Monte-Carlo simulation of ion distributions in a gas cell for multinucleon transfer reaction products at LENSHIAF spectrometer: Postprint

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Abstract

The multinucleon transfer (MNT) reaction is one promising way to produce neutron-rich heavy nuclei and even super heavy nuclei and attracts more and more attentions theoretically and experimentally. A low energy nuclear structure spectrometer called LENSHIAF specific to the MNT reactions will be designed and constructed in the ongoing big project HIAF in China. In the LENSHIAF spectrometer, the most challenge part is how to collect and stop efficiently the high-energy MNT products into the gas cell. By using Monte-Carlo method, the geometry of the gas cell, the thickness of the titanium window/degrader, and the optimal gas pressure filled in the gas cell have been calculated and estimated. For neutron-rich nuclei around N=126 from 136Xe+198Pt reaction, with a titanium window/degrader with a thickness of 2.5–3.5 um, a cylindrical helium gas cell with a length of 0.6 m and a diameter of 1.2 m can satisfy the requirements to stop the target-like fragments. For heavier and super heavy nuclei from 238U+238U reaction, with a 5–8 um thick titanium window/degrader, the cylindrical gas cell has to be as big as a length of at least 1.6 m and a diameter of 1.6 m.

Full Text

Preamble

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Abstract

The multinucleon transfer (MNT) reaction represents a promising approach for producing neutron-rich heavy nuclei and even superheavy nuclei, attracting increasing attention from both theoretical and experimental communities. Within the ongoing High Intensity heavy-ion Accelerator Facility (HIAF) project in China, a low-energy nuclear structure spectrometer called LENSHIAF, specifically designed for MNT reactions, will be constructed. The most challenging aspect of the LENSHIAF spectrometer is efficiently collecting and stopping the high-energy MNT reaction products within the gas cell. Using Monte Carlo methods, we have calculated and optimized the gas cell geometry, titanium window/degrader thickness, and optimal gas pressure. For neutron-rich nuclei near N=126 produced via the 136Xe+198Pt reaction, a cylindrical helium gas cell with a length of 0.6 m and diameter of 1.2 m, combined with a titanium window/degrader thickness of 2.5–3.5 µm, can effectively stop the target-like fragments. For heavier and superheavy nuclei from the 238U+238U reaction, a much larger cylindrical gas cell is required—at least 1.6 m in both length and diameter—with a titanium window/degrader thickness of 5–8 µm.

Keywords: neutron-rich nuclide, multinucleon transfer, radioactive ion beam, HIAF, Monte-Carlo method

1. Introduction

Approximately half of the nuclei in nature heavier than iron are believed to be synthesized through the rapid neutron capture process (r-process), which occurs in stellar environments with high neutron densities and temperatures [**?**]. The remnants on the r-process path decay toward the valley of β-stability, and the observed solar r-abundance distribution exhibits a peak around mass number 195, attributed to waiting-point nuclei with the "magic" neutron number N=126. Experimental information on these nuclei is extremely scarce for Z$ $80 because they cannot be produced through conventional fusion, fission, or fragmentation methods. Multinucleon transfer (MNT) reactions offer an alternative mechanism for producing neutron-rich nuclei far from stability. Cross sections for nuclei produced in 64Ni+207Pb [**?**], 136Xe+208Pb [**?**], and 136Xe+198Pt [**?**] have been measured experimentally. At GANIL in France, Watanabe et al. [**?**] measured absolute cross sections for isotopically identified products from MNT

in the 136Xe+198Pt system, confirming that MNT reactions are an optimal method for populating and characterizing neutron-rich isotopes around N=126.

MNT reactions are also attractive for studying superheavy nuclei synthesis. The synthesis of neutron-rich heavy and superheavy nuclei and investigation of their properties represent important current frontiers in both experimental and theoretical nuclear science. To date, the primary technique for synthesizing heavy isotopes with Z>100 has been fusion of a heavy target nucleus with a light-to-medium projectile nucleus. However, cross sections decrease dramatically as the isotopes of interest move further northeast on the chart of nuclides—for example, reaching approximately 0.5 picobarns for producing oganesson (Z=118)—and the resulting compound nuclei remain neutron-deficient relative to the β-stability line. Consequently, alternative reaction mechanisms such as MNT reactions have been proposed and explored. Numerous reaction systems, including 238U+238U [**?**, **?**], 238U+232Th [**?**], and 238U+248Cm [**?**], have been studied experimentally.

Today, MNT reactions between heavy nuclei are considered a promising pathway for producing neutron-rich heavy nuclei and superheavy nuclei to investigate nuclear structure properties far from β-stability. These reactions have been studied extensively for decades, both theoretically and experimentally (see references in Ref. [**?**]).

Within the ongoing HIAF (High Intensity heavy-ion Accelerator Facility) project [**?**], a low-energy nuclear structure spectrometer called LENSHIAF, specifically designed for MNT reactions, will be constructed [**?**]. Figure 1 [Figure 1: see original paper] schematically illustrates the conceptual design. In this spectrometer, research will focus on the synthesis and identification of new neutron-rich nuclei and investigation of their nuclear structure and decay properties. In the preliminary design, primary beams from the accelerator bombard a rotating target to produce neutron-rich nuclei via MNT reactions. These high-energy ions are stopped in the gas cell by optimizing the titanium degrader thickness and gas density. The ions are transported to the gas cell exit through a combination of electrostatic and radio-frequency fields, then extracted by an electrostatic field and supersonic gas flow. The extracted ions pass through a differential pumping section via a sextupole ion guide (SPIG) before injection into a radio-frequency quadrupole cooler and buncher (RFQCB). After cooling and accumulation, ion bunches are ejected and accelerated to kinetic energies of a few keV. The ions are separated by one or two mass separators according to their mass-to-charge ratio, with ions of interest directed to subsequent workstations for collinear laser spectroscopy, decay spectroscopy, and mass measurements using Penning traps [**?**] and multi-reflection time-of-flight mass spectrometers (MRTOF-MS) \cite{14–16}.

Among all these processes and devices, the greatest challenge lies in efficiently collecting and stopping the high-energy MNT reaction products within the gas cell. The primary parameters under investigation are the gas cell geometry, titanium window/degrader thickness, and optimal gas pressure. This paper

reports the Monte Carlo simulation process and results.

2. Simulation Details and Results

We selected two projectile-target systems as simulation examples. The first is the 136Xe+198Pt (target) system at a beam energy of 7.98 MeV/A, for which Watanabe et al. [**?**] have measured absolute cross sections for isotopically identified MNT products. The second is the 238U+238U system at 7.0 MeV/A, which has been extensively investigated since the late 1970s at GSI in Germany [**?**], with abundant experimental data available for comparison with theoretical predictions.

2.1. Double Differential Cross Sections of MNT Reactions

To describe the MNT process in low-energy heavy-ion collisions and understand the underlying dynamics, various semiclassical and microscopic models have been proposed. Semiclassical models such as the dinuclear system (DNS) [**?**], GRAZING [**?**], and complex WKB (CWKB) [**?**] have demonstrated reasonable success in predicting production cross sections for neutron-rich heavy nuclei in MNT reactions.

Microscopic dynamics models including the time-dependent Hartree-Fock (TDHF) model [**?**] and the improved quantum molecular dynamics (ImQMD) model \cite{20–23} have been developed to study the dynamic characteristics and energy dissipation in MNT reactions. The ImQMD model is a semiclassical microscopic dynamics approach that incorporates mean-field effects, nucleon-nucleon collisions, and the Pauli principle, and has been successfully applied to heavy-ion fusion near the Coulomb barrier and intermediate-energy heavy-ion collisions. The dynamical evolution of both reaction systems has been calculated using the ImQMD model [**?**, **?**]. The de-excitation of primary fragments was treated with the GEMINI code [**?**] for the 136Xe+198Pt system and the HIVAP code [**?**] for 238U+238U.

Figure 2 [Figure 2: see original paper] shows the double differential cross sections for 200Os from the 136Xe+198Pt system and 243U from 238U+238U. The rationale for selecting 243U for simulation will be discussed later. The two distributions exhibit distinctly different characteristics. Most 200Os ions are emitted at laboratory angles around 60° with total kinetic energies of approximately 150 MeV, corresponding to residues from target-like primary fragments. In contrast, 243U ions are predominantly emitted at angles of 35–50° with total kinetic energies of 600–1000 MeV, corresponding to residues from both target-like and projectile-like primary fragments.

2.2. A Simple Model

The simulation model is illustrated in Figure 3 [Figure 3: see original paper], comprising a target, titanium foil, and cylindrical gas cell. For 200Os simu-

lations, the 198Pt target thickness was set to 1.3 mg/cm^2, matching the experimental configuration in Ref. [**?**], and artificially divided into six layers to account for energy loss of the produced 200Os ions. For 243U ions, the 238U target thickness was chosen as 95 mg/cm^2 after considering optimal combinations of target and titanium degrader. A titanium foil placed at the gas cell entrance serves as a window to seal the cell, accept injected ions, and function as a solid degrader. The target-to-window distance is set to 10 mm to accommodate a potential rotating target system.

The cryogenic gas cell is cooled to 90 K and filled with helium gas at 80 mbar pressure, corresponding to a gas density equivalent to 260 mbar at room temperature—a typical condition for such gas cells.

We employed the SRIM code [**?**] to calculate stopping powers and ranges, using these calculated values as "experimental" data. Paul and Schinner [**?**] compared extensive stopping power data from various tables and codes to evaluate their reliability, finding that SRIM performs reasonably well for all ions and energies. However, SRIM cannot handle isotopes with Z>92, which motivated our selection of 243U for the 238U+238U system simulation. We utilized the Monte Carlo method for these simulations.

2.3. Ion Distribution of 200Os Stopped in the Gas Cell

Figures 4(a) and 4(b) [Figure 4: see original paper] show the calculated distributions of 200Os ions in the gas cell with titanium window thicknesses of 2.5 µm and 5.0 µm, respectively. The helium gas temperature is 90 K and pressure is 80 mbar. Figure 4(c) presents the transmission efficiency as a function of titanium window thickness, where transmission efficiency is defined as the ratio of 200Os ions stopped in the gas cell to those produced in MNT reactions. While a thicker titanium window absorbs more ion energy and reduces the stopping range in the gas cell, transmission efficiency decreases because many ions are stopped in the window itself. To maintain high transmission efficiency and reasonable mechanical strength, a titanium window thickness of 2.5–3.5 µm is optimal. Consequently, a cylindrical gas cell with 0.6 m length and 1.2 m diameter can satisfy the requirements for stopping target-like fragments from the 136Xe+198Pt system.

2.4. Ion Distribution of 243U Stopped in the Gas Cell

Figure 5 [Figure 5: see original paper] shows the calculated distributions of 243U ions in the gas cell at a helium gas temperature of 90 K for all cases. Because 243U ions are emitted from the target with significantly higher energies and smaller outgoing angles than 200Os ions, the transmission efficiency is quite high (>80%) for all considered configurations.

Figures 5(a)–(c) correspond to gas cells with titanium window thicknesses of 3, 7, and 10 µm, respectively, at 80 mbar pressure. These results demonstrate that for the 238U+238U system, a reasonably thick titanium window of 5–8

μm requires a very large cylindrical gas cell—at least 1.6 m in both length and diameter.

The gas cell size can be reduced by increasing helium gas density, as shown in Figures 5(d)–(e), where the titanium window thickness is fixed at 7 μm. Figure 5(d) corresponds to 120 mbar pressure, and Figure 5(e) to 160 mbar. While the gas cell size decreases accordingly, higher gas pressure may introduce difficulties in transporting stopped ions to the cell exit due to longer transport times, higher required radio-frequency voltages, and other technical challenges.

3. Summary

Within the ongoing HIAF project in China, the LENSHIAF spectrometer specifically designed for multinucleon transfer (MNT) reactions will be constructed. Monte Carlo simulations have been used to study the gas cell geometry, titanium window/degrader thickness, and optimal gas pressure.

For neutron-rich nuclei near N=126, we examined 200Os from the 7.98 MeV/A 136Xe+198Pt reaction. The simulations indicate that a titanium window/degrader thickness of 2.5–3.5 μm provides optimal transmission efficiency and mechanical strength, and a cylindrical helium gas cell with 0.6 m length and 1.2 m diameter can effectively stop the target-like fragments.

For heavier and superheavy nuclei, we selected 243U from the 7.0 MeV/A 238U+238U reaction due to SRIM code limitations. The simulations show that with a reasonable titanium window thickness of 5–8 μm, the cylindrical gas cell for the 238U+238U system must be substantially larger—at least 1.6 m in both length and diameter. Although increasing helium gas density can reduce the cell size, higher pressure may complicate ion transport to the cell exit due to longer transport times and higher radio-frequency voltage requirements.

It appears that two different gas cells may be necessary for these distinct reaction systems. Future work must carefully investigate methods for transporting stopped ions to the gas cell exit and extracting them with high overall efficiency. Additionally, separating and eliminating the primary beam and scattered ions from the MNT products remains an open challenge.

Acknowledgments

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References

[1] H. Grawe, K. Langanke, G. Martínez-Pinedo, Nuclear structure and astrophysics, Rep. Prog. Phys. 70 (9) (2007) 1525.
[2] O. Beliuskina, S. Heinz, V. Zagrebaev, V. Comas, C. Heinz, S. Hofmann, et al., On the synthesis of neutron-rich isotopes along the N = 126 shell in multinucleon transfer reactions, Eur. Phys. J. A 50 (10) (2014) 161.
[3] J. S. Barrett, W. Loveland, R. Yanez, S. Zhu, A. D. Ayangeakaa, M. P. Carpenter, et al., 136Xe+208Pb reaction: A test of models of multinucleon transfer reactions, Phys. Rev. C 91 (6) (2015) 064615.
[4] Y. X. Watanabe, Y. H. Kim, S. C. Jeong, Y. Hirayama, N. Imai, H. Ishiyama, et al., Pathway for the production of neutron-rich isotopes around the N=126 shell closure, Phys. Rev. Lett. 115 (17) (2015) 172503.
[5] Y. T. Oganessian, V. K. Utyonkov, Y. V. Lobanov, F. S. Abdullin, A. N. Polyakov, I. V. Shirokovsky, et al., Synthesis of superheavy nuclei in the 48Ca+244Pu reaction, Phys. Rev. Lett. 83 (16) (1999) 3154–3157.
[6] M. Schädel, J. V. Kratz, H. Ahrens, W. Brüchle, G. Franz, H. Gäggeler, et al., Isotope distributions in the reaction of 238U with 238U, Phys. Rev. Lett. 41 (7) (1978) 469–472.
[7] C. Golabek, C. Simenel, Collision dynamics of two 238U atomic nuclei, Phys. Rev. Lett. 103 (4) (2009) 042701.
[8] S. Wuenschel, K. Hagel, M. Barbui, J. Gauthier, X. G. Cao, R. Wada, et al., Experimental survey of the production of α-decaying heavy elements in 238U +232 Th reactions at 7.5–6.1 MeV/nucleon, Phys. Rev. C 97 (6) (2018) 064602.
[9] M. Schädel, W. Brüchle, H. Gäggeler, J. V. Kratz, K. Sümmerer, G. Wirth, et al., Actinide production in collisions of 238U with 248Cm, Phys. Rev. Lett. 48 (13) (1982) 852–855.
[10] L. Zhu, J. Su, P.-W. Wen, C.-C. Guo, C. Li, Multinucleon transfer process in the reaction 160Gd + 186W, Phys. Rev. C 98 (3) (2018) 034609.
[11] J. C. Yang, J. W. Xia, G. Q. Xiao, H. S. Xu, H. W. Zhao, X. H. Zhou, et al., High intensity heavy ion accelerator facility (HIAF) in China, Nucl. Instrum. Methods B 317, Part B (2013) 263–265.
[12] W. X. Huang, Y. L. Tian, Y. S. Wang, J. Y. Wang, Z. G. Gan, Z. Liu, et al., Opportunities and challenges of the general purpose spectrometer specific to multinucleon transfer reactions at HIAF, Nuclear Physics Review 34 (3) (2017) 409–413.
[13] W. X. Huang, Y. L. Tian, J. Y. Wang, Y. L. Sun, Y. S. Wang, Y. Wang, et al., Status of Lanzhou Penning Trap for accurate mass measurements, Nucl. Instrum. Methods B 317, Part B (2013) 528–531.
[14] Y. L. Tian, Y. S. Wang, J. Y. Wang, X. H. Zhou, W. X. Huang, Designing a multi-reflection time-of-flight mass analyzer for LPT, Int. J. Mass Spectrom. 408 (2016) 28–32.
[15] Y. S. Wang, Y. L. Tian, J. Y. Wang, X. H. Zhou, W. X. Huang, Design and optimization of a multi-reflection time-of-flight mass spectrometer for LPT, Nuclear Physics Review 34 (3) (2017) 624–629.
[16] W.-X. Huang, Y.-L. Tian, Y.-S. Wang, J.-Y. Wang, X.-H. Zhou, Optimiza-

tion of multi-reflection time-of-flight mass analyzer operating in in-trap-lift mode, Radiat Detect Technol Methods 2 (1) (2018) 1.
[17] A. Winther, Grazing reactions in collisions between heavy nuclei, Nucl. Phys. A 572 (1) (1994) 191–235.
[18] S. Szilner, L. Corradi, G. Pollarolo, S. Beghini, B. R. Behera, E. Fioretto, et al., Multinucleon transfer processes in 40Ca+208Pb, Phys. Rev. C 71 (4) (2005) 044610.
[19] K. Sekizawa, K. Yabana, Particle-number projection method in time-dependent Hartree-Fock theory: Properties of reaction products, Phys. Rev. C 90 (6) (2014) 064614.
[20] C. Li, F. Zhang, J. Li, L. Zhu, J. Tian, N. Wang, F.-S. Zhang, Multinucleon transfer in the 136Xe+208Pb reaction, Phys. Rev. C 93 (1) (2016) 014618.
[21] C. Li, P. W. Wen, J. J. Li, G. Zhang, B. Li, X. X. Xu, et al., Production mechanism of new neutron-rich heavy nuclei in the 136Xe+198Pt reaction, Phys. Lett. B 776 (2018) 278–283.
[22] K. Zhao, Z. Li, Y. Zhang, N. Wang, Q. Li, C. Shen, et al., Production of unknown neutron-rich isotopes in 238U+238U collisions at near-barrier energy, Phys. Rev. C 94 (2) (2016) 024601.
[23] N. Wang, K. Zhao, Z. Li, Systematic study of 16O-induced fusion with the improved quantum molecular dynamics model, Phys. Rev. C 90 (5) (2014) 054610.
[24] R. J. Charity, M. A. McMahan, G. J. Wozniak, R. J. McDonald, L. G. Moretto, D. G. Sarantites, et al., Systematics of complex fragment emission in niobium-induced reactions, Nucl. Phys. A 483 (2) (1988) 371–401.
[25] C. Shen, G. Kosenko, Y. Abe, Two-step model of fusion for the synthesis of superheavy elements, Phys. Rev. C 66 (6) (2002) 061602.
[26] J. F. Ziegler, M. D. Ziegler, J. P. Biersack, SRIM – the stopping and range of ions in matter (2010), Nucl. Instrum. Methods B 268 (11-12) (2010) 1818–1823.
[27] H. Paul, A. Schinner, Judging the reliability of stopping power tables and programs for heavy ions, Nucl. Instrum. Methods B 209 (2003) 252–258.

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