

β -decay studies across $N = 126$

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Abstract. With the advent of the first Radioactive Ion Beam facilities of new generation, the investigation of the neutron-rich side of the nuclear chart has experienced an impressive progress. However, the discovery and study of new nuclear species in the region around the heaviest known neutron shell closure, $N = 126$, is still one of the most coveted experimental challenges. At a slower pace, the exploitation of alternative reaction mechanisms and/or advanced instrumentation has opened the possibility to investigate the isomeric and β decay of new, moderately neutron-rich $N \sim 126$ nuclei. These are of relevance for the understanding of the nuclear structure below the doubly-magic ^{208}Pb and for their role in the synthesis of the trans-bismuth fissile elements in the r process. In this contribution, a general overview of the β -decay experiments performed at both sides of $N = 126$ is provided, with a main focus on the experiments carried out at the fragmentation facilities GSI and RIBF.

1. Introduction

The spontaneous phenomenon of β decay has for a long time been a powerful tool to study newly synthesized exotic nuclei, since key properties such as β -decay half-lives or the lowest-lying excited states in the descendants can be measured only with a few hundred decays [1, 2]. At present, it is often the first or even the only mechanism available to investigate structural properties of the most exotic neutron-rich nuclei produced in Radioactive Ion Beam (RIB) facilities. Furthermore, in the rapid neutron-capture process (r -process) of explosive nucleosynthesis, the (n, γ) rates drop quickly near the neutron shell closures with $N = 50, 82$ and 126 , and β decay becomes the dominant nuclear mechanism, giving rise to the synthesis of heavier elements. Hence, understanding the formation of half the abundances of the existing chemical elements strongly depends on our knowledge of gross β decay properties such as half-lives, β -delayed neutron emission probabilities, and Q_β energies of very exotic neutron-rich nuclei [3].

Of particular interest is the nuclear region approaching the *Terra Incognita*, which lies far below the heaviest doubly magic ^{208}Pb and is related to the formation of the 3^{rd} r -process abundance peak and the crossing of the neutron shell closure with $N = 126$. Only a few nucleons away from ^{208}Pb , the most exotic heavy neutron-rich $N \sim 126$ nuclei investigated thus far had been at the exclusive reach of the GSI Helmholtz Centre for Heavy Ion Research (Germany). For more than twenty years, GSI has been the only facility in the world with optimal operational conditions to produce and separate heavy $N \sim 126$ nuclei. To this purpose, the fragmentation of relativistic ^{208}Pb and ^{238}U beams at 1 GeV/nucleon colliding on light, thin targets has been exploited. This production mechanism has allowed for an unambiguous identification in flight of the reaction residues in mass A and charge Q using the high-resolution magnetic



spectrometer Fragment Separator (FRS) [4]. However, relevant recent advances exploiting new production mechanisms and methods of identification involving cutting-edge instrumentation have challenged the European leadership on the investigation of $N \sim 126$ nuclei [5, 6]. In the present contribution, a general overview of the status of the β -decay studies across $N = 126$ is provided. The most important projects focusing on this mass region in fragmentation facilities are discussed [7, 8, 9], and a quick glance at near future perspectives is provided [10].

2. Scientific interest of the $N \sim 126$ region below ^{208}Pb

At present, the r -process calculations involving the $A \sim 195$ peak must rely on theoretical predictions that can only be tested near stability, with no guarantee on their predictive power approaching the r -process reaction path. For this reason, new structural information on the properties of nuclei lying a few nucleons below ^{208}Pb , even if not extremely exotic, is crucial. Apart from the gross β -decay properties aforementioned, experimental observables such as the energies of excited nuclear states, spin and parities, and nuclear lifetimes are necessary to derive two-body matrix elements (TBME) and trace the evolution of the single-particle energies (SPE) for nuclei with $N < 126$. Reliable information on these parameters is essential to test the large-scale shell model calculations towards the $A \sim 195$ bottleneck and calculate the more complex configurations of the r -process progenitors, which are completely out of experimental reach.

An important question open to debate is to what extent and how the first-forbidden (FF) transitions contribute to the β decay of these nuclei. FF decays are expected to be enhanced around the 3rd r -abundance peak due to the ordering of the proton and neutron orbitals below ^{208}Pb . In a single-particle picture, the model space describing $N < 126$, $Z < 82$ nuclei involves only one allowed Gamow-Teller (GT) transition of low energy transforming a neutron in the $0\nu h_{9/2}$ orbital into a proton in the $0\pi h_{11/2}$ shell. This transition is further hampered by the partial filling of the $0\pi h_{11/2}$ orbital and the location of the $0\nu h_{9/2}$ sub-shell, which the deepest lying orbital of the $82 < N < 126$ major shell. As a result, the appearance of fast FF transitions exceeding the GT strength is predicted in the $N \sim 126$ region [11]. These are expected to significantly reduce the theoretical half-lives [11, 12, 13, 14, 15], accelerating the nucleosynthesis of the actinides and the latter fission recycling. Improved simulations of the matter flow through the third r -process bottleneck are also important to constrain the relative abundances of the nuclear cosmo-chronometers of U and Th, which have for a long time been used to measure the age of stars [16] and identify r -process sites and stellar progenitors [17].

3. The production mechanisms. Multi-nucleon transfer versus fragmentation

Hitherto, the cold fragmentation of relativistic heavy stable projectiles of ^{208}Pb and ^{238}U on thin light targets has been used to synthesize the most exotic $N \sim 126$ neutron-rich nuclei [19, 20]. Cold fragmentation reactions [21] are modeled as very peripheral relativistic nuclear collisions taking place in a participant-spectator picture that can be described in two steps. In the first stage, called abrasion, the projectile nucleus is cut by the target, becoming highly excited. In the second stage, called ablation, the projectile pre-fragment de-excites emitting particles and γ rays, even through fission, giving rise to the final fragment. There are two main advantages of this production mechanism. On the one hand, the neutron-rich reaction residues can be unambiguously identified in flight in a very short time period, down to $\sim 300\text{ns}$; on the other hand, as the relativistic reaction takes place in inverse kinematics, the fragmentation residues are forwarded focused with small emission angles, resulting in high transmission rates, close to 100%, in zero-degree magnetic spectrometers [22]. The detection efficiency of the tracking detectors is also good, resulting in small losses during the particle identification. In contrast, the cold fragmentation cross sections of the $N = 126$ isotones decrease rapidly as protons are removed from the projectile, resulting in too small production cross sections, below the order of the nb for $Z \leq 77$.

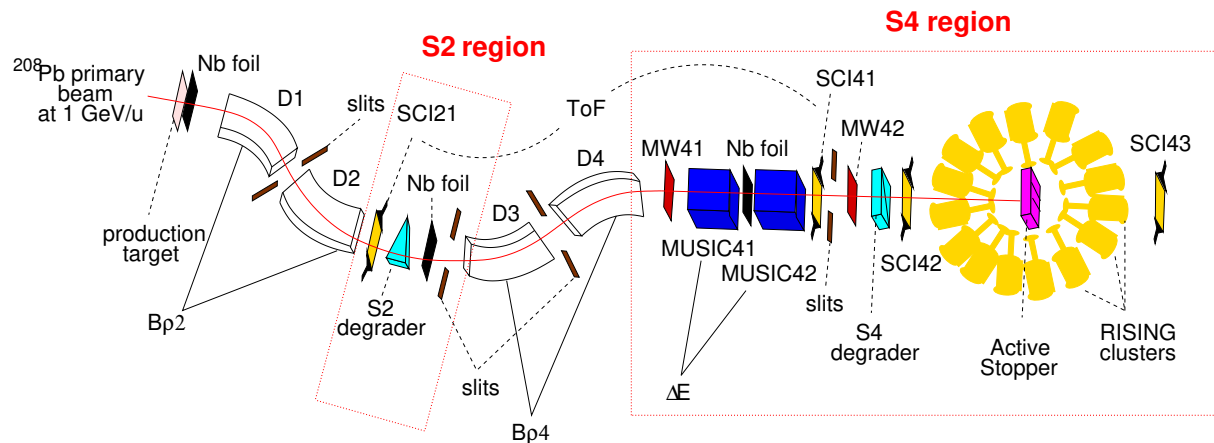


Figure 1. Layout of the in-flight setup used at GSI for isomer and β -decay studies, consisting of the magnetic spectrometer FRS for particle identification and the stopped RISING detection system for β and γ -ray detection [7]. Figure taken from [18].

An alternative production mechanism presently attracting much attention is the multi-nucleon transfer (MNT) [23]. The pioneering KISS project at RIBF has shown that MNT reactions, in combination with ISOL techniques for particle identification, are optimal to study $N < 126$ nuclei [5]. In these reactions, a large number of nucleons are exchanged between two heavy nuclei at energies near the Coulomb barrier, giving rise to very large production cross sections using combinations such as (^{136}Xe , ^{198}Pt) or (^{136}Xe , ^{208}Pb). However, the angular distributions of the products are broad, resulting in small collection efficiencies. Furthermore, the low emission energies of the target-like fragments (TLF) make their extraction and separation very difficult, with rather small extraction efficiencies and long identification times, ~ 300 ms.

4. The quest for $N = 126$ nuclei

The number of active or planned research programs around the world aiming at reaching the $N \sim 126$ nuclei below ^{208}Pb [5, 6, 24, 10, 25] is a clear sign that the *Terra Incognita* is one of the major milestones of the latest generation of RIB laboratories. Due to length limitations, only the most important projects carried out in fragmentation facilities will be discussed here.

4.1. The past: RISING at GSI

The main facility contributing thus far to β -decay studies across $N = 126$ has been GSI. There, the β decay of nearly 40 neutron-rich nuclei was investigated using different in-flight β -decay setups [1, 26, 27, 28, 18, 2, 29, 30, 31]. The most relevant was RISING, the schematic layout of which is shown in Fig 1. In RISING, the measured β -decay half-lives of $N \leq 126$, $Z < 82$ nuclei were well reproduced by models including a microscopic treatment of the FF transitions, such as the DF3+cQRPA approach [11] or the RHB+ pn -RQRPA model [13]; while the FRDM+QRPA model [15], extensively used in calculations of r -process nucleosynthesis, significantly overestimated the half-lives of $N \leq 126$ nuclei. This excess is in line with the expected enhancement of the FF transitions discussed in Section 2, as the FRDM+QRPA model calculates the FF strength using the gross theory, a treatment that might not be sufficient. But surprisingly, for $N > 126$, $Z \geq 80$ nuclei, the FRDM+QRPA agrees remarkably well with the half-lives in contrast to the DF3+cQRPA and RHB+ pn -RQRPA models, which underestimate the experimental results –the later by orders of magnitude [27, 31].

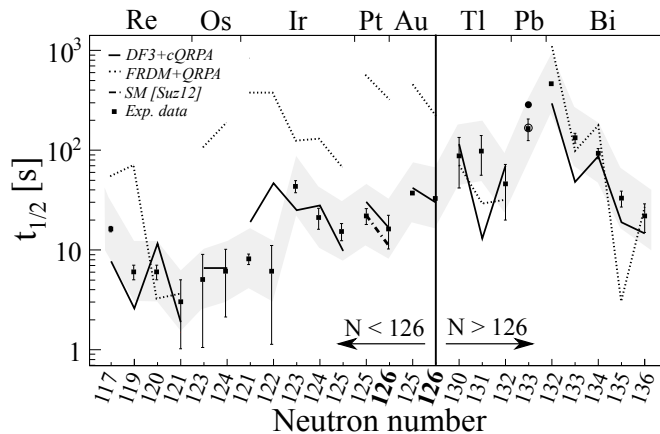


Figure 2. Systematics of β half-lives of nuclei crossing $N = 126$. The shaded region indicates the typical deviation between DF3+cQRPA and experiment in $N \sim 82$ nuclei. Figure adapted from Ref. [29].

Ref. [33]. For ^{215}Pb , the FRDM+QRPA and DF3+cQRPA predictions are shown with filled and empty circles, respectively.

4.2. The present: DESPEC at FAIR

The DESPEC project aims at continuing the Nuclear Structure and Astrophysics research program started with RISING by extending the scope to more exotic neutron-rich nuclei and more varied observables, thus helping to advance our knowledge on the structural properties of nuclei crossing $N = 126$. This mass region has been targeted at GSI very recently, during the FAIR Phase 0 campaign in Spring 2022, using for the first time new instrumentation developed for DESPEC: the DEGAS and DTAS γ -ray detector arrays [10]. The former is intended for high-resolution γ spectroscopy and consists of a series of EUROBALL HPGe crystals rearranged in triple clusters packed in a high-efficiency configuration. The latter is a modular total-absorption spectrometer made of 16 NaI crystals that acts as a calorimeter. Hence, it is specifically designed to maximize the γ -ray detection efficiency for the measurement of β intensities in fragmentation facilities. Pictures of the two setups are shown in Fig. 3.

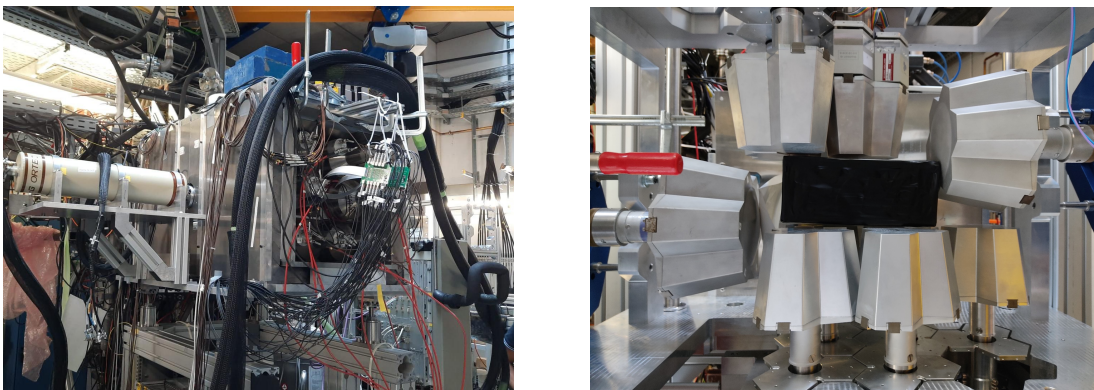


Figure 3. Left: DTAS γ -ray calorimeter and narrow AIDA implant-decay detector. Right: DEGAS HPGe spectrometer surrounding the wide AIDA active stopper. All the systems are part of the advanced instrumentation developed for DESPEC [10].

With DTAS, the first worldwide systematic measurement of β strengths for neutron-rich nuclei across $N = 126$ has been performed at GSI. The β strengths, derived from the measured β intensities, will provide an excellent experimental probe to test how the β decay proceeds for $N \sim 126$ nuclei, as a complete picture of the wave-function overlap between parent and daughter states in the decay energy window can be obtained. They are hence better suited to understand the underlying mechanisms leading to the discrepancies in β half-lives observed in RISING (see Fig. 2). With DEGAS, the isomeric and β decay of the most exotic $N = 126$ isotones ^{203}Ir and ^{202}Os will soon be investigated. As a result, the knowledge of excitation energies, transition strengths, and β -decay properties downward $N = 125$ – 127 will be extended by the DESPEC collaboration in the incoming years. These findings, in turn, might help improve the nuclear models in their predictions towards the unknown r -process progenitors.

4.3. The big surprise: BRIKEN at RIBF

Although GSI has been leading the investigation of $N \sim 126$ nuclei for more than twenty years, the ground-breaking progress carried out recently at RIBF has broken the long-term rampart of heavy-ion identification for lower primary beam energies, opening up new opportunities to investigate this almost unexplored nuclear region.

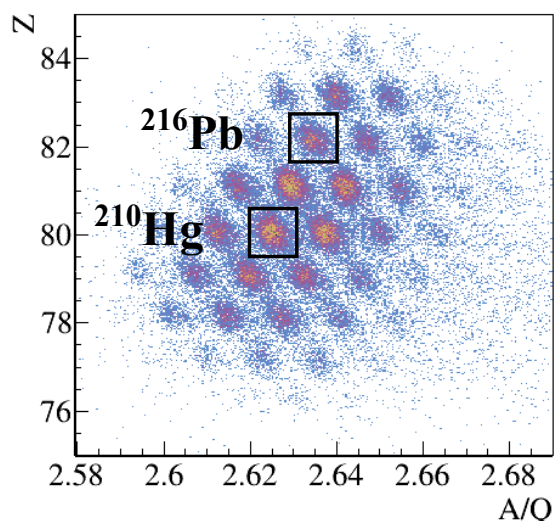


Figure 4. Two-dimensional particle identification matrix showing the atomic charge Z as a function of the A/Q ratio for fully-stripped ions. Setting centered in ^{202}Os [6].

spectrometer, whilst that in Z has been reached with a novel Si telescope system consisting of a stack of four wedge-shaped Si detectors of dimensions $93 \times 93 \text{ mm}^2$ and 0.6-mm thick each. The particle-identification (PID) cluster matrix of the exotic heavy fragments produced, with Z ranging from 77 to 83, is shown in Fig. 4. The PID has been confirmed by the observation of the previously reported (8^+) seniority isomer in ^{216}Pb [34] and other known transitions in ^{210}Hg and ^{213}Tl [36, 37]. Newly observed isomers have also been identified in ^{213}Tl - ^{215}Tl , 211 – ^{212}Hg and ^{206}Pt .

5. Conclusions

Until recently, GSI has been the only facility where the β decay of $N \sim 126$ nuclei could be investigated. However, the great progress carried out recently at RIBF via both multi-nucleon

At RIBF, the only heavy stable primary beam available is ^{238}U , with an energy of 345 MeV/nucleon and an intensity reaching 100 pA. These conditions have allowed the observation of the first isomeric γ rays in $N \gtrsim 126$, $Z < 82$ nuclei since 2009 [34]. The first experiment with such capabilities was run in spring 2021 by the BRIKEN collaboration [6]. BRIKEN is made of 140 ^3He tubes surrounded by a polyethylene (PE) moderator matrix. Two CLOVER-type HPGe detectors are inserted into the PE matrix transversely to the beam direction at an angle of 90° for γ spectroscopy studies [9]. The main technical challenge to identify in-flight heavy nuclei is related to the contamination arising from the atomic charge states produced in the interaction of the nuclei with the matter of the optical elements and detectors placed along the BigRIPS magnetic spectrometer [35]. The required resolution in A/Q has been achieved by minimizing the matter placed along the

transfer and fragmentation of ^{238}U establishes it as both a competitive and complementary facility in the quest for the most exotic heavy systems towards the *Terra Incognita*.

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