Opportunities for production and property research of neutron-rich nuclei around N=126 at HIAF

Authors: Xin-Tong Du, Xiao-Bao Wei, Shao-Bo Ma, Li-Na Sheng, Xue-Heng Zhang, Shi-Tao Wang, Kai-Long Wang, Chun-Wang Ma, Hool-Jin Ong, Zhi-Yu Sun, Shu-Wen Tang, Yu-Hong Yu, Xue-Heng Zhang

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Abstract

The study of nuclide production and its properties in the N=126 neutron-rich region is the frontier and hot topic in nuclear physics and astrophysics research. The upcoming High energy FRagment Separator (HFRS) at the High Intensity heavy-ion Accelerator Facility (HIAF), an in-flight separator at relativistic energies, is characterized by high beam intensity, large ion-optical acceptance, high magnetic rigidity, and high momentum resolution power. It provides an opportunity for the study of the production and properties of neutron-rich nuclei around N=126. In this paper, an experimental scheme is proposed to produce the neutron-rich nuclei around N=126 and simultaneously measure their mass and lifetime based on the HFRS separator, and the feasibility of this scheme is evaluated by the simulations. The results show that under the high resolution optical mode many new neutron-rich nuclei approaching the r-process abundance peak around A=195 can be produced for the first time, and many nuclei with unknown mass and lifetime can be produced with high statistics. Using the time-of-flight corrected by the measured dispersive position and the energy loss information, the cocktails produced from the 208Pb fragmentation can be unambiguously identified. Moreover, the masses of some neutron-rich nuclei in the vicinity of N=126 can be measured with high precision using the time-of-flight magnetic rigidity technique. This indicates that the HIAF-HFRS facility has potential for the production and property research of neutron-rich nuclei around N=126, which is of great significance for expanding chart of nuclides, developing nuclear theories, and understanding the origin of heavy elements in the universe.

Full Text

Preamble

The study of nuclide production and properties in the neutron-rich N=126 region represents a frontier and hot topic in nuclear physics and astrophysics research. The upcoming High-energy FRagment Separator (HFRS) at the High Intensity heavy-ion Accelerator Facility (HIAF) is an in-flight separator operating at relativistic energies, characterized by high beam intensity, large ion-optical acceptance, high magnetic rigidity, and high momentum resolution power. This facility provides unprecedented opportunities for investigating the production and properties of neutron-rich nuclei around N=126. In this paper, we propose an experimental scheme to produce neutron-rich nuclei near N=126 and simultaneously measure their masses and lifetimes using the HFRS separator, evaluating its feasibility through detailed simulations. Our results demonstrate that under the high-resolution optical mode, many new neutron-rich nuclei approaching the r-process abundance peak around A=195 can be produced for the first time, with numerous nuclei of unknown mass and lifetime generated at high statistical yields. By employing time-of-flight corrected by measured dispersive position information combined with energy loss data, the cocktail products from 208Pb fragmentation can be unambiguously identified. Moreover, the masses of selected neutron-rich nuclei near N=126 can be measured with high precision using the time-of-flight magnetic rigidity technique. These findings indicate that the HIAF-HFRS facility holds significant potential for production and property studies of neutron-rich nuclei around N=126, which is crucial for expanding the chart of nuclides, developing nuclear theories, and understanding the origin of heavy elements in the universe.

Keywords: HFRS, fragmentation, neutron-rich nuclei around N=126, mass measurement, lifetime

Introduction

The investigation of nuclide production and properties in the neutron-rich N=126 region is essential for expanding the nuclear landscape, revealing the evolution of shell structure, and understanding astrophysical nucleosynthesis. According to nuclear astrophysics theory, approximately half of all nuclei heavier than iron in nature are believed to be produced through the rapid neutron capture process, or r-process [1-3]. The properties of N=126 neutron-rich nuclei, particularly their masses and lifetimes, play a crucial role in understanding the r-process abundance peak around A=195 [4-6]. However, experimental access to this region is extremely challenging due to low production cross-sections and the formidable difficulties associated with separation and identification. This lack of experimental data introduces significant uncertainties in predicted abundance patterns [7-10]. Consequently, research on the production and properties of neutron-rich nuclei around N=126 is of exceptional importance.

Over the past decades, producing N=126 neutron-rich nuclei in the laboratory

has remained a formidable challenge. Multi-nucleon transfer (MNT) reactions at near-barrier energies are expected to be a powerful technique for synthesizing and studying nuclides in the neutron-rich N=126 region [11-14]. Several facilities based on MNT reactions have been constructed or are being planned worldwide, including KISS at RIKEN [15], IGISOL at JYFL [16], the N=126 factory at ANL [17], and INCREASE at GSI [18]. Some neutron-rich isotopes of Pt, Ir, and Os have been successfully extracted as target-like fragments using the 136Xe+198Pt reaction system at the KISS facility [19,20]. However, to reduce plasma density in the gas cell induced by the primary beam and elastic products [15,21,22], experiments at these facilities typically employ low primary beam intensities. Furthermore, thin reaction targets must be used due to the low beam energies, which combined with low beam intensity, limits fragment yields. To increase available primary beam intensity, new designs incorporating gas-filled solenoids to suppress unwanted elastic particles have been proposed for future facilities such as NEXT at Groningen [23] and KISS-II at RIKEN [24].

In addition to MNT reactions at near-barrier energies, experimental results indicate that projectile fragmentation of 208Pb or 238U at relativistic energies may be an effective method for producing heavy neutron-rich nuclei in this region [25,26]. This approach requires simultaneous fulfillment of three conditions: high beam intensity, relativistic beam energy, and high-performance in-flight separators. High beam intensity is necessary for producing low cross-section products, while relativistic energy reduces the number of populated ionic charge states, thereby increasing collection efficiency. High-performance separators are crucial for separating and identifying heavy neutron-rich fragments [27]. The future Super-FRS in-flight facility at FAIR [28] meets these requirements, and searching for new isotopes while studying their properties along the N=126 line below 208Pb has been proposed as a primary physics objective for FAIR Phase-0 experiments [29].

The High-energy FRagment Separator (HFRS) [30,31] is an in-flight separator at relativistic energies currently under construction at the High Intensity heavy-ion Accelerator Facility (HIAF) [32,33] and will commence operation in a few years. Like the Super-FRS separator, it features large ion-optical acceptance, high resolution power, high magnetic rigidity, and excellent particle identification. Combined with the HIAF accelerator facility, which will provide beams up to 34 Tm corresponding to 238U35+ ions at 833 MeV/nucleon with intensities as high as 1$×10^{11}$ ions per pulse, neutron-rich nuclei around N=126 from projectile fragmentation at relativistic energies can be produced and purified using the HFRS separator. This provides a new opportunity for studying the properties of N=126 neutron-rich nuclei and understanding the third abundance peak in the r-process.

In this paper, we focus on the production of N=126 neutron-rich nuclei and the feasibility of studying their properties using the HIAF-HFRS facility. We first introduce measurement methods for nuclear properties such as mass and lifetime,

along with the layout of related experimental setups, followed by presentation of simulation results to verify feasibility.

Experimental Setups and Methods

Nuclear masses and lifetimes are of fundamental importance for r-process simulations. Using the HFRS separator at the HIAF facility, neutron-rich nuclei in the region along the N=126 line below 208Pb could be produced, and their properties such as mass and lifetime could be experimentally measured.

The layout of experimental setups for the HFRS separator is shown in Fig. 1 [Figure 1: see original paper]. A relativistic 208Pb or 238U primary beam will be extracted from the HIAF accelerator facility in slow extraction mode and implanted into a carbon production target at the HFRS separator entrance. Fragments of interest produced via fragmentation reactions will be collected and separated using the B -ΔE-B method [34,35], which combines magnetic rigidity (B) analysis with energy loss in an achromatic degrader (ΔE) at the pre-separator stage. The achromatic degrader will be placed at the PF2 dispersive plane. Unreacted primary beam will be intercepted in beam dump systems installed after each dipole magnet in the pre-separator according to the B deviation between the primary beam and desired isotopes.

The main separator will function as a spectrometer. At this stage, cocktail products will be identified by combining the ΔE-TOF-B method with isomer tagging techniques [36–38]. Energy loss (ΔE), time-of-flight (TOF), and B are measured to determine the atomic number Z and mass-to-charge ratio A/Q of fragments. By detecting delayed γ-rays emitted from short-lived isomeric states of certain fragments, the cocktails can be unambiguously identified. The schematic layout of particle identification setups is shown in Fig. 1. A multiple sampling ionization chamber (MUSIC) placed at MF6 will be used for ΔE measurement [39,40]. TOF information will be obtained from detectors installed at the PF4 and MF6 foci with a flight path of 118.03 m [31,41]. The B value will be determined from position measurements at the MF4 dispersive plane. At the HFRS final focal plane, a decay detector array consisting of a silicon array stopper surrounded by high-purity germanium detectors will be used for isomer tagging of selected fragments.

In the ΔE-TOF-B method, the mass-to-charge ratio A/Q of a fragment is determined using the following equations:

$$TOF = \frac{L}{v} = \frac{L\gamma}{\sqrt{\gamma^2 - 1}} \cdot \frac{1}{c}$$

Here L is the flight path length, v is the fragment velocity, γ is the relativistic Lorentz factor, and c represents the speed of light. The fragment mass m can then be expressed as:

$$m = Q\sqrt{(c \cdot TOF)^2 - 1}$$

From this equation, nuclear mass can be measured from the measured TOF and B while performing particle identification. This nuclear mass measurement method is called the B -TOF method [42,43]. Typically, precise B determination is achieved through trajectory reconstruction [44]. Assuming negligible object spot size, B values can be calculated from:

$$B\rho = B\rho_0 \left[1 + \frac{x_D}{(x|\delta)}\right]$$

where B $_0$ represents the central magnetic rigidity, x_D denotes the horizontal position at the dispersive plane, and (x|δ) represents the momentum dispersion. The B -TOF method features simple equipment, high measurement accuracy, low fragment yield requirements, and short measurement time, making it particularly suitable for measuring masses of short-lived nuclei with very low yields far from stability. Using this method, masses of several very neutron-rich nuclei have been accurately measured for the first time, including 48,49Ar and 56,57Sc with the A1900 separator and S800 spectrometer at NSCL [45,46], and 55–57Ca, 58–60Sc, 60–62Ti, and 62–64V with the BigRIPS separator and SHARAQ spectrometer at RIKEN [47,48].

From Eqs. (3) and (4), the mass resolution σ_m/m of the B -TOF method can be deduced as:

$$\left(\frac{\sigma_m}{m}\right)^2 = \left(\frac{\sigma_{B\rho}}{B\rho}\right)^2 + \left(\frac{\gamma^2 \sigma_{TOF}}{TOF}\right)^2$$

where σi *represents the standard deviation of measured quantity "i". To improve mass measurement accuracy, the common approach is to simultaneously improve the position resolution of detectors at the dispersive plane, the time resolution of the TOF system, and the momentum dispersion. For position measurement at dispersion focal planes, detectors with minimal material thickness should be used to reduce beam energy loss and multiple scattering effects on beam trajectory. Position-sensitive micro-channel-plate (MCP) tracking detectors with ~0.5 mm (σ) resolution [49] and low-pressure delay-line parallel-plate avalanche counters (DL-PPAC) with ~0.43 mm (σ) resolution [50] have been used for B -TOF mass measurements at NSCL and RIKEN, respectively. Using a typical ~0.5 mm (σ) position detector resolution combined with a high-resolution optical mode featuring ~10 cm/% momentum dispersion specially designed for the HFRS main separator, the uncertainty* σ{B }/B can be estimated at approximately 5$\times$10^{-5}$.

For TOF measurement, lower ion energy yields longer flight times, which improves TOF measurement accuracy. However, for N=126 neutron-rich heavy

nuclei, low ion energy can alter charge state populations passing through materials at the foci, affecting collection efficiency. Fig. 2 [Figure 2: see original paper] (a) shows the fractions of fully stripped ions in equilibrium charge states after passing through an Al degrader for N=126 region elements as a function of kinetic energy behind the degrader, calculated using the Global code [51]. The fractions decrease with increasing charge number and decreasing kinetic energy. When ion energy behind the Al degrader exceeds 350 MeV/nucleon, even for the heaviest Hg element, the fully stripped ion proportion remains above 50%, which is acceptable for mass measurement experiments. The HFRS flight path length is 118.03 m. Fig. 2 (b) shows the effect of TOF system time resolution on mass measurement accuracy at different ion energies. For an ion with 350 MeV/nucleon kinetic energy, the TOF resolution contribution to final mass resolution is ~9.9$×10^{-5}$ under a system resolution of ~30 ps (σ). This TOF resolution requirement is experimentally achievable. For example, at NSCL, two plastic scintillator detectors read out by photomultiplier tubes achieved ~30 ps (σ) resolution in primary beam tests [52]. An upgraded TOF system for B -TOF mass measurements developed at NSCL achieved better time resolution of 7.5 ps (σ) [53]. Additionally, two CVD diamond detectors forming a TOF system at RIKEN mass measurement experiments achieved 27 ps (σ) system resolution [54].

Based on the position measurement accuracy (~9.9$×10^{-5}$) and TOF measurement accuracy (5×10^{-5}) obtained above, a mass resolution of 1.1×10^{-4}$ can be achieved from Eq. (5), corresponding to σ_m ~460 keV for ~2000 statistical events and neutron-rich nuclei with mass number ~200 near N=126. This mass excess accuracy is generally sufficient to reveal shell structure evolution and constrain mass models far from stability [55].

Additionally, mass shifts contributed by isomers will be estimated from isomer measurements using the decay detector array at the HFRS final focal plane. Fragments will be stopped in the silicon array stopper after mass measurement, and germanium detectors installed near the stopper will detect isomeric γ-rays. From measurements of time elapsed between implantation and subsequent decay, isomeric lifetimes of implanted ions can be obtained by correlating with HFRS particle identification. Simultaneously, using a stopper composed of multiple highly-pixelated Double-Sided Silicon Strip Detectors (DSSDs) such as AIDA [56] or WAS3ABi [57], implanted nuclei and decay-emitting β-rays can be directly correlated within each detector pixel, providing direct measurement of β-decay lifetimes. This capability is critical for understanding the third abundance peak in the r-process.

Simulation and Analysis

With the HFRS separator at the HIAF facility, many neutron-rich nuclei around N=126 could be produced and their properties such as mass and lifetime experimentally measured. This is of great significance for expanding nuclide maps, developing nuclear theories, and understanding the origin of heavy elements in the universe. In this section, we first introduce a high-resolution optical mode

of the HFRS specifically developed for B -TOF mass measurement experiments, then investigate production, separation, identification, and nuclear mass measurement accuracy using the Monte Carlo simulation program MOCADI [58] with high-resolution ion-optics for neutron-rich nuclei around N=126.

High Resolution Ion-Optics

For B -TOF mass measurement experiments, the HFRS pre-separator will operate as a separator while the main separator functions as a spectrometer. High-resolution ion-optics for the spectrometer are necessary for accurate ion magnetic rigidity measurement. Using parameterized magnetic field distributions [31], the high-resolution ion-optics were designed with Winagile [59] and GICOSY [60] codes. Fig. 3 [Figure 3: see original paper] shows beam envelopes with initial beam spot sizes of X=$±1*mmandY* =±$1.5 mm. To improve momentum resolution compared to normal mode [31], horizontal angular acceptance is decreased to $±$5 mrad and momentum acceptance reduced to $±0.2 $ mm • mrad and horizontal beam spot size of $±$1 mm. The momentum dispersion at MF4 is 12 cm/%. With this dispersion, σ_{B }/B uncertainty can be estimated at ~4.17$×10^{-5}$ using a typical ~0.5 mm (σ) position detector resolution at the dispersive plane.

Production and Separation

To produce neutron-rich nuclei around N=126 via fragmentation, available projectiles mainly include 208Pb and 238U. Both projectiles are used in this simulation, with the specific choice for a given nucleus of interest determined by calculated yields. The HIAF Booster Ring (BRing) synchrotron has a maximum magnetic rigidity of 34 Tm and can accelerate 208Pb31+ and 238U35+ ions up to 850.74 and 833.15 MeV/nucleon, respectively. Beam intensities for lead and uranium are as high as 1.1$×10^{11}$ and 1.0$×10^{11}$ ions per pulse, respectively. Typical beam extraction time in slow extraction mode is 3 s with a 13 s repetition period. Corresponding beam spots on the production target are assumed to have Gaussian distributions with standard deviations of 0.4 mm and 0.6 mm in X and Y directions, respectively.

Using 204Au ion production as an example, the production and separation capability for neutron-rich nuclei around N=126 is simulated and studied using the HFRS high-resolution ion-optics. In the simulation, a graphite target installed at the PF0 focal plane serves as the production target. The graphite target thickness is set to 4.4 g/cm^2 for both Pb and U fragmentation reactions, corresponding to 50.1% of the Pb range and 56.5% of the U range, respectively. Additionally, a 75 mg/cm^2 niobium foil placed behind the production target achieves efficient electron stripping in both reactions, with over 75% of 204Au ions fully stripped, which is crucial for high transmission.

To purify fragments of interest, an achromatic Al degrader placed at the PF2 dispersive plane is used. As mentioned above, when ion energy behind the Al degrader exceeds 350 MeV/nucleon, the fully stripped ion fraction exceeds 50% for N=126 neutron-rich nuclei. Therefore, degrader thickness is optimized to

ensure fragment energy remains above 350 MeV/nucleon. The center thickness of the Al degrader is set to 44% and 36.8% of the 204Au range for Pb and U fragmentation reactions, respectively. This thickness combination ensures 204Au ions have approximately 356 MeV/nucleon kinetic energy after the degrader. Global calculations show the fully stripped 204Au ion proportion at this energy is as high as 57%. Considering the fully stripped ion proportion, HFRS magnetic rigidity is set according to fully stripped ions in both reactions.

Fig. 4 [Figure 4: see original paper] shows simulated transmissions of 204Au fragments from Pb and U fragmentation reactions as a function of separator length. A significant decrease occurs near PF1 and PF2, primarily caused by momentum deviation. At the PF2 focal plane, momentum slits are set to allow fragments with $±$0.2% momentum deviation to pass. Additionally, 204Au fragments from U fragmentation show greater transmission reduction due to larger momentum deviation compared to Pb fragmentation, because more nucleons must be removed to produce 204Au in U fragmentation, resulting in greater momentum deviation according to the Goldhaber model [61]. The opening of mass slits at the PF4 focal plane can be adjusted based on desired transmission and required nucleus count for mass measurements. In the simulation, mass slits are set to $±$5 mm, also causing transmission reduction due to fragment charge state populations. At the final focal plane, 204Au ion transmissions are 7% and 2% for Pb and U fragmentation, respectively—significantly lower than transmissions under normal optical modes described in Ref. [31], primarily due to smaller momentum and horizontal angular acceptances in the high-resolution optical mode.

The yields and purities of 204Au ions from Pb and U fragmentation reactions are estimated and shown in Fig. 5 [Figure 5: see original paper] (a) and (b), respectively. Isotope areas in the N-Z plane represent corresponding yields at the MF6 focal plane, obtained from the product of production cross-section, target nucleon density, and transmission. The parameterized FRACS formula provides reliable production cross-section estimates [62]. Target nucleon density is calculated from production target thickness, and transmission is obtained from MOCADI simulations. To assess purity, nuclei within Z$±10$and$N±10$regionsaround204Auareselected,withpuritydefinedastheratioof$fragment−of−interestyieldtototalyield.Fig.5showsthatPbfragmentationyieldsupto9.09×10^{4}$ ppp for 204Au ions with ~3.69% purity, both higher than U fragmentation results. Therefore, Pb fragmentation will be selected for future 204Au production experiments.

Using calculated cross-sections and simulated transmissions, yields of neutron-rich nuclei around N=126 are estimated and shown in Fig. 6 [Figure 6: see original paper]. In these estimates, primary beam, production target, and HFRS settings are similar to those used for 204Au production and purification. Production cross-sections are calculated with the FRACS formula, and based on simulation results, fragment transmissions from Pb and U fragmentation reactions are fixed at 7% and 2%, respectively. The figure presents results for a

5-day experiment, showing maximum fragment yields from Pb or U fragmentation. Clearly, many new neutron-rich nuclei approaching the r-process can be produced for the first time, alongside substantial yields of nuclei with unknown mass and lifetime. This demonstrates the great potential of the HIAF-HFRS facility for research on production and properties of neutron-rich nuclei around N=126.

Identification and Mass Measurement

Using 204Au production via Pb fragmentation as an example, this section studies particle identification and mass measurement accuracy using the B -TOF method.

As described above, particle identification is achieved through the ΔE-TOF-B method. In simulations, the influence of TOF and position detector material thickness on ion transmission and identification is ignored because they are thin compared to fragment ranges. The MUSIC energy loss detector thickness is equivalent to 300 μm silicon. TOF system time resolution (σ) is assumed to be 30 ps, while position detector resolution (σ) at the dispersive plane and ΔE detector energy resolution (σ) are set to 0.5 mm and 0.4%, respectively. To obtain unambiguous particle identification, TOF values must be corrected using measured dispersive position information at the MF4 focal plane to remove magnetic rigidity dependence from TOF spectra. Fig. 7 [Figure 7: see original paper] (a) shows the two-dimensional correlation between TOF and horizontal position x at the MF4 dispersion plane for Au isotopes. For all nuclides, the deviation between their TOF and central time-of-flight TOF_0 can be corrected using a linear function of dispersive position x:

$$TOF_0 = TOF - kx$$

where k represents the slope of the fitted linear function. The corrected TOF vs. x spectrum is shown in Fig. 7 (b), and comparison of original and corrected TOF spectra for Au isotopes appears in Fig. 7 (c). The corrected TOF shows improved resolution, benefiting particle identification.

The two-dimensional correlation spectrum of measured ΔE and corrected TOF provides unambiguous particle identification, as shown in Fig. 8 [Figure 8: see original paper]. Using isomer tagging, cocktails can be unambiguously identified. In this experimental setting, charge states between fully stripped ions and helium-like ions are observed. Hydrogen-like ions AZ(Z-1)+ generally appear between fully stripped ions with (A+2)Z(Z+) and (A+3)Z(Z+) in TOF spectra, while helium-like ions AZ(Z-2)+ appear between ions with (A+5)Z(Z+) and (A+6)Z(Z+). This pattern aids particle identification. Additionally, the degrader at the PF2 dispersive plane changes charge state populations of passing fragments. Nuclides circled with red dashed lines maintain unchanged charge states before and after the degrader. Nuclides stripped of one electron by the degrader fall within black dashed circles; under the same magnetic rigidity, these

nuclides have higher velocities and shorter flight times. Conversely, nuclides capturing an electron from the degrader have lower velocities and longer flight times, as shown in the green dashed circle in Fig. 8.

Using obtained particle identification spectra, we study mass measurement precision for N=126 neutron-rich nuclei via the B -TOF method at HFRS. The data analysis methodology follows Refs. [64,65]. Typically, nuclei with known masses calibrate the relationship between time-of-flight and mass-to-charge ratios, removing many experimental uncertainties. Among identified cocktails, ten fully stripped nuclides with well-known masses according to the 2012 Atomic Mass Evaluation (AME2012) [66] were selected as calibrants. These chosen nuclides only have known isomers with excitation energies below 454 keV, corresponding to typical B -TOF mass accuracy. Calibrants and their atomic mass excess values with uncertainties are listed in the left columns of Table 1 , while nuclides to be measured and their literature mass excess values appear in the right columns.

TABLE 1. Nuclides and their atomic mass excess values with uncertainties used for calibration and measurement [66]. Isotopes with known isomers having excitation energies below 454 keV are marked with m, and isotopes with estimated atomic mass excess are labeled with #.

Calibration nuclides (AME2012)	Nuclides to be measured (AME2012)
Isotope	Mass excess (keV)
194Os	-28961.5$±1.0\|198$Ir$#\| − 25821#\|\|195$Osm$\| − 29720±5\|200$Ir$#\| − 21611#\|\|196$Os$\| − 29532.7±1.0\|201$Ir$#\| − 19897#\|\|196$Irm$\| − 29220±11\|202$Pt$\| − 19627#\|\|197$Irm$\| − 28670±30\|203$Pt$#\| − 20650#\|\|199$Ir$\| − 27970±30\|203$Au$\| − 18770#\|\|199$Ptm$\| − 27670±30\|204$Au$#\| − \|\|200$Pt$\| − 27522.5±1.1\|205$Au$#\| − \|\|201$Pt$\| − 26870±30\| − \| − \|\|202Au| − 25821±$7

Nuclear masses m can be determined from corresponding atomic masses m_a using:

$$m = m_a - Zm_e + B_e(Z)$$

where Z and m_e represent nuclear charge number and electron rest mass, respectively, and B_e(Z) denotes total binding energy of extranuclear electrons, calculated with the approximate formula [67]:

$$B_e(Z) = 14.438Z^{2.39} + 1.55468 \times 10^{-6} Z^{5.35} \text{ [eV]}$$

From corrected TOF spectra, Gaussian fitting extracts centroids and standard deviations of TOF distributions for both calibration and measurement nuclides, yielding the mass calibration function f(τ,Z) relating time-of-flight centroids τ to mass-to-charge ratios m/q:

$$f(\tau, Z) = m/q = a_0 + a_1\tau + a_2\tau^2 + a_3\tau Z + a_{4Z} + a_{5Z}^2$$

where a_i are fit parameters. Z-related terms account for energy loss impact in the wedge degrader at the PF2 dispersive plane. Fit parameters in Eq. (9) are determined through iterative ^{2} minimization:

$$\chi^2 = \sum_{i=1}^{n} \frac{[(m/q)_{i,AME} - f(\tau_i, Z_i)]^2}{(\sigma_{AME})_i^2 + (\sigma_{stat})_i^2}$$

where n is the number of calibrants, (m/q)*{i,AME} is each calibration mass-to-charge ratio from AME2012 [66], and (*σ{AME})*i and (*σ{stat})_i denote literature [66] and statistical uncertainties, respectively. Statistical uncertainty is calculated based on TOF measurement uncertainty:

$$(\sigma_{stat})_i^2 = \sigma_{i,TOF}^2(a_1 + 2a_2\tau + a_{3Z})^2/N_i$$

where σ_{i,TOF} is the standard deviation of TOF distribution and N_i is the statistical count for each calibration.

After obtaining fit parameters, masses of measurement nuclides can be calculated from corresponding time-of-flight centroids using Eq. (9). Total uncertainties in mass results include statistical, fitting, and systematic uncertainties. Statistical uncertainty is estimated with Eq. (11). Fitting uncertainty σ_{fit} arises from calibration function parameter uncertainties, calculated via error propagation based on Eq. (9):

$$\sigma_{fit}^2 = \sum_{i,j} \frac{\partial f(\tau, Z)}{\partial a_i} \frac{\partial f(\tau, Z)}{\partial a_j} \sigma_{ij}$$

where *σ{ij} are fit parameter covariances. The fit is performed using the TMinuit class of the CERN ROOT package [68], which provides covariance matrix estimation. Systematic uncertainty* σ{sys} primarily originates from velocity differences caused by charge state changes in the wedge degrader and the method employed for TOF correction by dispersive position. Cross-validation of calibration nuclides evaluates systematic errors. Assuming n total calibration nuclides, the m/q value for each nuclide is determined by calibrating Eq. (9) fitting function with the remaining n-1 nuclides. The normalized chi-square value is then calculated as:

$$\chi^2_{norm} = \sum_{i=1}^{n} \frac{[(m/q)_{i,AME} - (m/q)_{i,fit}]^2}{(\sigma_{AME})_i^2 + (\sigma_{stat})_i^2 + (\sigma_{fit})_i^2 + \sigma_{sys}^2}$$

Differences between literature masses [66] and fitting function values as a function of mass-to-charge ratio are shown in Fig. 9 [Figure 9: see original paper] for calibration nuclides (circles) and measured nuclides (squares). Atomic mass excess results and uncertainty contributions for both calibration and measured nuclides are listed in Table 2 . Statistical uncertainties are estimated using 5-day statistical counts with Eq. (11). Nuclei 201Ir, 203Pt, and 205Au in Table 2 show significant fitting uncertainties because these nuclei have larger mass-to-charge ratios than calibration nuclides, requiring mass extrapolation. More calibration nuclides covering the mass-to-charge ratio range of measured nuclei would reduce fitting uncertainties. Systematic uncertainty is determined as 7.73 keV/q to achieve normalized chi-square unity in Eq. (13). Table 2 shows total measurement uncertainties are dominated by systematic uncertainties, primarily caused by TOF correction. Using additional measurement information such as position and angle data at PF4 or MF6 may reduce systematic uncertainties. Total measurement uncertainty for measured nuclei is better than 900 keV, meeting requirements for physical research and proving that properties of neutron-rich nuclei near N=126 can be studied based on the HFRS separator.

TABLE 2. Nuclides and their atomic mass excess values with uncertainties obtained from the mass calibration function, showing different contributions to total uncertainties. Isotopes with estimated atomic mass excess in literature [66] are labeled with #.

Isotope	m_{fit} (keV)	σ_{total} (keV)	σ_{fit} (keV)	σ_{stat} (keV)
194Os	-28961.5	$±$1.0	$±$0.5	$±$0.9
195Osm	-29720	$±$5	$±$2	$±$4
196Os	-29532.7	$±$1.1	$±$0.5	$±$1.0
196Irm	-29220	$±$11	$±$3	$±$10
197Irm	-28670	$±$30	$±$8	$±$29
199Ir	-27970	$±$30	$±$8	$±$29
199Ptm	-27670	$±$30	$±$8	$±$29
200Pt	-27522.5	$±$1.1	$±$0.5	$±$1.0
201Pt	-26870	$±$30	$±$8	$±$29
202Au	-25821	$±$7	$±$2	$±$7
198Ir#	-25821#	$±$850	$±$820	$±$30
200Ir#	-21611#	$±$870	$±$840	$±$30
201Ir#	-19897#	$±$890	$±$860	$±$30
202Pt	-19627#	$±$850	$±$820	$±$30
203Pt#	-20650#	$±$880	$±$850	$±$30
203Au	-18770#	$±$860	$±$830	$±$30

Isotope	m_{fit} (keV)	σ_{total} (keV)	σ_{fit} (keV)	σ_{stat} (keV)
204Au#	-	$±$870	$±$840	$±$30
205Au#	-	$±$890	$±$860	$±$30

Summary

The properties of N=126 neutron-rich nuclei play crucial roles in developing nuclear theories and understanding the r-process abundance peak around A=195. To produce these neutron-rich nuclei while measuring their masses and lifetimes, an experimental scheme has been proposed based on the HIAF-HFRS facility, with feasibility evaluated through simulations in this paper.

For these studies, a high-resolution optical mode of the HFRS was specially developed, featuring large momentum dispersion of 12 cm/% at the MF4 dispersive plane, which improves magnetic rigidity measurement accuracy in B -TOF mass measurement experiments. Under this high-resolution optical mode, yields of neutron-rich nuclei around N=126 from 208Pb or 238U fragmentation reactions were estimated using the FRACS formula and simulated transmissions. Results show that many new neutron-rich nuclei approaching the r-process abundance peak around A=195 can be produced for the first time, with many nuclei of unknown mass and lifetime generated at high statistics. Moreover, using time-of-flight corrected by measured dispersive position information and energy loss data, cocktail products from 208Pb fragmentation can be unambiguously identified, and masses of some neutron-rich nuclei around N=126 can be measured with accuracy better than 900 keV using the B -TOF technique. Using these new mass data combined with machine learning based on Bayesian neural networks as described in Refs. [7,8], nuclear masses in this region will be further accurately predicted, which is crucial for understanding the r-process abundance peak around A=195. These simulation results indicate that the HIAF-HFRS facility can provide opportunities for production and property research of neutron-rich nuclei around N=126.

Currently, the HIAF-HFRS facility is under construction. All devices including magnets, vacuum systems, power supplies, targets, degraders, and detectors are expected to be completed and tested by the end of 2024, after which they can be installed on-site. Meanwhile, high-performance detectors for TOF and position measurements in B -TOF mass measurement experiments have been proposed. For example, plastic scintillator detectors coupled with multiple photomultiplier tube readouts and diamond detectors are being developed for time measurements, and position-sensitive micro-channel-plate detectors with large active areas are being developed for position measurements. These developments may enable future property research experiments on neutron-rich nuclei around N=126.

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