



Searching for new neutron-rich isotopes in the rare-earth region at HIAF

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Abstract

The present study evaluates the production of new neutron-rich isotopes in the rare-earth region ($Z = 61 - 71$) using projectile fragmentation of primary beams at 800 MeV/nucleon at the HIGH-rigidity Radioactive Ion Beam Line (HIRIBL) of the High-Intensity heavy-ion Accelerator Facility (HIAF). The production potential of various projectiles was evaluated through measured and calculated production cross sections, revealing that ^{198}Pt may offer a clear advantage for accessing this region. With an optimized target thickness, fragmentation of ^{198}Pt could lead to the discovery of about 30 new isotopes in the rare-earth region at HIAF, thereby providing a strong opportunity for studies in both nuclear physics and nuclear astrophysics at HIAF.

Keywords New neutron-rich isotopes · Rare-earth region · Fragmentation reaction · HIAF

1 Introduction

Nuclei with extreme neutron-to-proton ratios, located far from the line of β stability, play a key role in modern nuclear physics. With major advances in developing next-generation radioactive isotope (RI) beam facilities, an increasing number of exotic nuclei have become accessible for experimental studies. As a consequence, new phenomena—particularly among neutron-rich nuclei—have been observed, including shape coexistence [1], shape deformation [2] and shell evolution [3], thereby reshaping our understanding of nuclear structure. In addition, studies on structural properties and

decay properties in heavy neutron-rich nuclei provide essential insights into nuclear astrophysics, particularly the rapid neutron-capture process (r -process), which is thought to synthesize approximately half of the elements heavier than iron in the universe. For instance, efforts have been made to produce neutron-rich nuclei that lie within the r -process abundance regions around $A \approx 80$ [4] and $A \approx 130$ [5].

In recent years, considerable attention has been devoted to the neutron-rich nuclei with $Z = 61 - 71$ and $A \approx 165$ in the rare-earth region, owing to their significance in both nuclear structure and nucleosynthesis. These neutron-rich nuclei are expected to exhibit strong deformation [6]. Moreover, their decay properties affect the small, broad peak at $A \approx 165$ in the r -process abundance distribution [7]. Despite their importance, experimental studies of these neutron-rich nuclei remain limited due to their low production yields. The current experimental frontier in this region [8–12] is shown in Fig. 1.

To study these neutron-rich rare-earth nuclei in the laboratory, it is critical to identify the most effective routes to produce them with radioactive isotope beam facilities. Over the past decades, the rare-earth region has been accessed mainly through fission-based methods, such as spontaneous fission of ^{252}Cf [13–16], thermal neutron-induced fission of ^{235}U [17–19], as well as multinucleon-transfer reactions [20–22]. These methods, however, are largely restricted to nuclei near the β stability

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line. Thanks to advances in in-flight separators, in-flight fission of a ^{238}U beam has been used successfully to produce neutron-rich rare-earth nuclei. For instance, new neutron-rich isotopes ranging from Nd ($Z = 60$) to Pt ($Z = 78$) [23], and from Ba ($Z = 56$) to Er ($Z = 68$) [9, 12, 24] were discovered at GSI and RIBF by means of in-flight fission of ^{238}U at 1 GeV/nucleon and 345 MeV/nucleon, respectively. Toward still more neutron-rich rare-earth isotopes, however, in-flight fission is hindered by the rapid decrease in cross section, which limits further access to this region.

To overcome this limitation, it is essential to explore new pathways for the production of neutron-rich nuclei. Projectile fragmentation of heavy ions has proven to be a powerful tool for producing such nuclei [25, 26]. By selecting a suitable projectile, large production cross sections can be achieved through fragmentation reactions. Indeed, fragmentation of a recently introduced projectile, ^{198}Pt , was performed at 85 MeV/nucleon [10] and 186 MeV/nucleon [11], leading to the identification of new isotopes $^{182,183}\text{Tm}$, $^{186,187}\text{Yb}$, $^{189,190}\text{Lu}$, and $^{191,192}\text{Hf}$. These discoveries demonstrate the strong potential of ^{198}Pt for accessing even more neutron-rich isotopes in the rare-earth region.

In this work, the production potential of several projectiles is evaluated for producing new neutron-rich rare-earth nuclei at the High-rigidity Radioactive Ion Beam Line (HIRIBL) of the High-Intensity heavy-ion Accelerator Facility (HIAF).

2 Experimental setup at HIRIBL

As a next-generation RI facility, HIAF is expected to provide a variety of beams ranging from hydrogen to uranium with high intensities [27], thereby providing new opportunities for the production and investigation of heavy neutron-rich nuclei. Primary beam intensities up to 1×10^{11} particles per pulse (ppp) can be expected in both fast- and slow-extraction modes after acceleration in the main synchrotron [27]. The HIRIBL is HIAF's primary in-flight separator for rare-isotope studies. HIRIBL has a two-stage structure, namely a Pre-Separator (from PF0 to PF4) and a Main-Separator (from MF0 to MF6), presenting a concept similar to that of other advanced in-flight separators worldwide, such as BigRIPS [28] at RIBF, SuperFRS at FAIR [29] and ARIS [30] at FRIB. HIRIBL offers a high magnetic rigidity of up to 25 Tm and a large acceptance, with angular acceptances of ± 30 mrad horizontally and ± 15 mrad vertically, and a momentum acceptance of $\pm 2\%$ [27, 31, 32]. These capabilities enable HIRIBL to produce, separate, and identify nuclei far away from the β -stability line. The schematic and detailed characteristics of the HIRIBL separator are presented in Refs. [31–33].

To search for new isotopes produced by fragmentation of primary beams, HIRIBL will be operated in the achromatic mode [31]. The primary beams will be delivered in the slow-extraction mode with an extraction time of 3 s and a repetition period of 13 s [33]. In this mode, the Pre-Separator is

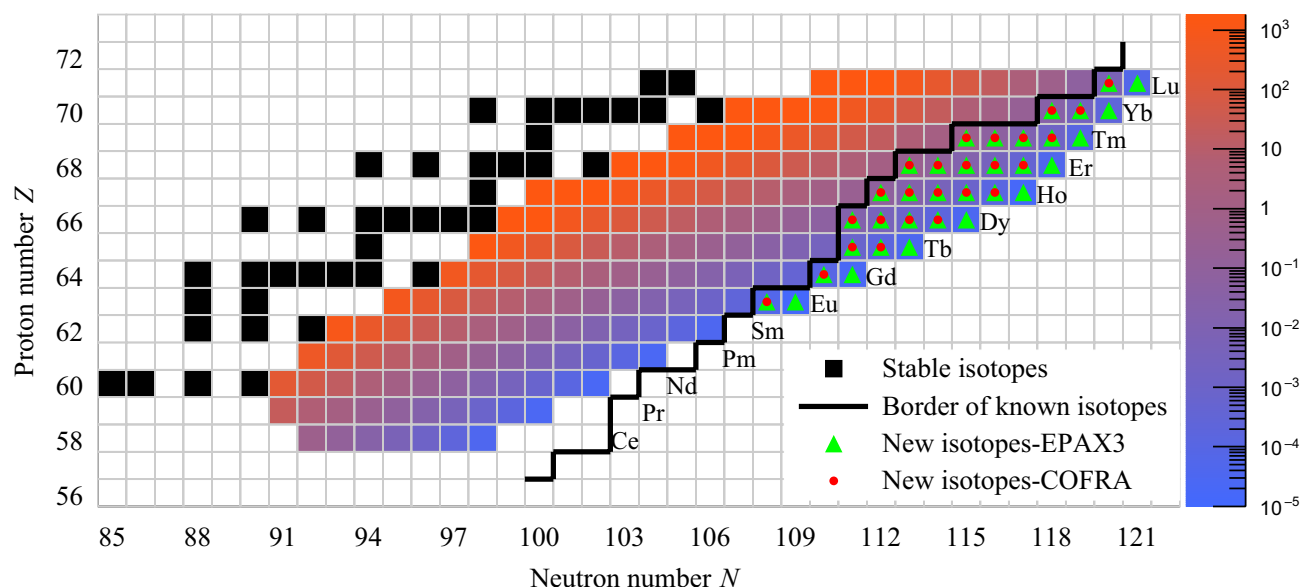


Fig. 1 (Color online) Part of nuclear chart showing the forefront of the rare-earth region. The black squares represent the stable nuclei. Colored squares show the isotopes can be produced by the fragmentation of ^{198}Pt at 800 MeV/nucleon on Be (4 g/cm^2) with an intensity of 1.0×10^{11} ppp, corresponding to 7.7×10^9 pps in the slow-extraction mode. The estimated production yields are given by different colors. The neutron-rich isotopes identified experimentally so far are

highlighted by the thick black lines. Highlighted by the green triangles and red circles are the new neutron-rich isotopes expected to be observed by the fragmentation of ^{198}Pt at HIAF. The numerical data for the production yields of these new isotopes are listed in Table 1 in the appendix. See text for details

used for separating and purifying the fragments, and the Main-Separator serves as a spectrometer to identify the isotopes event by event by measuring the time of flight (TOF), energy loss (ΔE) and magnetic rigidity ($B\rho$). The time of flight will be measured by plastic scintillators installed at the MF0 and MF6 focal planes. The magnetic rigidity will be determined by the trajectory reconstruction using the position and angle information measured at MF0, MF4, and MF6. The energy loss ΔE will be measured with an ionization chamber at MF6. The atomic number Z and the mass-to-charge ratio A/Q of nuclei produced by fragmentation will be derived from the TOF– ΔE and TOF– $B\rho$ correlations, respectively. To identify particles unambiguously, the isomer-tagging technique [34] will be used through detection of the delayed γ -rays emitted from known short-lived isomers with Ge detectors at MF6. The experimental setup is included in a LISE++ [35] simulation for the transmission efficiency of HIRIBL.

At in-flight separators, one challenge for the production of heavy nuclei is the charge-state distribution [36]. Indeed, at intermediate energies, a wide charge-state distribution [9, 11] causes difficulties in the identification and purification of heavy reaction products. To distinguish different charge states clearly for heavy nuclei at HIRIBL, a high A/Q resolution is required. This is because a fully-stripped ion with A and the hydrogen-like one with $A - 3$ are very close in the A/Q spectrum, for the same Z . Taking ^{181}Er as an example, the A/Q resolution should be better than 8.5×10^{-4} [given here as root mean square (RMS)] to separate $^{181}\text{Er}^{68+}$ ($A/Q = 2.6618$) and $^{178}\text{Er}^{67+}$ ($A/Q = 2.6567$) at the 6σ level.

With such a high requirement on A/Q separation, the resolution specifications for the beam-line detectors at HIRIBL were estimated. Based on the TOF– $B\rho$ – ΔE method, A/Q can be obtained as

$$\frac{A}{Q} = \frac{B\rho c}{\beta\gamma m_u} \quad (1)$$

$$\text{TOF} = \frac{L}{\beta c} \quad (2)$$

$$B\rho = B\rho_0 \left(1 + \frac{1}{\text{Det}} ((\theta|\theta)x - (x|\theta)\theta - x_0) \right) \quad (3)$$

$$\text{Det} = (x|\delta)(\theta|\theta) - (x|\theta)(\theta|\delta)$$

where x and x_0 represent the measured positions, and $B\rho_0$ represents the magnetic rigidity of the central trajectory. The coefficients $(x|\delta)$, $(\theta|\theta)$, $(x|\theta)$ and $(\theta|\delta)$ are the ion-optical transfer-matrix elements, which are given in Ref. [31].

According to Eqs. 1 and 2, the resolution of A/Q can be expressed as

$$\frac{\sigma(A/Q)}{A/Q} = \sqrt{\left(\frac{\sigma_{B\rho}}{B\rho} \right)^2 + \gamma^4 \left(\frac{\sigma_{\text{TOF}}}{\text{TOF}} \right)^2} \quad (4)$$

where $\sigma_{B\rho}$ and σ_{TOF} represent the RMS resolutions of $B\rho$ and TOF, respectively. From Eq. 3, the resolution of $B\rho$ can be expressed as

$$\left(\frac{\sigma_{B\rho}}{B\rho} \right)^2 = \left(\frac{(\theta|\theta)}{\text{Det}} \sigma_x \right)^2 + \left(\frac{(x|\theta)}{\text{Det}} \sigma_\theta \right)^2 + \left(\frac{1}{\text{Det}} \sigma_{x_0} \right)^2 \quad (5)$$

σ_x and σ_θ are the position and angle resolutions, respectively. Position and angle information will be measured using PPAC [37], MWDC [38] or GEM-TPC [39] detectors. For these detectors, a position resolution of $\sigma_x = 300 \mu\text{m}$ can be achieved. Thus, $\sigma_{B\rho}/B\rho$ is estimated to be 0.015%. Assuming an energy of approximately 600 MeV/nucleon for ^{181}Er ($\beta \approx 0.79$, $\gamma \approx 1.64$), the time resolution $\sigma_{\text{TOF}}/\text{TOF}$ should be better than 1.05×10^{-4} to separate the charge states $^{181}\text{Er}^{68+}$ and $^{178}\text{Er}^{67+}$ at the 6σ level. The flight length from MF0 to MF6 is 118 m, corresponding to a flight time of 500 ns, and thus requiring a TOF resolution of 53 ps (RMS).

3 Evaluation of production methods

To produce neutron-rich nuclei in the rare-earth region using projectile fragmentation, it is necessary to select a suitable primary-beam projectile. Here, ^{208}Pb ($Z = 82$, $N = 126$), ^{198}Pt ($Z = 78$, $N = 120$), and ^{197}Au ($Z = 79$, $N = 118$) can be plausible candidates, and their fragmentation cross sections are critical for evaluating their production potential. The experimental results on the production cross sections via the fragmentation of ^{208}Pb at 1 GeV/nucleon [25], ^{198}Pt at 85 MeV/nucleon [10] and ^{197}Au [26] at 950 MeV/nucleon on ^9Be are compared in Fig. 3. In general, fragmentation of ^{198}Pt yields larger cross sections than fragmentation of both ^{197}Au and ^{208}Pb . Cross sections for the fragmentation of ^{197}Au are higher than those for ^{208}Pb at $Z = 76$ and 77 as plotted in Fig. 3(g) and (h), but become smaller for $Z \leq 75$ as shown in Fig. 3(a)–(f). For ^{198}Pt and ^{208}Pb , the cross-section difference becomes smaller towards $N = 120$ along an isotopic chain, because of the neutron-number limit of ^{198}Pt . For instance, similar cross sections can be found around $N = 120$ between these two projectiles for Lu, Hf and Ta, leading to a crossover of the two isotopic distributions, as shown in Fig. 3(b)–(d). Beyond $N > 120$, fragmentation of ^{208}Pb presents larger cross sections than those for ^{198}Pt and ^{197}Au , because ^{208}Pb has more neutrons.

As shown in Fig. 3, cross-section data are available for isotopes with $Z \geq 70$. To estimate production of more neutron-rich isotopes with smaller Z , the available data are first used to assess the predictive power of the calculations, and the validated models are then applied to nuclei with $Z < 70$. So far, many models have been developed to

predict cross sections of fragmentation reactions [40–44]. To examine their predictive power, three sets of calculations were chosen for comparison with the data, as shown in Fig. 3. They are EPAX2 [45], EPAX3 [46] and COFRA [26], which are widely used to estimate the production yields at in-flight separators.

EPAX is an empirical parameterization that provides a universal description of fragmentation cross sections in high-energy heavy-ion reactions [45, 46]. The cross sections are assumed to be energy independent. EPAX2 was developed by fitting data from stable projectiles, such as ^{40}Ar , ^{58}Ni , ^{86}Kr , ^{129}Xe , and ^{208}Pb [47–51]. In EPAX2, the description of fragmentation yields close to the projectile and the memory effect of neutron-deficient projectiles were improved significantly. However, large discrepancies with measured data still remain for the production of extremely neutron-rich nuclei in EPAX2 predictions. EPAX3 was developed using a more comprehensive data set, such as $^{40,48}\text{Ca}$, $^{58,64}\text{Ni}$, ^{132}Sn [52, 53], among others. EPAX3 introduces several improvements: a revised treatment of the memory effect, an additional correction for the residue corridor, an empirical downscale factor to avoid the overestimation for the yields of extremely neutron-rich fragments, and improved parameterization of the charge dispersion width. As a result, EPAX3 provides a much better description of the most neutron-rich fragments while retaining the good performance of EPAX2 on the neutron-deficient side. EPAX3 has been applied successfully to predict cross sections in many cases, such as the fragmentation of ^{136}Xe , ^{81}Ga , ^{82}Ge , ^{132}Sn [4, 5, 54] and related systems. The detailed formulas and parameters of EPAX2 and EPAX3 are described in Ref. [45] and Ref. [46], respectively.

The COFRA code is a simplified version of the abrasion-ablation reaction model. In the first stage, the abrasion process determines the size of the pre-fragment based on the geometric overlap between projectile and target nuclei. The excitation energy gained during this stage is estimated from the energy of particle-hole excitations produced by the abraded nucleons. In the second stage, the ablation process is described within the framework of the statistical model using the Weisskopf formalism. It is treated under the assumption that only neutron evaporation occurs, which is a good approximation for nuclei with a large neutron excess. This assumption allows the statistical evaporation stage to be simplified using an analytical formulation. The detailed formalism of COFRA is given in Ref. [26].

The comparison results are shown in Fig. 3. EPAX2 cannot reproduce all three data sets. For ^{197}Au , EPAX2 reproduces the measured cross sections reasonably well overall. For ^{198}Pt and ^{208}Pb , however, it underestimates the cross sections for products close in Z to the projectile, such as $\text{Re}(Z = 75)$, $\text{Os}(Z = 76)$, and $\text{Ir}(Z = 77)$ isotopes produced by $^{198}\text{Pt}(Z = 78)$ and $^{197}\text{Au}(Z = 79)$, as presented in Fig. 3(f)–(h), whereas it overestimates the cross sections for products with Z far from the projectile, such as $\text{Lu}(Z = 71)$ and $\text{Hf}(Z = 72)$ isotopes produced

by ^{198}Pt , and especially $\text{Yb}(Z = 70)$, $\text{Lu}(Z = 71)$, $\text{Hf}(Z = 72)$, and $\text{Ta}(Z = 73)$ isotopes produced by ^{208}Pb , as displayed in Fig. 3(a)–(d). Such a large overestimation of the cross sections for low- Z neutron-rich nuclei was also reported in the $^{136}\text{Xe}+^9\text{Be}$ at 1 GeV/nucleon [54]. The limitation of EPAX2 on the neutron-rich side could be attributed to the limited availability of experimental cross-section data in that region during its development [46]. Both EPAX3 and COFRA show good agreement with the measured cross sections for all three projectiles. For products close to the projectile, such as Os and Ir isotopes produced by ^{208}Pb in Fig. 3(g)–(h), and W , Re , Os and Ir isotopes produced by ^{198}Pt and ^{197}Au in Fig. 3(e)–(h), COFRA gives a better description than EPAX3. For the products far from the projectile, COFRA gives larger cross sections than EPAX3 but predicts a rapid decrease toward the very neutron-rich side along the isotopic chains, leading to crossover points between the two calculations, as shown in Fig. 3(a)–(c). This behavior may be related to the treatment of the excitation energy and the neutron separation energy of the pre-fragments in the COFRA model [26, 53]. Because of their good agreement with data, both COFRA and EPAX3 were used to calculate production cross sections for neutron-rich nuclei with $Z < 70$ in the rare-earth region and to identify a suitable projectile.

To evaluate the production potential for the neutron-rich isotopes in the rare-earth region, the production cross sections for the isotopes with $Z = 61 - 71$, produced via fragmentation of ^{198}Pt , ^{197}Au , and ^{208}Pb on a Be target, are calculated with COFRA and EPAX3, as plotted in Fig. 4. For fragmentation reactions, the cross sections from ^{198}Pt are much larger than those from ^{208}Pb and ^{197}Au , especially for isotopes with $Z \geq 65$, $N \leq 120$ as presented in Fig. 4(e)–(k), demonstrating the advantage of using ^{198}Pt to produce neutron-rich rare-earth isotopes.

The measured cross sections for the ^{238}U fission [9, 23, 24] are also shown in Fig. 4 for comparison. For isotopes with $Z \leq 65$, the fragmentation cross sections of ^{198}Pt are smaller on the less neutron-rich side, as shown in Fig. 4(a)–(e). However, the cross-section difference between the two production mechanisms decreases with increasing neutron number, because the fission cross sections decrease rapidly [9]. This tendency leads to a crossover point, beyond which the ^{198}Pt fragmentation cross sections exceed those from the ^{238}U fission. Indeed, such a crossover is observed for $N > 108$ in the Dy, Ho and Er isotopic chains, as shown in Fig. 4(f)–(h). For the Tm, Yb and Lu isotopes, the fragmentation cross sections of ^{198}Pt are 1–2 orders higher than those from the ^{238}U fission, as displayed in Fig. 4 i–k. These results suggest that ^{198}Pt fragmentation may offer a promising alternative to ^{238}U fission in accessing very neutron-rich rare-earth isotopes, particularly for those with $Z > 65$.

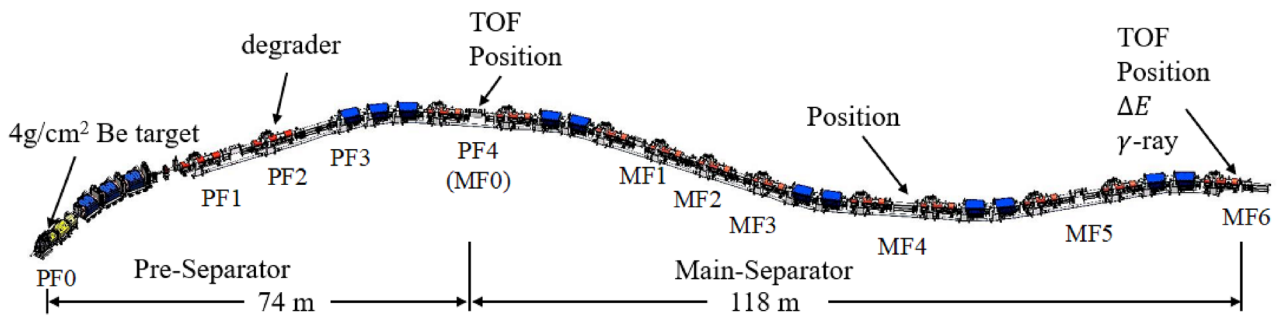
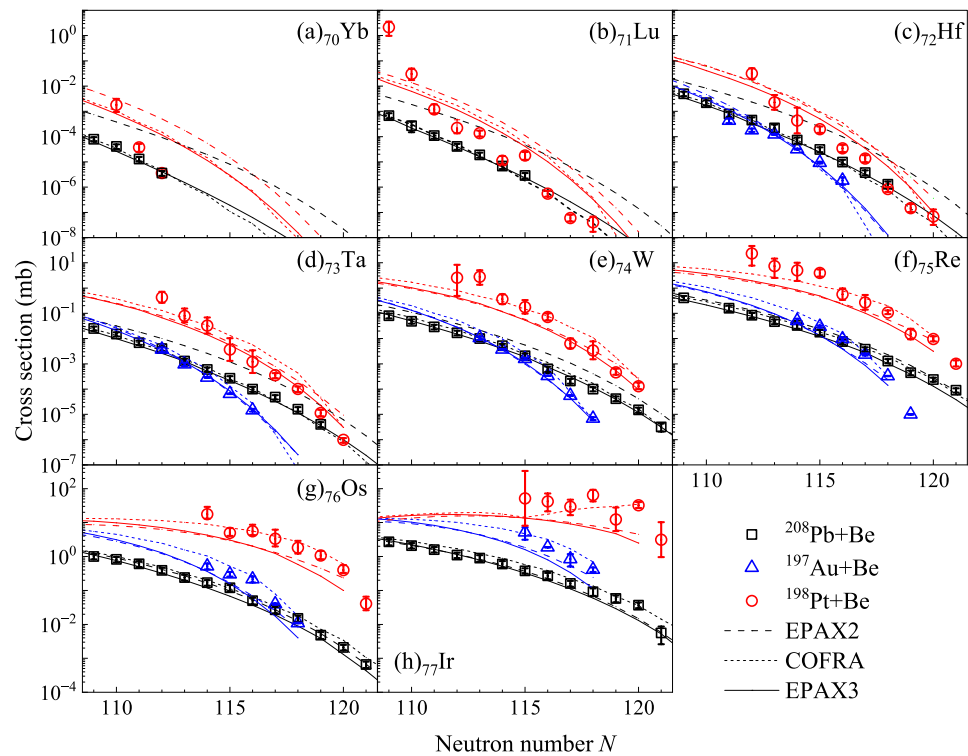


Fig. 2 (Color online) Layout of HIRIBL separator

Fig. 3 (Color online) Measured cross sections of isotopes from $_{70}\text{Yb}$ (a) to $_{77}\text{Ir}$ (h) produced by fragmentation of ^{208}Pb at 1 GeV/nucleon [25], ^{197}Au at 950 MeV/nucleon [26] and ^{198}Pt at 85 MeV/nucleon [10] on beryllium. The COFRA (dotted lines), EPAX2 (dashed lines), and EPAX3 (solid lines) calculations were plotted for comparison



4 Optimization of target thickness

To maximize the yield of neutron-rich rare-earth isotopes via the fragmentation of ^{198}Pt , it is essential to optimize the target thickness. An energy of 800 MeV/nucleon was adopted for ^{198}Pt , as it is the typical energy suggested for heavy-ion beams delivered to the HIRIBL beamline at HIAF [27, 55]. While increasing the target thickness enhances the initial production yield, it also introduces two counteracting effects: the fraction of fully-stripped ions decreases with increasing thickness, and reaction losses increase due to multi-step reactions within the thick target. Therefore, it is necessary to balance these competing factors to identify an optimal target thickness.

Taking the production yield of ^{181}Er by an 800-MeV/nucleon ^{198}Pt beam on Be as an example, the dependence of the survival probability (P_{surv}) and the fully-stripped fraction (R_{FS}) of ^{181}Er on the target thickness (T_{tar}) are shown in Fig. 5(a) and (b), respectively. The charge-state distributions were calculated using the GLOBAL [36] code. GLOBAL is a numerical program developed to simulate the charge-state evolution of relativistic heavy ions as they traverse matter. The model takes into account a broad distribution of charge states and equilibrium conditions for a wide range of projectiles and target materials at energies above 100 MeV/nucleon. A detailed description of the GLOBAL code can be found in Ref. [36]. Both the fully-stripped fraction and the survival probability decrease as the target thickness increases. By combining these effects, Fig. 5(c)

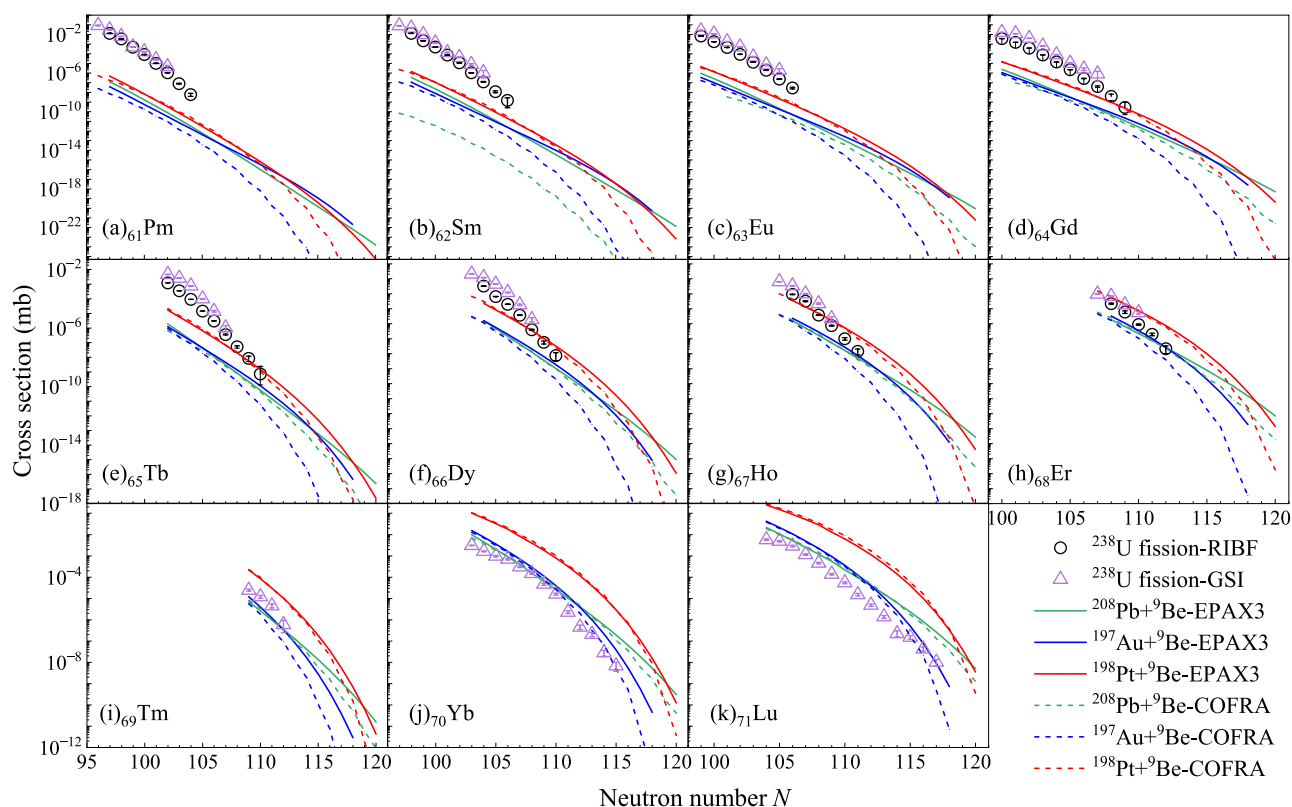


Fig. 4 (Color online) Comparison of production cross sections for isotopes from $_{61}\text{Pm}$ (a) to $_{71}\text{Lu}$ (k) by fragmentation of ^{198}Pt (red solid lines), ^{197}Au (blue dotted lines), and ^{208}Pb (green dashed lines), as well as by fission of ^{238}U . The fragmentation cross sections were calculated by EPAX3 and COFRA. It is noted that the cross sections for

Pm isotopes produced by fragmentation of ^{208}Pb can not be reached by COFRA. The fission cross sections were adopted from the measured data by RIBF [12, 24] (black circles) and GSI [23] (purple triangles), respectively

shows the product of the target thickness, the fully-stripped fraction, and the survival probability as a function of the target thickness, which provides an effective measure of yield estimation. As demonstrated in Fig. 5(c), the maximum value of the yield measure appears near 4 g/cm^2 , corresponding to an energy of 580 MeV/nucleon for ^{181}Er . In this case, the survival probability and fully-stripped fraction for ^{181}Er are approximately 40% and 80%, respectively, as displayed in Fig. 5a and b. It is noted that the thickness of 4 g/cm^2 is also applicable to the production of other nuclei in the rare-earth region. Thus, an optimal thickness of 4 g/cm^2 for Be was adopted to estimate the production of neutron-rich isotopes in the rare-earth region from fragmentation of ^{198}Pt .

5 Production yield

Based on the discussion above, the calculated production yields of neutron-rich nuclei in the rare-earth region from fragmentation of ^{198}Pt at HIRIBL are plotted in Fig. 1, using a beam intensity of $1 \times 10^{11} \text{ pps}$, corresponding to $7.7 \times 10^9 \text{ pps}$ in the slow-extraction mode. The production

cross sections were calculated using EPAX3 and COFRA. A 4 g/cm^2 Be target was selected as the reaction target. The transmission efficiencies and production yields were simulated with LISE++ [35]. It predicts beam intensity, purity, and transmission for experiment planning by incorporating physical processes such as projectile fragmentation, fission, and related reactions. LISE++ provides flexibility to design and optimize separator configurations for experiment planning and beamline tuning for rare-isotope facilities. In the present work, the configuration of the HIRIBL separator at HIAF, which is presented in Fig. 2, was implemented to calculate the transmission efficiency. According to the LISE++ simulation, the transmission efficiency is approximately 90%. As shown in Fig. 1, about 36 and 27 new isotopes with $63 \leq Z \leq 71$ can be detected with a production rate higher than $1.5 \times 10^{-5} \text{ pps}$, corresponding to 1 event per day, according to the calculations by EPAX3 and COFRA, respectively. The yields for these new isotopes expected to be discovered at HIAF are listed in Table 1. This result demonstrates strong potential for the production of new neutron-rich rare-earth isotopes at the HIRIBL in-flight separator at HIAF.

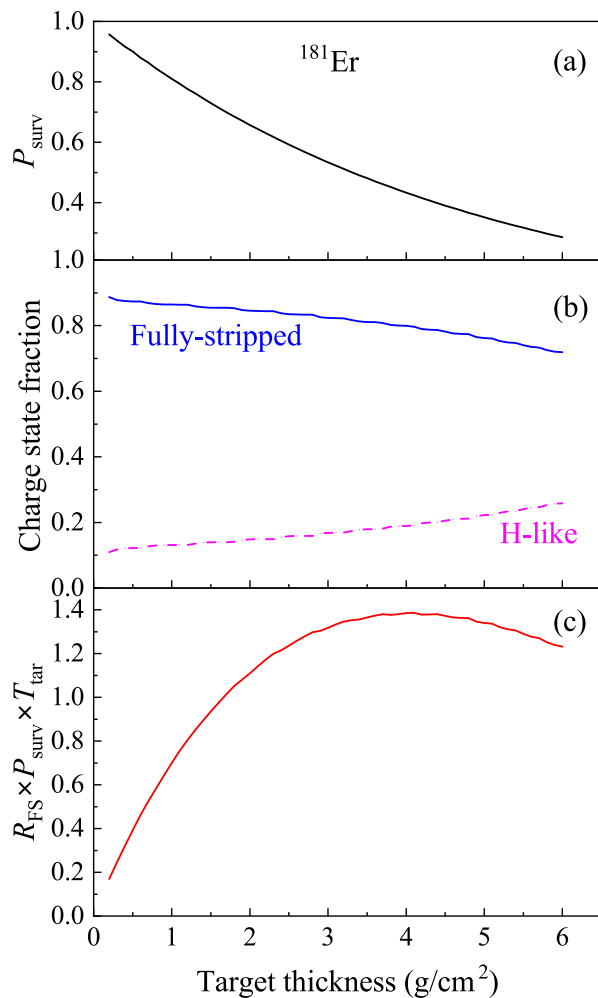


Fig. 5 (Color online) **(a)** Survival probability of ^{181}Er as a function of Be target thickness, calculated by LISE++ [35]. **(b)** Charge state fractions of fully-stripped (blue solid line) and H-like (magenta dashed line) ions of ^{181}Er with the thickness of Be target, calculated by GLOBAL [36] code. **(c)** The product of the fully-stripped fraction, the survival probability and the target thickness as a function of target thickness

6 Summary

In summary, the production of new neutron-rich rare-earth isotopes through fragmentation reactions of primary beams at 800 MeV/nucleon at HIRIBL has been evaluated. By comparing the fragmentation of ^{198}Pt with that of ^{208}Pb and ^{197}Au as well as with the fission of ^{238}U , it was found that ^{198}Pt may offer advantages for producing new isotopes in this region. The measured production cross sections for the heavy projectiles ^{208}Pb , ^{197}Au , and ^{198}Pt are well reproduced by EPAX3 and COFRA. Using EPAX3 and COFRA, the production yields of new isotopes from the fragmentation of ^{198}Pt were estimated. About 30 new isotopes could be discovered through the fragmentation of ^{198}Pt at HIRIBL at HIAF, providing a valuable opportunity to extend experimental access to the rare-earth region for studies in both nuclear physics and nuclear astrophysics.

Appendix A: Appendix

Table 1 summarizes the estimated production yields of the candidate new isotopes expected at HIAF.

Table 1 The estimated production yields for the new isotopes expected to be discovered at HIAF, calculated by EPAX3 and COFRA, respectively

Isotopes	Z	N	Production yield (pps)	
			EPAX3	COFRA
^{171}Eu	63	108	6.2×10^{-5}	7.2×10^{-5}
^{172}Eu	63	109	1.4×10^{-5}	—
^{173}Gd	64	109	4.4×10^{-4}	2.9×10^{-4}
^{174}Gd	64	110	1.1×10^{-4}	7.9×10^{-5}
^{175}Gd	64	111	2.4×10^{-5}	—
^{175}Tb	65	110	2.8×10^{-3}	2.1×10^{-3}
^{176}Tb	65	111	7.1×10^{-4}	3.1×10^{-4}
^{177}Tb	65	112	1.6×10^{-4}	7.0×10^{-5}
^{178}Tb	65	113	3.3×10^{-5}	—
^{177}Dy	66	111	1.6×10^{-2}	8.3×10^{-3}
^{178}Dy	66	112	4.1×10^{-3}	2.3×10^{-3}
^{179}Dy	66	113	9.2×10^{-4}	2.5×10^{-4}
^{180}Dy	66	114	1.8×10^{-4}	5.4×10^{-5}
^{181}Dy	66	115	3.2×10^{-5}	—
^{179}Ho	67	112	8.3×10^{-2}	5.4×10^{-2}
^{180}Ho	67	113	2.1×10^{-2}	8.2×10^{-3}
^{181}Ho	67	114	4.5×10^{-3}	1.8×10^{-3}
^{182}Ho	67	115	8.3×10^{-4}	1.6×10^{-4}
^{183}Ho	67	116	1.3×10^{-4}	2.3×10^{-5}
^{184}Ho	67	117	1.7×10^{-5}	—
^{181}Er	68	113	3.7×10^{-1}	2.0×10^{-1}
^{182}Er	68	114	8.9×10^{-2}	5.6×10^{-2}
^{183}Er	68	115	1.8×10^{-2}	6.2×10^{-3}
^{184}Er	68	116	3.2×10^{-3}	1.1×10^{-3}
^{185}Er	68	117	4.5×10^{-4}	5.3×10^{-5}
^{186}Er	68	118	5.1×10^{-5}	—
^{184}Tm	69	115	3.4×10^{-1}	2.0×10^{-1}
^{185}Tm	69	116	6.6×10^{-2}	4.0×10^{-2}
^{186}Tm	69	117	1.0×10^{-2}	3.0×10^{-3}
^{187}Tm	69	118	1.3×10^{-3}	2.9×10^{-4}
^{188}Tm	69	119	1.2×10^{-4}	—
^{188}Yb	70	118	2.9×10^{-2}	1.7×10^{-2}
^{189}Yb	70	119	3.1×10^{-3}	3.2×10^{-4}
^{190}Yb	70	120	2.3×10^{-4}	—
^{191}Lu	71	120	6.6×10^{-3}	6.7×10^{-4}
^{192}Lu	71	121	6.6×10^{-5}	—

Results are shown only for isotopes with production yields higher than 1.5×10^{-5} pps, which corresponds to one event per day

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Xiao-Hui Sun and He Wang. The first draft of the manuscript was written by Xiao-Hui Sun, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability The data that support the findings of this study are openly available in Science Data Bank at <https://cstr.cn/31253.11.sciedb.j00186.00901> and <https://doi.org/10.57760/sciedb.j00186.00901>

Declarations

Declaration of Non-Use of Generative AI The authors declare that no generative artificial intelligence (AI) or AI-assisted technologies were used in the writing, data analysis, code generation, or preparation of this manuscript. All work presented herein is the original product of the human authors.

Conflict of interest The authors declare that they have no conflict of interest.

References

1. A. Gade, S.N. Liddick, Shape coexistence in neutron-rich nuclei. *J. Phys. G Nucl. Part. Phys.* **43**, 024001 (2016). <https://doi.org/10.1088/0954-3899/43/2/024001>
2. N. Tsunoda, T. Otsuka, K. Takayanagi et al., The impact of nuclear shape on the emergence of the neutron dripline. *Nature* **587**, 66–71 (2020). <https://doi.org/10.1038/s41586-020-2848-x>
3. T. Otsuka, A. Gade, O. Sorlin et al., Evolution of shell structure in exotic nuclei. *Rev. Mod. Phys.* **92**, 015002 (2020). <https://doi.org/10.1103/RevModPhys.92.015002>
4. X. Sun, H. Wang, K. Yoneda et al., Production of neutron-rich nuclei in the vicinity of ^{78}Ni : Fragmentation reactions of unstable ^{81}Ga and ^{82}Ge beams. *Phys. Lett. B* **858**, 139081 (2024). <https://doi.org/10.1016/j.physletb.2024.139081>
5. H. Suzuki, K. Yoshida, N. Fukuda et al., Experimental studies of the two-step scheme with an intense radioactive ^{132}Sn beam for next-generation production of very neutron-rich nuclei. *Phys. Rev. C* **102**, 064615 (2020). <https://doi.org/10.1103/PhysRevC.102.064615>
6. K.A. Erb, J.E. Holden, I.Y. Lee et al., Quadrupole and hexadecapole deformations in rare-earth nuclei. *Phys. Rev. Lett.* **29**, 1010–1014 (1972). <https://doi.org/10.1103/PhysRevLett.29.1010>
7. J. Wu, S. Nishimura, G. Lorusso et al., 94β -decay half-lives of neutron-rich ^{55}Cs to ^{67}Ho : Experimental feedback and evaluation of the r -process rare-earth peak formation. *Phys. Rev. Lett.* **118**, 072701 (2017). <https://doi.org/10.1103/PhysRevLett.118.072701>
8. G.G. Kiss, A. Vitéz-Sveicz, Y. Saito et al., Measuring the β -decay properties of neutron-rich exotic Pm, Sm, Eu, and Gd isotopes to constrain the nucleosynthesis yields in the rare-earth region. *Astrophys. J.* **936**, 107 (2022). <https://doi.org/10.3847/1538-4357/ac80fc>
9. N. Fukuda, T. Kubo, D. Kameda et al., Identification of new neutron-rich isotopes in the rare-earth region produced by 345 MeV/nucleon ^{238}U . *J. Phys. Soc. Jpn.* **87**, 014202 (2018). <https://doi.org/10.7566/JPSJ.87.014202>
10. K. Haak, O.B. Tarasov, P. Chowdhury et al., Production and discovery of neutron-rich isotopes by fragmentation of ^{198}Pt . *Phys. Rev. C* **108**, 034608 (2023). <https://doi.org/10.1103/PhysRevC.108.034608>
11. O.B. Tarasov, A. Gade, K. Fukushima et al., Observation of new isotopes in the fragmentation of ^{198}Pt at FRIB. *Phys. Rev. Lett.* **132**, 072501 (2024). <https://doi.org/10.1103/PhysRevLett.132.072501>
12. T. Sumikama, N. Fukuda, T. Kubo et al., Expanding the isotopic frontier: Seven new neutron-rich rare-earth isotopes observed at RIKEN RI beam factory. *J. Phys. Soc. Jpn.* **95**, 024202 (2026). <https://doi.org/10.7566/JPSJ.95.024202>
13. R.C. Greenwood, R.A. Anderl, J.D. Cole et al., Identification of new neutron-rich rare-earth isotopes produced in ^{252}Cf fission. *Phys. Rev. C* **35**, 1965–1968 (1987). <https://doi.org/10.1103/PhysRevC.35.1965>
14. W. Urban, J.A. Pinston, G.S. Simpson et al., The $11/2^-$ [505] neutron extruder orbital in ^{159}Sm . *Phys. Rev. C* **80**, 037301 (2009). <https://doi.org/10.1103/PhysRevC.80.037301>
15. G.S. Simpson, W. Urban, J. Genevey et al., Two-quasiparticle isomers and bands of $^{154,156}\text{Nd}$ and $^{156,158,160}\text{Sm}$. *Phys. Rev. C* **80**, 024304 (2009). <https://doi.org/10.1103/PhysRevC.80.024304>
16. G.S. Simpson, W. Urban, J.A. Pinston et al., Near-yrast structure of $N = 93$ neutron-rich lanthanide nuclei. *Phys. Rev. C* **81**, 024313 (2010). <https://doi.org/10.1103/PhysRevC.81.024313>
17. H. Mach, A. Piotrowski, R.L. Gill et al., Identification of four new neutron-rich rare-earth isotopes. *Phys. Rev. Lett.* **56**, 1547–1550 (1986). <https://doi.org/10.1103/PhysRevLett.56.1547>
18. I. Tago, Y. Kawase, K. Oknao, Identification of ^{152}Ce . *Zeitschrift für Physik A Atomic Nuclei* **335**, 477–478 (1990). <https://doi.org/10.1007/BF01290198>
19. Y. Kawase, K. Okano, Identification of a new isotope ^{154}Pr . *Zeitschrift für Physik A Atomic Nuclei* **330**, 231–232 (1988). <https://doi.org/10.1007/BF01293404>
20. G.D. Dracoulis, G.J. Lane, R.O. Hughes et al., Structure of three-quasiparticle isomers in ^{169}Ho and ^{171}Tm . *Phys. Rev. C* **82**, 034317 (2010). <https://doi.org/10.1103/PhysRevC.82.034317>
21. P.A. Söderström, J. Nyberg, P.H. Regan et al., Spectroscopy of neutron-rich $^{168,170}\text{Dy}$: Yrast band evolution close to the $N_p N_n$ valence maximum. *Phys. Rev. C* **81**, 034310 (2010). <https://doi.org/10.1103/PhysRevC.81.034310>
22. K. Rykaczewski, K.L. Gippert, N. Kaffrell et al., Investigation of neutron-rich rare-earth nuclei including the new isotopes ^{177}Tm and ^{184}Lu . *Nucl. Phys. A* **499**, 529–545 (1989). [https://doi.org/10.1016/0375-9474\(89\)90544-7](https://doi.org/10.1016/0375-9474(89)90544-7)
23. J. Kurcewicz, F. Farinon, H. Geissel et al., Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS. *Phys. Lett. B* **717**, 371–375 (2012). <https://doi.org/10.1016/j.physletb.2012.09.021>
24. RIKEN BigRIPS Information, $^{238}\text{U} + \text{Be}$ fission cross sections (LISE++ data file). RIKEN Nishina Center, https://ribf.riken.jp/BigRIPSInfo/lise/238U_Be_fission.cs. Accessed 2025.
25. T. Kurtukian-Nieto, J. Benlliure, K.H. Schmidt et al., Production cross sections of heavy neutron-rich nuclei approaching the nucleosynthesis r -process path around $A = 195$. *Phys. Rev. C* **89**, 024616 (2014). <https://doi.org/10.1103/PhysRevC.89.024616>
26. J. Benlliure, K.H. Schmidt, D. Cortina-Gil et al., Production of neutron-rich isotopes by cold fragmentation in the reaction $^{197}\text{Au} + \text{Be}$ at 950 A MeV. *Nucl. Phys. A* **660**, 87–100 (1999). [https://doi.org/10.1016/S0375-9474\(99\)00386-3](https://doi.org/10.1016/S0375-9474(99)00386-3)
27. X. Zhou, J. Yang, the HIAF project team, Status of the high-intensity heavy-ion accelerator facility in china. *AAPPS Bull.* **32**, 35 (2022). <https://doi.org/10.1007/s43673-022-00064-1>
28. T. Kubo, D. Kameda, H. Suzuki et al., Bigrips separator and zero-degree spectrometer at RIKEN RI beam factory. *Progr. Theor. Exp. Phys.* **2012**, 03C003 (2012). <https://doi.org/10.1093/ptep/pts064>

29. H. Geissel, H. Weick, M. Winkler et al., The Super-FRS project at GSI. Nucl. Instrum. Meth. Phys. Res. Sect. B **204**, 71–85 (2003). [https://doi.org/10.1016/S0168-583X\(02\)01893-1](https://doi.org/10.1016/S0168-583X(02)01893-1)
30. M. Portillo, B. Sherrill, Y. Choi et al., Commissioning of the advanced rare isotope separator ARIS at FRIB. Nucl. Instrum. Meth. Phys. Res. Sect. B **540**, 151–157 (2023). <https://doi.org/10.1016/j.nimb.2023.04.025>
31. L. Sheng, X. Zhang, J. Zhang et al., Ion-optical design of high energy fragment separator (HFRS) at HIAF. Nucl. Instrum. Meth. Phys. Res. Sect. B **469**, 1–9 (2020). <https://doi.org/10.1016/j.nimb.2020.02.026>
32. L. Sheng, X. Zhang, H. Ren et al., Ion-optical updates and performance analysis of high energy fragment separator (HFRS) at HIAF. Nucl. Instrum. Meth. Phys. Res. Sect. B **547**, 165214 (2024). <https://doi.org/10.1016/j.nimb.2023.165214>
33. S.B. Ma, L.N. Sheng, X.H. Zhang et al., Opportunities for production and property research of neutron-rich nuclei around $N = 126$ at HIAF. Nucl. Sci. Tech. **35**, 97 (2024). <https://doi.org/10.1007/s41365-024-01454-w>
34. R. Grzywacz, R. Anne, G. Auger et al., Identification of μ s-isomers produced in the fragmentation of a ^{112}Sn beam. Phys. Lett. B **355**, 439–446 (1995). [https://doi.org/10.1016/0370-2693\(95\)00501-B](https://doi.org/10.1016/0370-2693(95)00501-B)
35. O. Tarasov, D. Bazin, Lise++: Radioactive beam production with in-flight separators. Nucl. Instrum. Meth. Phys. Res. Sect. B **266**, 4657–4664 (2008). <https://doi.org/10.1016/j.nimb.2008.05.110>
36. C. Scheidenberger, T. Stöhlker, W. Meyerhof et al., Charge states of relativistic heavy ions in matter. Nucl. Instrum. Meth. Phys. Res. B **142**, 441–462 (1998). [https://doi.org/10.1016/S0168-583X\(98\)00244-4](https://doi.org/10.1016/S0168-583X(98)00244-4)
37. H. Kumagai, T. Ohnishi, N. Fukuda, et al., Development of Parallel Plate Avalanche Counter (PPAC) for BigRIPS fragment separator. Nucl. Instrum. Meth. Phys. Res. Sect. B **317**, 717–727 (2013). <https://doi.org/10.1016/j.nimb.2013.08.050>
38. Y. Sun, Z. Sun, S. Wang et al., The drift chamber array at the external target facility in HIRFL-CSR. Nucl. Instrum. Meth. Phys. Res. Sect. A **894**, 72–80 (2018). <https://doi.org/10.1016/j.nima.2018.03.044>
39. F. García, T. Grah, J. Hoffmann et al., A GEM-TPC in twin configuration for the super-FRS tracking of heavy ions at fair. Nucl. Instrum. Meth. Phys. Res. Sect. A **884**, 18–24 (2018). <https://doi.org/10.1016/j.nima.2017.11.088>
40. X.B. Wei, H.L. Wei, Y.T. Wang et al., Multiple-models predictions for drip line nuclides in projectile fragmentation of $^{40,48}\text{Ca}$, $^{58,64}\text{Ni}$, and $^{78,86}\text{Kr}$ at 140 MeV/u. Nucl. Sci. Tech. **33**, 155 (2022). <https://doi.org/10.1007/S41365-022-01137-4>
41. C.W. Ma, H.L. Wei, X.Q. Liu et al., Nuclear fragments in projectile fragmentation reactions. Prog. Part. Nucl. Phys. **121**, 103911 (2021). <https://doi.org/10.1016/j.pnpnp.2021.103911>
42. C.W. Ma, X.X. Chen, X.B. Wei et al., Systematic behavior of fragments in Bayesian neural network models for projectile fragmentation reactions. Phys. Rev. C **108**, 044606 (2023). <https://doi.org/10.1103/PhysRevC.108.044606>
43. X.B. Wei, H.L. Wei, C.W. Ma et al., Predictions from several models for the cross sections of light neutron-rich isotopes by Q_g systematics in ^{40}Ar projectile-fragmentation reactions. Phys. Rev. C **111**, 034607 (2025). <https://doi.org/10.1103/PhysRevC.111.034607>
44. B. Mei, Improved empirical parameterization for projectile fragmentation cross sections. Phys. Rev. C **95**, 034608 (2017). <https://doi.org/10.1103/PhysRevC.95.034608>
45. K. Sümmerner, B. Blank, Modified empirical parametrization of fragmentation cross sections. Phys. Rev. C **61**, 034607 (2000). <https://doi.org/10.1103/PhysRevC.61.034607>
46. K. Sümmerner, Improved empirical parametrization of fragmentation cross sections. Phys. Rev. C **86**, 014601 (2012). <https://doi.org/10.1103/PhysRevC.86.014601>
47. A. Ozawa, O. Bochkarev, L. Chul'kov et al., Production cross-sections of light neutron-rich nuclei from ^{40}Ar fragmentation at about 1 GeV/nucleon. Nucl. Phys. A **673**, 411–422 (2000). [https://doi.org/10.1016/S0375-9474\(00\)00147-0](https://doi.org/10.1016/S0375-9474(00)00147-0)
48. B. Blank, S. Andriamonje, R. Del Moral et al., Production cross sections and the particle stability of proton-rich nuclei from ^{58}Ni fragmentation. Phys. Rev. C **50**, 2398–2407 (1994). <https://doi.org/10.1103/PhysRevC.50.2398>
49. M. Weber, C. Donzau, J. Dufour et al., Longitudinal momenta and production cross-sections of isotopes formed by fragmentation of a 500 A MeV ^{86}Kr beam. Nucl. Phys. A **578**, 659–672 (1994). [https://doi.org/10.1016/0375-9474\(94\)90766-8](https://doi.org/10.1016/0375-9474(94)90766-8)
50. J. Reinhold, J. Friese, H.J. Körner et al., Projectile fragmentation of ^{129}Xe at $E_{\text{lab}} = 790\text{A MeV}$. Phys. Rev. C **58**, 247–255 (1998). <https://doi.org/10.1103/PhysRevC.58.247>
51. M. de Jong, K.H. Schmidt, B. Blank et al., Fragmentation cross sections of relativistic ^{208}Pb projectiles. Nucl. Phys. A **628**, 479–492 (1998). [https://doi.org/10.1016/S0375-9474\(97\)00608-8](https://doi.org/10.1016/S0375-9474(97)00608-8)
52. M. Mocko, M.B. Tsang, L. Andronenko et al., Projectile fragmentation of ^{40}Ca , ^{48}Ca , ^{58}Ni , and ^{64}Ni at 140 MeV/nucleon. Phys. Rev. C **74**, 054612 (2006). <https://doi.org/10.1103/PhysRevC.74.054612>
53. D. Pérez-Loureiro, J. Benlliure, H.Á. Pol, Production of neutron-rich nuclei in fragmentation reactions of ^{132}Sn projectiles at relativistic energies. Phys. Lett. B **703**, 552–556 (2011). <https://doi.org/10.1016/j.physletb.2011.08.037>
54. J. Benlliure, M. Fernández-Ordóñez, L. Audouin et al., Production of medium-mass neutron-rich nuclei in reactions induced by ^{136}Xe projectiles at 1 A GeV on a beryllium target. Phys. Rev. C **78**, 054605 (2008). <https://doi.org/10.1103/PhysRevC.78.054605>
55. L.J. Mao, J.C. Yang, D.Q. Gao et al., Status of the HIAF accelerator facility in China. in *27th Russian Particle Accelerator Conference* (2021). <https://doi.org/10.18429/JACoW-RuPAC2021-TUX01>

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