracks), each with ν local parameters $\mathbf{q}_t$ ($t = 1, \dots, N$), and n global (alignment) parameters $\mathbf{p} = (p_1, \dots, p_n)^T$. For a measurement i belonging to local object t , the predicted value f_i depends on both $\mathbf{q}_t$ and $\mathbf{p}$. The complete system of normal equations takes the block-matrix form

$$\begin{pmatrix} \mathbf{C} & \mathbf{G}_1^T & \mathbf{G}_2^T & \cdots & \mathbf{G}_N^T \\ \mathbf{G}_1 & \mathbf{\Gamma}_1 & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{G}_2 & \mathbf{0} & \mathbf{\Gamma}_2 & \cdots & \mathbf{0} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{G}_N & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{\Gamma}_N \end{pmatrix} \begin{pmatrix} \Delta \mathbf{p} \\ \Delta \mathbf{q}_1 \\ \Delta \mathbf{q}_2 \\ \vdots \\ \Delta \mathbf{q}_N \end{pmatrix} = \begin{pmatrix} \sum_{t=1}^N \mathbf{g}_t \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_N \end{pmatrix}. \quad (\text{B.6})$$

Note that $\Delta \mathbf{p}$ are the sought global calibration parameter corrections, while $\Delta \mathbf{q}$ are the local track parameter adjustments, which will not be explicitly solved for. The blocks are assembled from per-measurement contributions:

$$\mathbf{C} = \sum_{\ell} \mathbf{C}_{1\ell} = \sum_i \frac{1}{\sigma_i^2} \mathbf{a}_i \mathbf{a}_i^T \quad (n \times n), \quad (\text{B.7})$$

$$\mathbf{\Gamma}_t = \sum_{i \in t} \frac{1}{\sigma_i^2} \mathbf{b}_i \mathbf{b}_i^T \quad (\nu \times \nu), \quad (\text{B.8})$$

$$\mathbf{G}_t = \sum_{i \in t} \frac{1}{\sigma_i^2} \mathbf{b}_i \mathbf{a}_i^T \quad (\nu \times n), \quad (\text{B.9})$$

$$\mathbf{g}_t = \sum_{i \in t} \frac{1}{\sigma_i^2} \mathbf{a}_i r_i \quad (n), \quad (\text{B.10})$$

$$\beta_t = \sum_{i \in t} \frac{1}{\sigma_i^2} \mathbf{b}_i r_i \quad (\nu), \quad (\text{B.11})$$

where the vectors

$$\mathbf{a}_i = \frac{\partial f_i}{\partial \mathbf{p}} \in \mathbb{R}^n, \text{ and} \quad (\text{B.12})$$

$$\mathbf{b}_i = \frac{\partial f_i}{\partial \mathbf{q}} \in \mathbb{R}^\nu \quad (\text{B.13})$$

are the derivatives of the prediction f_i with respect to the global and local parameters, i.e. the global and local Jacobian rows for measurement i .

$\mathbf{\Gamma}_t$ and β_t are the local matrix and right-hand side for track t ; $\mathbf{G}_t$ couples the local and global parameters; $\mathbf{C}$ is the global block built from the global derivatives $\partial f / \partial \mathbf{p}$; and $\mathbf{g}_t$ is the global right-hand side, i.e. the global counterpart of β_t .

B.2.1 Reduction to a global system-only

The key feature of the algorithm is the exploitation of the block-diagonal structure of the problem. The local blocks $\mathbf{\Gamma}_t$ are mutually independent and appear only on the diagonal, so each local correction can be expressed in terms of $\Delta \mathbf{p}$ alone and eliminated, leaving an $n \times n$ system in the global parameters. From the t -th local row,

$$\mathbf{G}_t \Delta \mathbf{p} + \mathbf{\Gamma}_t \Delta \mathbf{q}_t = \beta_t \Rightarrow \Delta \mathbf{q}_t = \mathbf{\Gamma}_t^{-1} (\beta_t - \mathbf{G}_t \Delta \mathbf{p}). \quad (\text{B.14})$$

Substituting into the global (top) row $\mathbf{C} \Delta \mathbf{p} + \sum_t \mathbf{G}_t^T \Delta \mathbf{q}_t = \sum_t \mathbf{g}_t$ gives

$$\boxed{\tilde{\mathbf{C}} \Delta \mathbf{p} = \tilde{\mathbf{g}}} \quad (\text{B.15})$$

with

$$\tilde{\mathbf{C}} = \mathbf{C} - \sum_{t=1}^N \mathbf{G}_t^T \mathbf{\Gamma}_t^{-1} \mathbf{G}_t, \quad (\text{B.16})$$

$$\tilde{\mathbf{g}} = \sum_{t=1}^N \mathbf{g}_t - \sum_{t=1}^N \mathbf{G}_t^T \mathbf{\Gamma}_t^{-1} \boldsymbol{\beta}_t. \quad (\text{B.17})$$

The reduced matrix $\tilde{\mathbf{C}}$ is $n \times n$ regardless of the number of tracks. The local inversions $\mathbf{\Gamma}_t^{-1}$ are independent and can be computed in parallel. The solution

$$\Delta \mathbf{p} = \tilde{\mathbf{C}}^{-1} \tilde{\mathbf{g}} \quad (\text{B.18})$$

is the correction to the global parameters, with covariance $\tilde{\mathbf{C}}^{-1}$.

For a typical alignment problem with $n \sim 10^5$ global parameters and $N \sim 10^6$ tracks (for large-scale detector systems like CMS [164]), this reduction is essential. The local inversions can be parallelised, making the algorithm computationally efficient even at large scale. The solution is iterative: at each step the detector geometry is updated with $\Delta \mathbf{p}$, tracks are refitted, and outliers are progressively removed by tightening residual cuts. Convergence is typically reached within a few iterations.

Appendix C

Ring-by-ring charge-identification plots

In the charge-identification section (Section 9.3) the ΔE – E correlations, the interpolated-charge spectra and the linear calibrations were shown only for a few representative rings. For completeness, the corresponding plots for the full set of rings are collected here. The ring-dependent behaviour discussed in the main text—the shift of the correlation towards lower deposited energy and the narrowing of the resolved charge range with increasing ring ID—is visible across the whole detector.

As shown in Figure C.1, the ΔE – E correlation retains a well-populated fission-fragment band only up to Ring 19: from Ring 20 onwards the statistics collapse and the band is no longer discernible, consistent with the loss of acceptance at the largest entrance angles. For this reason, only the first 20 rings (Ring 0 to Ring 19) were retained in the fission-fragment analysis of Section 9.3.

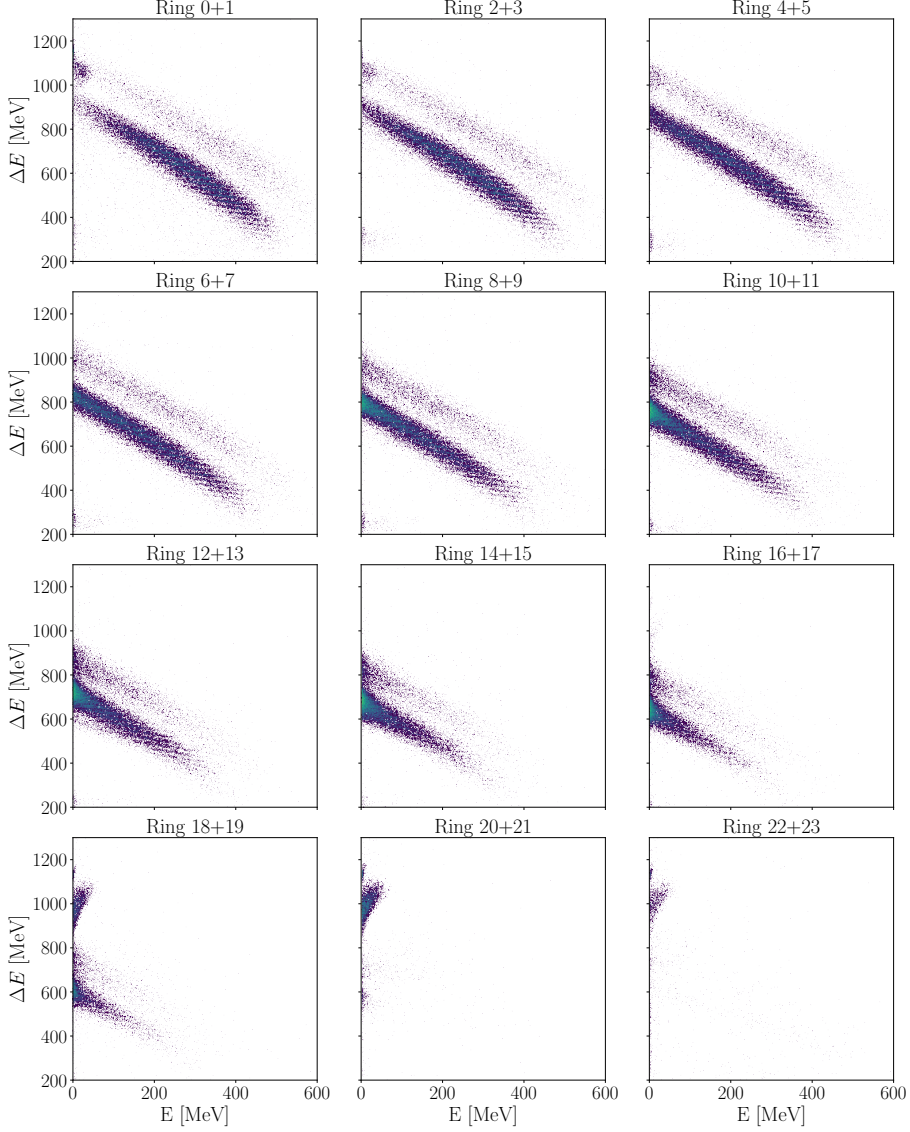


Figure C.1: Experimental ΔE – E correlations for all ring pairs, from Ring 0+1 to Ring 22+23. Rings are paired here only for visualization; they were treated individually in the analysis. As the ring ID increases, the correlation band shifts towards lower E and shortens: at the highest rings (from $\sim$ Ring 18+19) the fragments are increasingly stopped in the ΔE layer, leaving almost no punch-through and no usable $\Delta E - E$ correlation.

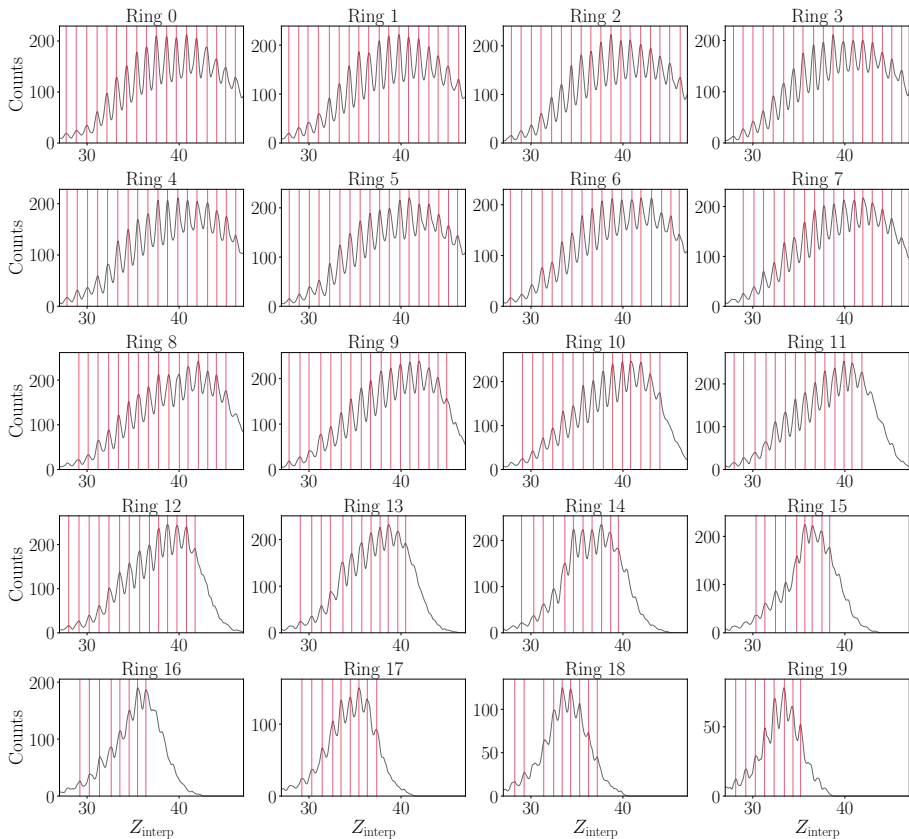


Figure C.2: Interpolated-charge (Z_{interp}) spectra for all rings (Ring 0 to Ring 19). Vertical red lines mark integer- Z positions. The charge peaks are resolved in every ring, but both the accessible charge range and the peak sharpness degrade with increasing ring ID, consistent with the larger effective dead-layer thickness at larger entrance angles.

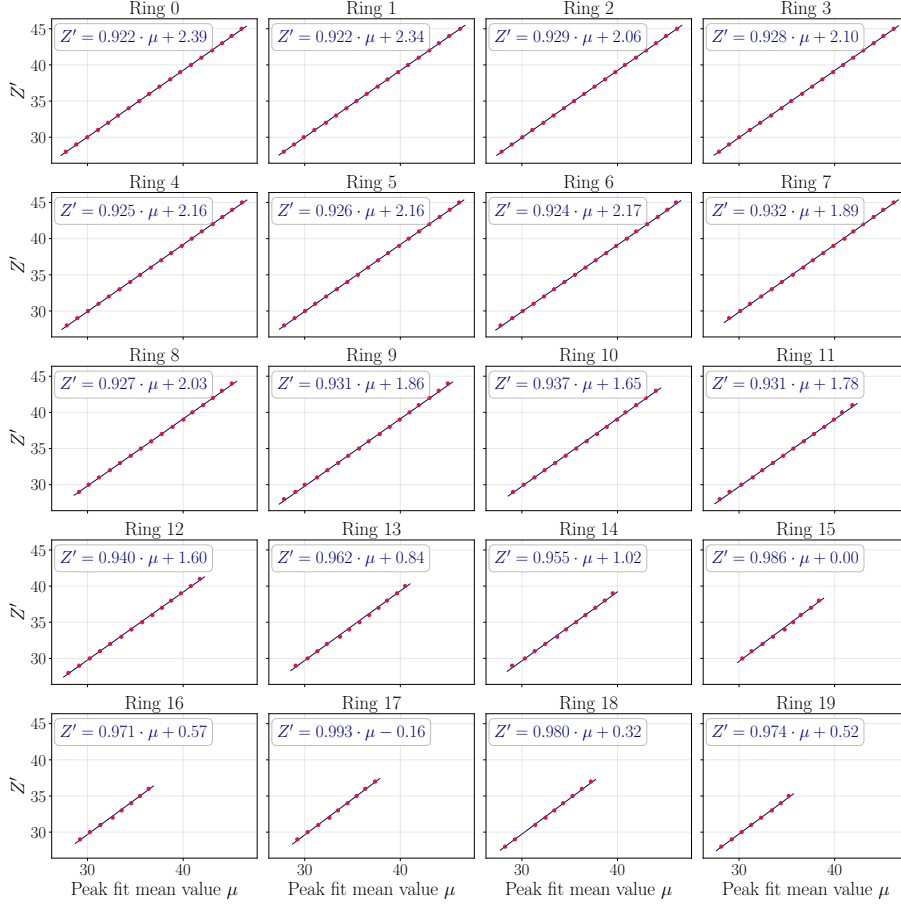


Figure C.3: Linear charge calibration $Z' = \text{gain} \cdot \mu + \text{offset}$ for all rings (Ring 0 to Ring 19), relating the fitted peak positions μ to the assigned integer pseudo-charge Z' . The fitted gains and offsets are reported in each panel. The number of calibration points decreases at higher ring ID, reflecting the reduced number of resolved charge peaks.

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