20TH RUSSBACH SCHOOL ON NUCLEAR ASTROPHYSICS

EXPLORING THE ISLAND OF STABILITY: SYNTHESIZING SUPER-HEAVY ELEMENTS BEYOND Z = 118

RIKEN Institute Nishina Center for Accelerator-Based Science
nSHE Collaboration

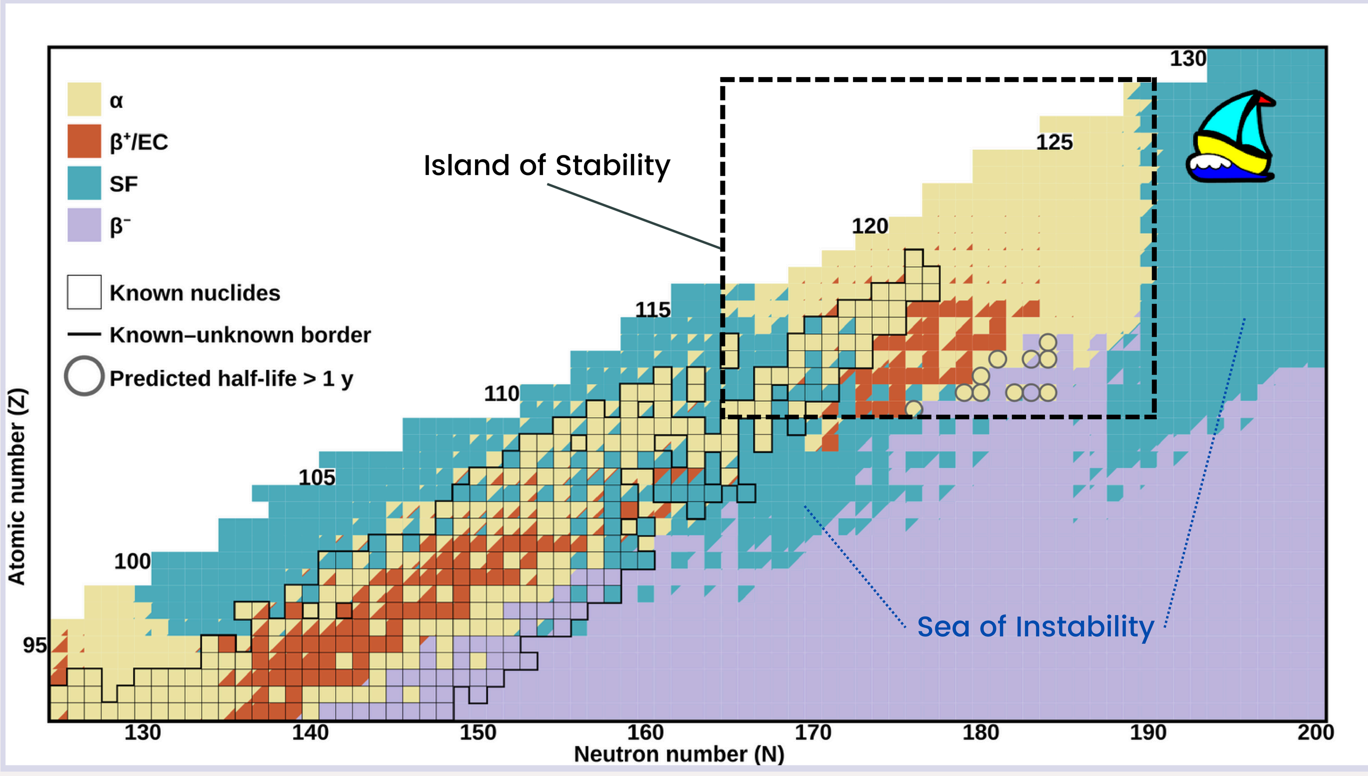
Linda Müller
PhD Student at IPHC
23 rue du Loess,
Strasbourg, France
Contact:
linda.muller@iphc.cnrs.fr

INTRODUCTION

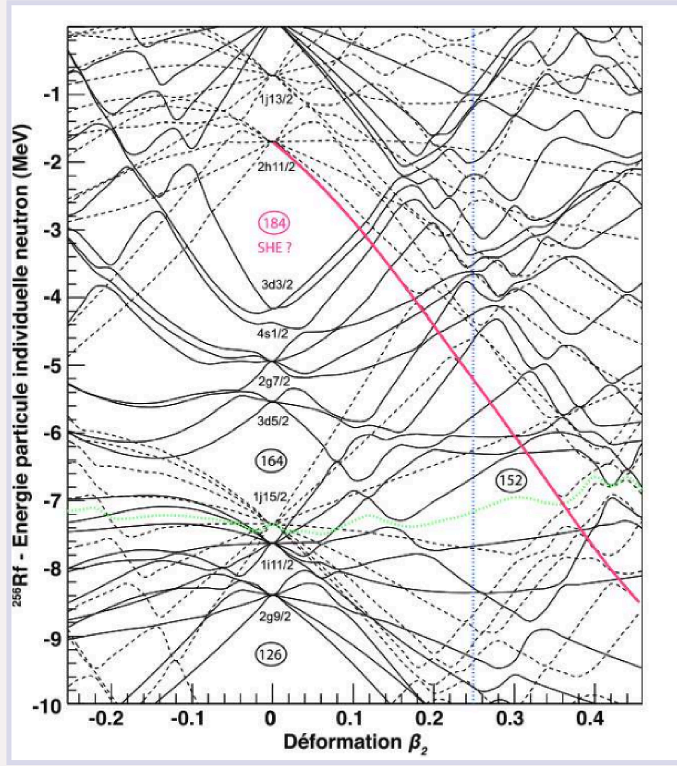
The liquid drop model no longer predicts a nuclear potential well for elements **beyond Z = 104**, making the existence of bound states for **Super-Heavy Elements** (SHE) remarkable.

To this day, SHE have been successfully synthesized up to Oganesson (Z = 118). Their existence hinges solely on **quantum mechanical effects**, particularly **nuclear deformation** into elongated (prolate) or flattened (oblate) shapes. These deformations shift certain spherical orbitals to lower energies, making the deformed nucleus more stable than its spherical counterpart.

The **island of stability** refers to the region near yet unknown **shell closures** in SHE, where certain nucleon configurations exhibit increased stability. These nuclei are located in a **sea of instability**, where neighboring isotopes undergo **rapid spontaneous fission**. Locating this region by synthesizing elements 119, 120 and beyond plays a crucial role in extending our understanding of nuclear structure and stability.



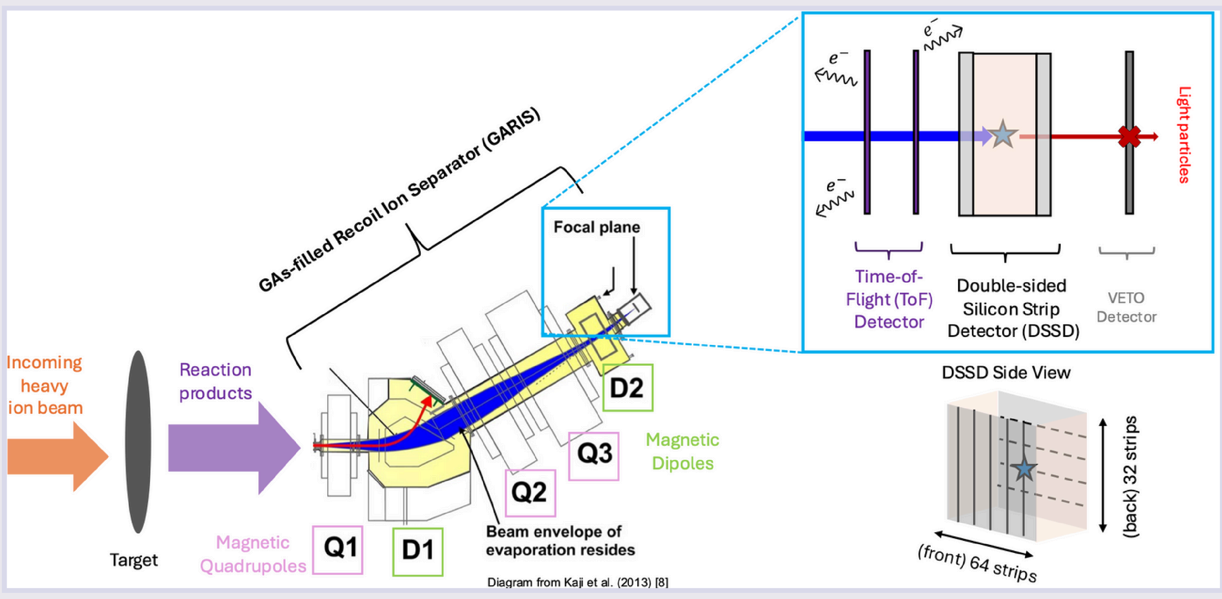
A diagram depicting the main decay modes of nuclei around the super-heavy (Z > 103) mass area, illustrating the idea of an island of stability floating in an ocean of spontaneous fission. Adapted from [1]



This Nilson diagram depicts the next predicted neutron shell closures with respect to the quadrupole deformation parameter β2 [2].

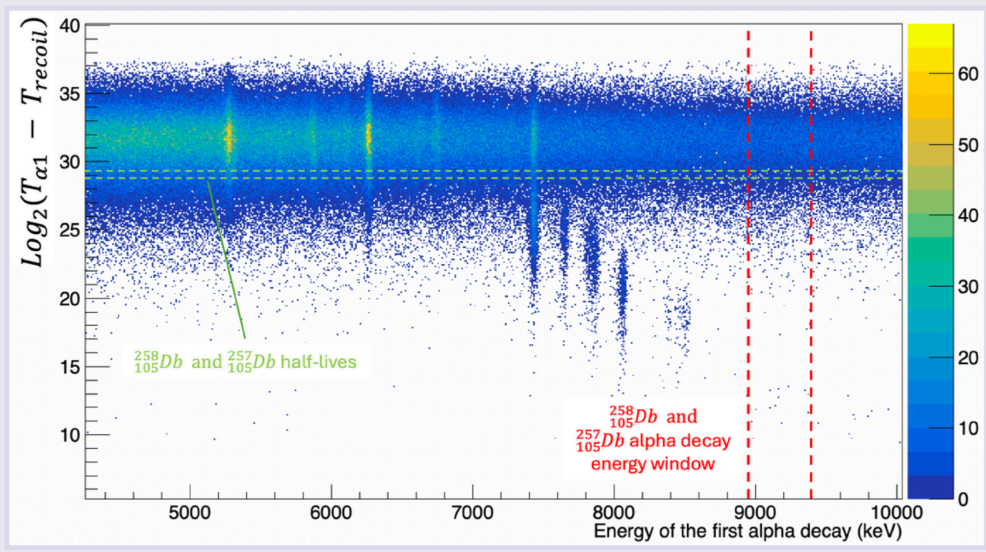
CREATING AND IDENTIFYING SUPER-HEAVY ELEMENTS

SHE are synthesized via **fusion-evaporation.** A beam of heavy ions strikes a rotating target, forming a **compound nucleus** in an excited state that releases its excess energy by evaporating neutrons. Reaction products are separated using magnetic dipoles (D) and quadrupoles (Q) in a Q-D-Q-Q-D formation (see figure below), which steer nuclei based on their **mass-to-charge ratio and velocity**. The implantation detector is a **Double-Sided Strip Silicon Detector (DSSD)** divided into **pixels** so nuclei may be identified through a space-time correlation.

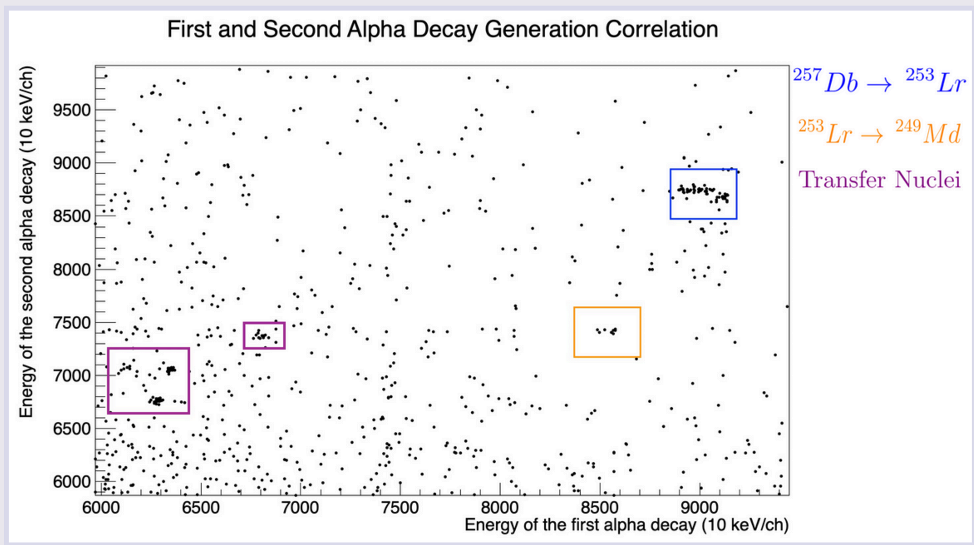


The experimental setup at the RIKEN Institute (Wako City, Japan) that is currently used to synthesize element 119. GARIS Diagram extracted from [3].

A 2D plot representing a recoil nucleus' **decay energy with respect to its decay time** can be used to identify events of interest. For **rare events**, however, as can be seen in the figure below (left), the nuclei of interest are drowned in a background of parasite reactions. They can be revealed on a **genetic correlation matrix** (right), which is a 2D plot correlating, for a given recoil nucleus, the decay energies of the daughter and grand-daughter nuclei.



The 2D plot representing the decay time of Dubnium isotopes with respect to their decay energy. The isotopes should appear in the box outlined by the dashed lines but are too few to be distinguishable from the background [4].



The genetic correlation matrix highlighting the decay of Dubnium isotopes into Lorenzium, then Mendelevium. In contrast to the previous plot, the events of interest can be distinguished with the naked eye. Transfer nuclei, nuclei that originate from the transfer of but a few nucleons between beam and target, also appear visible [4].

MAXIMISING THE CHANCES OF DETECTION

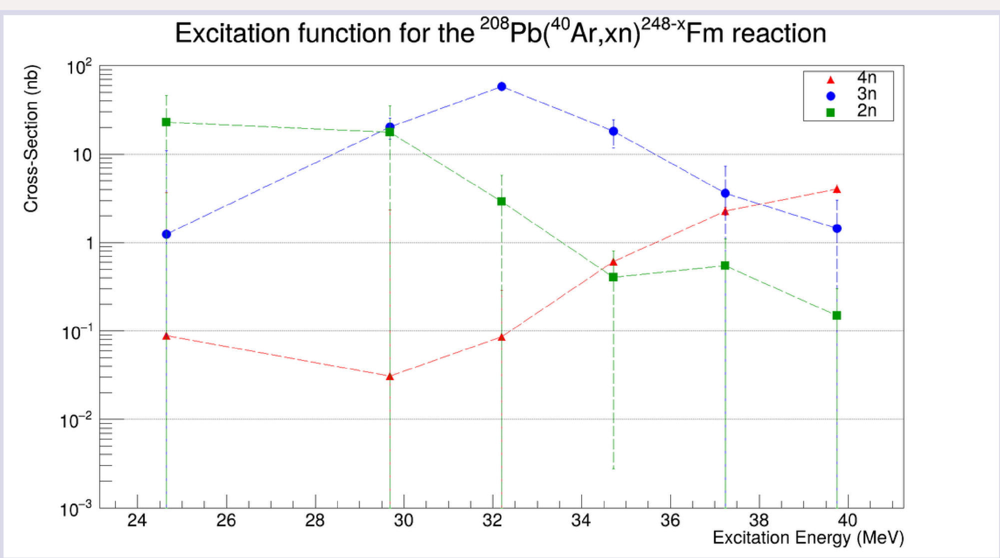
To synthesize **element 119**, the RIKEN Institute's Nishina Center (RNC) underwent a facility upgrade in 2016. This process included the original LINAC's transformation into a super-conducting LINAC capable of accelerating heavy ions up to 6.5 MeV/u, warranting the construction of a copy of the RNC's **Gas-Filled Recoil Ion Separator** (GARIS), and the introduction of **digital electronics** inside the detection system [4]. While RIKEN has focused their super-heavy element research program on element 119, Berkeley Lab (California, USA) is currently undertaking the production of **element 120**.

CHARACTERIZING THE SEPARATOR

To characterize the copy of GARIS and ensure its optimal performance, an excitation function was plotted using the following reaction [4].

$$^{40}Ar + ^{208}Pb \longrightarrow \ ^{248-x}Fm + xn$$

An **excitation function** compares the production cross-section of different evaporation channels with the excitation energy of the compound nucleus at mid-target. For the above reaction, the 4n, 3n and 2n evaporation channel cross-sections were compared for six different beam energies.



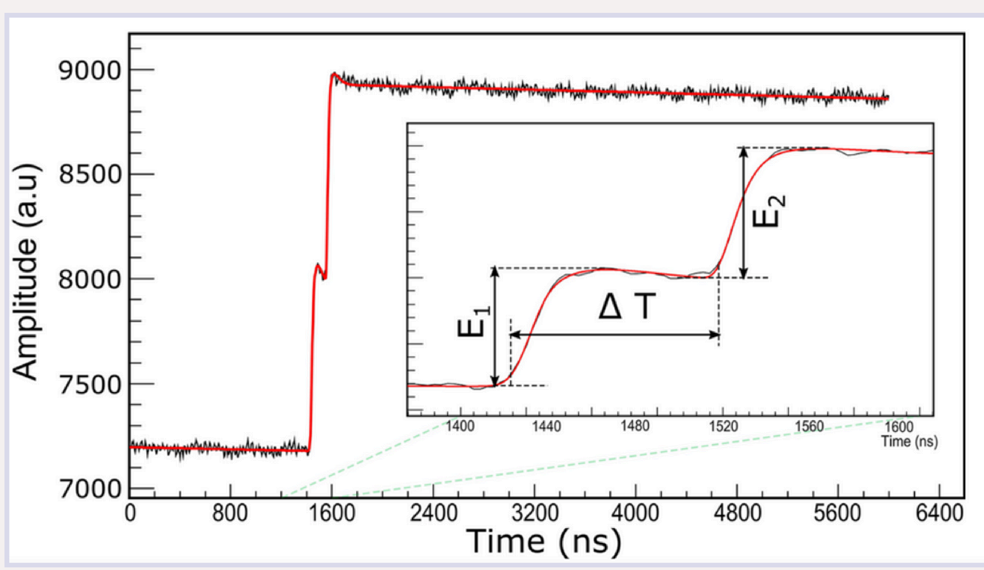
The excitation function used to characterize the copy of GARIS-II, highlighting the relationship between beam energy, production cross-section and most favorable evaporation channel of a given reaction [4].

Excitation functions are powerful tools for selecting the beam energy that maximizes the cross-section of the desired evaporation channel. While these functions cannot be directly plotted for unknown elements, extrapolating data from lighter elements to element 119 and beyond helps to validate theoretical models and refine beam energy calculations for the production of new super-heavy elements.

DIGITAL ELECTRONICS

Compared to their analog counterpart, digital electronics have two advantages, namely: the reduction of detector dead-time and the improvement of energy resolution.

DECOMPOSING PILE-UP PULSES



A pile-up pulse recorded using digital electronics. Despite being separated by only 100 ns, the two energies can be extracted, which is not possible for analog systems [5].

If a second event occurs before the pre-amplifier returns to baseline, a pile-up event occurs. In analog systems, such events go undetected, but in digital systems, where individual traces are recorded, pile-up pulses can be decomposed, allowing both energies to be recovered.

This capability is crucial for the synthesis of element 119, where every event matters. The digital system's dead time is as low as 100 ns—dramatically shorter than the 60 µs of its analog predecessor—ensuring fewer missed detections.

IMPROVED ENERGY RESOLUTION

Recording individual traces also enables more precise pulse amplitude measurements, which are directly proportional to an event's energy. Unlike analog systems, where amplitude is extracted from a simple fit, the trace can be transformed into a flat-top shape—such as a trapezoid—using a recursive algorithm known as the Jordanov algorithm. The flat top and well-defined baseline make amplitude measurement significantly more accurate and reliable.

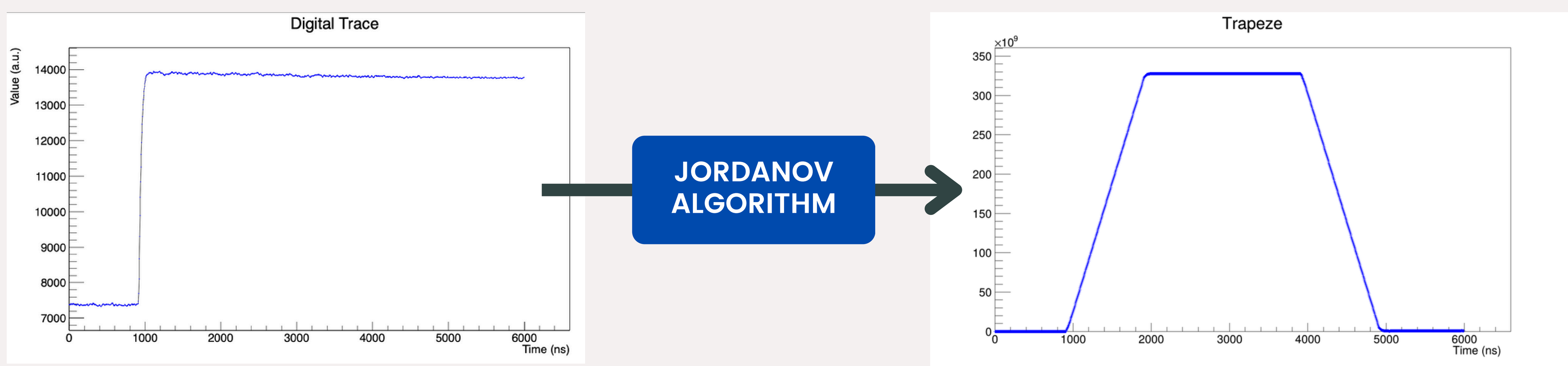


Illustration of the transformation of a digital trace into a flat-top trapezoid using the recursive Jordanov algorithm for a more precise amplitude measurement [4].

REFERENCES

[1] Wikipedia Commons, derived from theoretical research of the Japan Atomic Energy Agency.
[2] P. Brionnet, Study of the isomeric states in the superheavy nuclei : particular case of the 257Db and 253Lr nuclei, Thesis (2017).
[3] Kaji, D. et al. Gas-filled Recoil Ion Separator GARIS-II. Nuclear Instruments and Methods in Physics Research (2013).
[5] Plotted from nSHE Collaboration experimental data obtained at the RIKEN Nishina Center for Accelerator Based Science.
[4] Sakai, H. et al. Facility Upgrade for Superheavy-Element Research at RIKEN. The European Physical Journal A (2022).