Advances in Heavy-Ion Collision Transport Theory for Superheavy Nuclei Synthesis: Postprint

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Abstract

The synthesis of superheavy nuclei is of great significance for expanding the nuclear chart, exploring nuclear properties under extreme conditions, and understanding the rapid neutron-capture process in nuclear astrophysics, representing a frontier field in nuclear physics research. This article reviews the current status and progress of heavy-ion collision transport theory, introduces several representative transport models, and presents the current status and latest research advances in the synthesis of superheavy nuclei based on both transport theory and experiments, with a focus on discussing the research status of heavy-ion fusion reactions and multi-nucleon transfer reactions. It also summarizes the progress of next-generation large-scale nuclear science facilities worldwide and outlines future international research plans for superheavy nuclei synthesis.

Full Text

Preamble

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Progress in Transport Models of Heavy-Ion Collisions for the Synthesis of Superheavy Nuclei

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Abstract

The synthesis of superheavy nuclei is crucial for expanding the nuclear landscape, exploring nuclear properties under extreme conditions, and understanding the rapid neutron capture process (r-process) in nuclear astrophysics, representing a frontier field in nuclear physics research. This article reviews the current status and progress of heavy-ion collision transport theory, introducing several representative transport models and their applications to superheavy nuclei synthesis, with a focus on fusion reactions and multinucleon transfer reactions. We also summarize the progress of new-generation nuclear science facilities worldwide and outline future research plans for superheavy nuclei synthesis.

Keywords: Transport theory, Superheavy nuclei, Fusion reaction, Multinucleon transfer reaction

1. Introduction

In 1966, Myers and Swiatecki predicted based on shell model theory that an "island of stability" exists near proton number Z=114 and neutron number N=184, where superheavy nuclei would exhibit significantly greater stability than others [1]. Recent theoretical models also predict doubly magic structures at Z=120 or 126 and N=184 [2,3], making the exploration of this island and the limits of nuclear mass and charge a persistent frontier in nuclear physics. Since the 1980s, major heavy-ion accelerator facilities have been constructed worldwide, including the GSI (Gesellschaft für Schwerionenforschung) heavy-ion accelerator system in Germany, the Dubna/FLNR-DRIBs (Dubna Radioactive Ion Beam accelerator complex) in Russia, the RIKEN-RARF (RIKEN Accelerator Research Facility) in Japan, the Berkeley 88-inch cyclotron complex in the United States, and China's HIRFL (Heavy Ions Research Facility in Lanzhou) [4]. These facilities have enabled nuclear physicists to further expand the nuclear chart into the superheavy region. Notably, the GSI laboratory discovered elements 107–112 through cold fusion reactions with ^{208}Pb and ^{209}Bi targets [5], while the RIKEN laboratory in Japan synthesized element 113 via the cold fusion reaction ^{70}Zn+^{209}Bi [6]. The Dubna laboratory in Russia synthesized elements 114–118 through hot fusion reactions using ^{48}Ca bombarding actinide targets [7], completing the seventh period of the periodic table. In 2022, the RIKEN laboratory extracted the quasielastic scattering barrier distribution from the fusion reaction ^{51}V+^{248}Cm to estimate the optimal incident energy for synthesizing element 119 [8]. The Dubna laboratory synthesized ^{286}Mc through the fusion reaction ^{48}Ca+^{243}Am and discovered the new nuclide ^{264}Lr in its decay products [9,10]. The Institute of Modern Physics of the Chinese Academy of Sciences synthesized ^{204}Ac and ^{207}Th [11,12] and collaborated with Argonne National Laboratory to produce ^{251}Lr [13]. By the end of 2022, nuclear physicists had discovered 3,338 nuclides, including 317 transuranium nuclides [14], as shown in Figure 1 [Figure 1: see original paper], where the crossed region represents the theoretically predicted "island of stability." However, more than 5,000 theoretically predicted nuclides remain undiscovered in the superheavy and neutron-rich heavy nuclear regions [15].

Currently, fusion reactions are the primary experimental method for synthesizing superheavy nuclei with Z > 103, with production cross sections typically ranging from nanobarns to femtobarns. These cross sections decrease as the proton number of the produced superheavy nucleus increases, making experimental identification extremely challenging [16]. Consequently, theoretical predictions of optimal projectile-target combinations and incident energies are critical. Moreover, using stable projectile-target combinations in fusion reactions tends to produce neutron-deficient nuclides, necessitating exploration of new mechanisms to synthesize neutron-rich superheavy nuclei. In 2018, Wuenschel et al. [17] measured significant α-particle emission in the multinucleon transfer reaction ^{238}U+^{232}Th, suggesting possible production of unknown neutron-rich nuclei with atomic numbers up to Z=116, though detection limitations prevented measurement of production cross sections. With future advances in detection technology, multinucleon transfer reactions hold promise as a new pathway to synthesize neutron-rich superheavy nuclei and reach the island of stability [18].

To accurately describe the dynamics of superheavy nuclei synthesis and predict production cross sections and optimal incident energies, nuclear physicists have developed various transport models. These include phenomenological models such as the nuclear diffusion model [19], two-step model [20], nucleon collectivization model [21], GRAZING model [22], and dinuclear system (DNS) model [23,24], as well as microscopic models like quantum molecular dynamics (QMD) type models [33–41], Boltzmann type models [33,47–54], and time-dependent Hartree-Fock (TDHF) type models [42–47]. While these models have achieved varying degrees of success in describing heavy-ion collisions, their different approximations of the dynamical process lead to discrepancies in predicting optimal projectile-target combinations and production cross sections for new nuclides [55].

2. DNS Model Framework for Superheavy Nuclei Synthesis

Phenomenological transport models describe nuclear reaction dynamics by introducing collective coordinates to establish dynamical evolution equations, thereby ignoring complex internal nucleon motions, reducing computational cost, and enabling broad application to heavy-ion collisions near the Coulomb barrier. The DNS model, proposed by Volkov and developed by Adamian et al. [23], can be applied to both fusion and multinucleon transfer reactions. As illustrated in

Figure 2 [Figure 2: see original paper], in multinucleon transfer reactions, the projectile and target undergo quasielastic or deep-inelastic scattering to form projectile-like and target-like fragments. Quasifission during the evolution of the dinuclear system across the Coulomb barrier also produces such fragments, which then de-excite to form final products. In fusion reactions, the dinuclear system formed after overcoming the Coulomb barrier evolves along the mass asymmetry degree of freedom under the potential energy surface to form a compact-shaped compound nucleus. The excited compound nucleus may either fission or de-excite to its ground state by evaporating light particles, ultimately forming the desired evaporation residue.

In the DNS model framework, fusion reactions can be divided into capture, fusion, and survival processes, with the evaporation residue cross section expressed as [24]:

$$\sigma_{ER}(E_{c.m.}) = \frac{2\mu}{E_{c.m.}} \sum_J (2J+1) T(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J) \quad (1)$$

where μ is the reduced mass, $E_{c.m.}$ is the center-of-mass energy, J is the angular momentum, T is the transmission coefficient, P_{CN} is the fusion probability, and W_{sur} is the survival probability.

Based on the DNS model, Ref. [25] found that stable beam ^{36}S produces neutron-deficient isotopes $^{280-283}$Fl with higher cross sections, while neutron-rich radioactive ^{46}Ar-induced reactions could also produce new neutron-rich isotopes $^{290-292}$Fl with sufficient beam intensity. Ref. [26] investigated orientation effects on evaporation residue cross sections in hot fusion reactions. As shown in Figure 3 [Figure 3: see original paper], where the bold curve represents the angular average, the DNS model reproduces experimental values well when orientation effects are considered. Using this approach, the production cross sections for synthesizing Z=119 and Z=120 superheavy elements via fusion reactions ^{48}Ca+^{252}Es and ^{48}Ca+^{257}Fm were calculated to be 0.32 pb and 0.23 pb, respectively. Since the DNS model only considers nucleon transfer along the mass asymmetry degree of freedom, it lacks dynamical effects on fusion reactions. Therefore, Ref. [27] introduced orientation effects and dynamical deformation into the model.

The capture process in multinucleon transfer reactions is calculated similarly to fusion reactions [24], with the initial fragment production cross section given by:

$$\sigma_{pr}(Z_1, N_1, E_{c.m.}) = \frac{2\mu}{E_{c.m.}} \sum_J (2J+1) T(E_{c.m.}, J) P(Z_1, N_1, t=\tau_{int}) \quad (2)$$

where $P(Z_1, N_1, t=\tau_{int})$ is the fragment distribution probability obtained from the potential energy surface [24]. The initial fragments are typically excited and must de-excite through particle evaporation or fission to produce secondary fragments, a process usually calculated using statistical models GEMINI or GEMINI++.

Ref. [28] validated the DNS model for multinucleon transfer reactions and predicted production cross sections for four new Rf isotopes via the $^{238}U+^{252}Cf$ reaction. Ref. [29] found complementarity between the GRAZING model and DNS model frameworks for multinucleon transfer reactions, and their combination significantly improved theoretical descriptions of experimental production cross sections. Building on this, Ref. [30] calculated production cross sections for neutron-rich isotopes with Z=99–102 via the $^{132}Sn+^{249}Cf$ reaction. Ref. [31] introduced deformation degrees of freedom and Monte Carlo de-excitation methods to develop an improved DNS-sysu model, which was used to investigate projectile effects in multinucleon transfer reactions, finding that ^{238}U beams are more advantageous for producing neutron-rich heavy nuclei. Additionally, the DNS model can be applied to pre-equilibrium cluster emission studies in multinucleon transfer reactions [32]. However, the model only considers sequential single-nucleon transfer, lacking cluster transfer that may exist in extremely neutron-rich or proton-rich nuclei, and its limited collective coordinates cannot provide dynamical information about intermediate reaction processes. Therefore, microscopic transport models are needed to track the entire reaction process.

3. QMD-Type Model Framework for Superheavy Nuclei Synthesis

The QMD model is a microscopic dynamical model based on molecular dynamics concepts that can comprehensively describe the entire nuclear reaction process and provide various intermediate information. In the QMD framework, each nucleon's single-particle wavefunction is described by a coherent Gaussian wave packet [33]:

$$\phi_i(r) = \frac{1}{(2\pi\sigma^2)^{3/4}} \exp\left[-\frac{(r-r_i)^2}{4\sigma^2} + \frac{i}{\hbar} r \cdot p_i\right] \tag{3}$$

where r_i and p_i are the coordinate and momentum of the i-th nucleon, and σ is the wave packet width.

In this framework, the projectile and target are first initialized in phase space using the Monte Carlo method, with sampling constrained by the ground-state properties of the nuclei. Qualified initial nuclei then evolve under the mean field according to canonical equations of motion, yielding final coordinate and momentum distributions for each nucleon. The QMD model simulates nuclear reactions event-by-event, enabling consideration of many-body correlations and fluctuations. However, except for treating nucleons as Gaussian wave packets, QMD shares the same physical concepts as classical molecular dynamics, limiting its applicability to low-energy heavy-ion reactions. To better describe heavy-ion collisions, several improved versions have been developed, including the isospin-dependent IQMD model [35,36], the EQMD model with phenomenological Pauli potential [37], and the ImQMD model [38,39]. The ImQMD model incorporates phase-space constraints, surface terms, and symmetry energy terms, successfully reproducing experimental data in the low-energy heavy-ion collision region.

In the ImQMD model, fusion is considered to occur when two independent nuclei overcome the Coulomb barrier and the mononuclear density remains stable during rotation or oscillation. Fusion cross sections at given incident energies can then be obtained through statistical analysis of numerous simulated events. Ref. [39] compared ImQMD calculations for ^{48}Ca+^{208}Pb producing No isotopes with DNS model results and experimental data, validating ImQMD for fusion reactions. Based on this, optimal projectile-target combinations for producing ^{243_248}No isotopes were identified.

For heavy systems with Coulomb factor $Z_p Z_t \geq 1600$, strong Coulomb repulsion inhibits compound nucleus formation, causing projectile and target to exchange nucleons through a neck formation until separation [56]. The resulting excited projectile-like and target-like fragments de-excite to produce final fragments. Ref. [40] compared DNS and ImQMD calculations of initial fragment mass distributions for the ^{136}Xe+^{208}Pb reaction with experimental data (Figure 4 [Figure 4: see original paper]), finding that ImQMD better reproduces experimental values for large nucleon transfers due to its inclusion of dynamical fluctuations. Similarly, Ref. [41] studied production cross sections for transuranium nuclides in ^{238}U+^{238}U collisions, finding that neutron-rich isotopes ^{254_256}Cf have production cross sections nearly three orders of magnitude smaller than ^{249}Cf due to the isospin dependence of fission barriers. Since QMD-type models require event-by-event simulation, they demand substantial computational resources. To reduce calculation time, the N-body wavefunction is approximated as a product of single-nucleon wavefunctions without antisymmetrization, and QMD models lack spin-orbit interactions, preventing proper treatment of shell effects. Therefore, microscopic transport models that automatically include quantum effects like exchange antisymmetry are needed.

4. TDHF-Type Model Framework for Superheavy Nuclei Synthesis

In the TDHF model based on mean-field approximation, the many-body wavefunction $\Psi(r,t)$ is expressed as a Slater determinant of single-particle states $\phi_\lambda(r,t)$: $\Psi(r,t) = \det\{\phi_\lambda(r,t)\}$. The TDHF equation is derived by varying the action S with respect to Ψ^* [42]:

$$i\hbar \frac{\partial}{\partial t}\phi_\lambda = \hat{h}\phi_\lambda \tag{4}$$

where the complex nucleon-nucleon interaction is described by Skyrme interactions. The TDHF framework incorporates quantum properties such as exchange antisymmetry and the Pauli exclusion principle, and its calculations are system-independent without adjustable parameters, enhancing predictive reliability. In nucleon transfer processes, the ground-state wavefunction is first solved using the Hartree-Fock equation, then translated according to the initial relative distance and impact parameter, and evolved via the TDHF equation to obtain the wavefunction at each time step. This yields time-dependent expectation values of physical quantities, enabling self-consistent description of nuclear reaction dynamics.

The density-constrained TDHF (DC-TDHF) model is obtained by applying constraints to the density distribution from TDHF evolution, which can extract microscopic nucleus-nucleus interaction potentials in heavy-ion reactions and solve for fusion probabilities using the Incoming Wave Boundary Condition (IWBC) method. Ref. [43] investigated the effect of tensor forces in Skyrme interactions on fusion reactions within the DC-TDHF framework, finding that the added tensor term suppresses sub-barrier fusion cross sections. Ref. [44] further confirmed the feasibility of producing Z=119 compound nuclei via the ^{50}Ti+^{249}Bk fusion reaction (Figure 5 [Figure 5: see original paper]). TDHF models can also be combined with macroscopic models for more accurate predictions. Ref. [45] successfully reproduced capture and fusion cross sections for cold fusion reactions producing compound nuclei with Z=102, 104, and 106 by incorporating TDHF constraints into coupled-channels and nuclear diffusion models.

In multinucleon transfer reactions, TDHF models calculate production probabilities using particle number projection methods and have recently been applied to superheavy region cross section calculations. Ref. [46] found that in the ^{238}U+^{124}Sn reaction, ^{124}Sn can transfer numerous nucleons to ^{238}U through inverse quasifission, forming new superheavy nuclides. Ref. [47] merged the Stochastic Mean-Field (SMF) model with TDHF to calculate mass distributions for ^{238}U+^{238}U and plans to incorporate GEMINI++ for final de-excited projectile-like and target-like products. Since TDHF lacks tunneling effects, it cannot describe sub-barrier fusion, and its mean-field approximation averages over all reaction channels, preventing extraction of single-channel information and potentially missing cluster effects. Future incorporation of fluctuation effects and pairing correlations will enable more appropriate descriptions of heavy-ion reaction dynamics.

5. Boltzmann-Type Model Framework for New Nuclide Synthesis

The semiclassical approximation of the TDHF equation is the Vlasov equation. Uehling and Uhlenbeck introduced a Pauli-blocking collision term into the Boltzmann equation, which combined with the Vlasov drift term yields the Boltzmann-Uehling-Uhlenbeck (BUU) equation [48]. Boltzmann-type models obtain initial nucleon distributions through nonlinear relativistic mean-field theory or Skyrme-Hartree-Fock methods and solve them numerically using the test-particle and grid methods [49]. Various improved versions have been developed by adding different physical quantities and detailed treatments, such as the isospin-dependent IBUU model [50], SMF model [51], and Boltzmann-Langevin-Equation (BLE) model [52], with comprehensive comparisons provided in Ref. [57].

Fragmentation reactions can synthesize nuclei near the dripline in light mass regions, which is crucial for studying the nuclear equation of state [58,59]. Although Boltzmann-type models accurately describe single-particle observables like collective flow and particle emission, ensemble averaging in the test-particle method loses many-body correlations, preventing description of many-body correlation observables such as mass distributions in multifragmentation. The BLE model addresses this by introducing a fluctuation term δK in the collision term:

$$\frac{\partial}{\partial t}f + \left(\frac{\mathbf{p}}{m}\cdot\nabla_r - \nabla_r U(\hat{f})\cdot\nabla_p\right)\hat{f}(r,p,t) = K(\hat{f}) + \delta K(r,p,t) \tag{5}$$

Further development of the IBLE model [53,54] incorporating isospin-dependent Pauli blocking effects successfully reproduces experimental values for light-region nuclide production in intermediate-energy fragmentation reactions. Ref. [54] calculated production cross sections for proton-rich nuclei with Z=20–25 based on radioactive ion beams and plans to extend the model to low-energy regions near the Coulomb barrier for superheavy nuclei synthesis predictions. Although Boltzmann-type models can theoretically derive mean fields and two-body collisions from nucleon-nucleon interactions, the enormous computational cost typically necessitates using parameterized mean fields and two-body collisions in practical calculations. This inconsistent treatment introduces many adjustable parameters, limiting predictive power and requiring unification of mean fields and two-body collisions within the same nucleon-nucleon interaction framework for self-consistent solutions.

6. Summary and Outlook

The synthesis of new superheavy nuclides is essential for studying superheavy nuclear properties, testing nuclear shell model theory, and exploring astrophysical r-process nucleosynthesis. With new reaction mechanisms and advances in accelerator and detection technologies, the number of artificially synthesized superheavy nuclides has grown continuously in recent decades. However, current experimental facilities still struggle to extend the nuclear chart to the island of stability due to limited beam intensities and separation/detection capabilities, necessitating new-generation large-scale facilities and exploration of novel reaction mechanisms.

This article reviewed the development and progress of heavy-ion collision transport theory, introducing experimental production mechanisms and recent advances in superheavy nuclei synthesis. We focused on the physical concepts and theoretical frameworks of phenomenological transport models (DNS), QMD-type models, TDHF-type models, and Boltzmann-type models, and discussed theoretical progress in synthesizing new neutron-rich superheavy nuclei based on these models, with emphasis on heavy-ion fusion and multinucleon transfer reactions. Phenomenological transport models like DNS have been widely applied to superheavy nuclei synthesis, though limited collective degrees of freedom restrict microscopic description capabilities. Recent improvements incorporating dynamical deformation and excitation energy effects on shell structure have further refined the theoretical framework. Semiclassical QMD and Boltzmann models have also achieved success in heavy-ion collisions, with ImQMD successfully applied to low-energy reactions, but both require unified descriptions of nucleon-nucleon interactions for self-consistent solutions. TDHF models, combined with density constraints and mean-field theory, can self-consistently describe superheavy nuclear reaction dynamics, though mean-field approximations prevent extraction of single-channel information. Future incorporation of pairing correlations and fluctuation effects will expand TDHF applications and complement macroscopic models for improved theoretical predictions.

In 2022, the Facility for Rare Isotope Beams (FRIB) in the United States successfully delivered beams and measured half-lives of new nuclides near N=28 close to the neutron dripline [60]. This facility can accelerate heavy-ion beams including ^{238}U to energies up to 200 MeV/u, expecting to synthesize 1,000 neutron-rich new nuclides [61]. China's High Intensity heavy-ion Accelerator Facility (HIAF) in Huizhou is scheduled for operation in 2025, providing the most intense low-energy heavy-ion beams for new superheavy element synthesis [62] and featuring a unique neutron-rich heavy nucleus separator for multinucleon transfer reactions. Japan's RIKEN SRILAC (Superconducting RIKEN Linear Accelerator), completed in 2019, will increase beam energies from 5.5 MeV/u to 6.5 MeV/u, with intense ^{51}V beams expected to accelerate the synthesis of element 119 [8,63]. Germany's GSI FAIR and France's GANIL-SPIRAL2 will provide 1–2 GeV/u heavy-ion beams upon completion. Russia's Dubna/FLNR laboratory commissioned the DC-280 cyclotron in 2018 with beam intensities up to 20 A, increasing superheavy nuclei production rates by two orders of magnitude, with the next goal being synthesis of new superheavy region nuclides [15]. With these new-generation facilities, nuclear physicists anticipate breakthroughs in understanding unknown superheavy nuclear properties and synthesis mechanisms, providing further tests and refinements of existing transport models.

Author Contributions

ZHANG Minghao: Drafted and revised the manuscript.
ZHANG Yuhai: Collected references and revised portions of the manuscript.
LI Jingjing: Revised model-related content.
TANG Na: Revised portions of the manuscript.
SUN Shuai: Provided reference opinions on mean-field sections.
ZHANG Fengshou: Supervised manuscript preparation, reviewed and ensured

scientific rigor.

References

1. Myers W D, Swiatecki W J. Nuclear masses and deformations[J]. Nuclear Physics, 1966, 81(1): 1–60. DOI: 10.1016/0029-5582(66)90639-0.
2. Rutz K, Bender M, Bürvenich T, et al. Superheavy nuclei in self-consistent nuclear calculations[J]. Physical Review C, 1997, 56(1): 238–243. DOI: 10.1103/physrevc.56.238.
3. Goriely S, Chamel N, Pearson J M. Hartree-Fock-Bogoliubov nuclear mass model with 0.50 MeV accuracy based on standard forms of Skyrme and pairing functionals[J]. Physical Review C, 2013, 88(6): 061302. DOI: 10.1103/physrevc.88.061302.
4. ZHANG Yuhai, ZHANG Gen, LI Jingjing, et al. Progress in the production of new radioactive nuclides based on large-scale scientific facilities[J]. Journal of Isotopes, 2022, 35(2): 104–113. DOI: 10.7538/tws.2022.35.02.0104.
5. Hofmann S, Münzenberg G. The discovery of the heaviest elements[J]. Reviews of Modern Physics, 2000, 72(3): 733–767. DOI: 10.1103/revmodphys.72.733.
6. Morita K, Morimoto K, Kaji D Y, et al. Observation of second decay chain from \$^{278}\$113[J]. Journal of the Physical Society of Japan, 2007, 76(4): 045001. DOI: 10.1143/jpsj.76.045001.
7. Oganessian Y T, Utyonkov V K, Kovrizhnykh N D, et al. New isotope ^{286}Mc produced in the ^{243}Am+^{48}Ca reaction[J]. Physical Review C, 2022, 106(6): 064306. DOI: 10.1103/physrevc.106.064306.
8. Tanaka M, Brionnet P, Du M T, et al. Probing optimal reaction energy for synthesis of element 119 from ^{51}V+^{248}Cm reaction with quasielastic barrier distribution measurement[J]. Journal of the Physical Society of Japan, 2022, 91(8): 084201. DOI: 10.7566/jpsj.91.084201.
9. Oganessian Y T, Utyonkov V K, Kovrizhnykh N D, et al. First experiment at the super heavy element factory: high cross section of ^{288}Mc in the ^{243}Am+^{48}Ca reaction and identification of the new isotope ^{264}Lr[J]. Physical Review C, 2022, 106(3): L031301. DOI: 10.1103/physrevc.106.l031301.
10. Yang H B, Gan Z G, Zhang Z Y, et al. New isotope ^{204}Ac[J]. Physics Letters B, 2022, 834: 137484. DOI: 10.1016/j.physletb.2022.137484.
11. Yang H B, Gan Z G, Zhang Z Y, et al. New isotope ^{207}Th and odd-even staggering in α-decay energies for nuclei with Z>82 and N<126[J]. Physical Review C, 2022, 105(5): L051302. DOI: 10.1103/physrevc.105.l051302.
12. Roberto J B, Alexander C W, Boll R A, et al. Actinide targets for the synthesis of super-heavy elements[J]. Nuclear Physics A, 2015, 944: 99–116. DOI: 10.1016/j.nuclphysa.2015.06.009.
13. Thoennessen M. Discovery of nuclides project[EB/OL]. (2022.12.21) [2023.02.01]. https://people.nscl.msu.edu/~thoennes/isotopes/index.html.
14. Loveland W D. The synthesis of new neutron-rich heavy nuclei[J]. Frontiers in Physics, 2019, 7: 23. DOI: 10.3389/fphy.2019.00023.

15. Cap T, Siwek-Wilczyńska K, Wilczyński J. No chance for synthesis of super-heavy nuclei in fusion of symmetric systems[J]. Physics Letters B, 2014, 736: 478–481. DOI: 10.1016/j.physletb.2014.07.062.
16. Zagrebaev V I. Synthesis of superheavy nuclei: nucleon collectivization as a mechanism for compound nucleus formation[J]. Physical Review C, 2001, 64(3): 034606. DOI: 10.1103/physrevc.64.034606.
17. Wuenschel S, Hagel K, Barbui M, et al. Experimental survey of the production of α-decaying heavy elements in $^{238}U+^{232}Th$ reactions at 7.5–6.1 MeV/nucleon[J]. Physical Review C, 2018, 97(6): 064602. DOI: 10.1103/physrevc.97.064602.
18. Zhu L, Feng Z Q, Li C, et al. Orientation effects on evaporation residue cross sections in ^{48}Ca-induced hot fusion reactions[J]. Physical Review C, 2014, 90(1): 014612. DOI: 10.1103/physrevc.90.014612.
19. Bao X J. Possibility to produce $^{293,295,296}Og$ in the reactions $^{48}Ca+^{249,250,251}Cf$[J]. Physical Review C, 2019, 100(1): 011601. DOI: 10.1103/physrevc.100.011601.
20. Zhang G, Sokhna C A T, Liu Z, et al. Production of neutron-rich isotopes $^{264,266,268,269}Rf$ by multinucleon transfer reactions based on ^{238}U beam[J]. Physical Review C, 2019, 100(2): 024613. DOI: 10.1103/physrevc.100.024613.
21. Wen P W, Li C, Zhu L, et al. Mechanism of multinucleon transfer reaction based on the GRAZING model and DNS model[J]. Journal of Physics G: Nuclear and Particle Physics, 2017, 44(11): 115101. DOI: 10.1088/1361-6471/aa8b07.
22. Tang N, Zhang X R, Li J J, et al. Production of unknown neutron-rich isotopes with Z=99–102 in multinucleon transfer reactions near the Coulomb barrier[J]. Physical Review C, 2022, 106(3): 034601. DOI: 10.1103/physrevc.106.034601.
23. Adamian G G, Antonenko N V, Scheid W, et al. Fusion cross sections for superheavy nuclei in the dinuclear system concept[J]. Nuclear Physics A, 1998, 633(3): 409–420. DOI: 10.1016/S0375-9474(98)00124-9.
24. Li J J, Li C, Zhang G, et al. Theoretical study on production of unknown neutron-deficient $^{280-283}Fl$ and neutron-rich ^{292}Fl isotopes by fusion reactions[J]. Physical Review C, 2018, 98(1): 014626. DOI: 10.1103/physrevc.98.014626.
25. Zhu L, Feng Z Q, Li C, et al. Orientation effects on evaporation residue cross sections in ^{48}Ca-induced hot fusion reactions[J]. Physical Review C, 2014, 90(1): 014612. DOI: 10.1103/physrevc.90.014612.
26. Bao X J. Possibility to produce $^{293,295,296}Og$ in the reactions $^{48}Ca+^{249,250,251}Cf$[J]. Physical Review C, 2019, 100(1): 011601. DOI: 10.1103/physrevc.100.011601.
27. Zhang G, Sokhna C A T, Liu Z, et al. Production of neutron-rich isotopes $^{264,266,268,269}Rf$ by multinucleon transfer reactions based on ^{238}U beam[J]. Physical Review C, 2019, 100(2): 024613. DOI: 10.1103/physrevc.100.024613.
28. Wen P W, Li C, Zhu L, et al. Mechanism of multinucleon transfer reaction

based on the GRAZING model and DNS model[J]. Journal of Physics G: Nuclear and Particle Physics, 2017, 44(11): 115101. DOI: 10.1088/1361-6471/aa8b07.

29. Tang N, Zhang X R, Li J J, et al. Production of unknown neutron-rich isotopes with Z=99–102 in multinucleon transfer reactions near the Coulomb barrier[J]. Physical Review C, 2022, 106(3): 034601. DOI: 10.1103/physrevc.106.034601.
30. Zhu L. Selection of projectiles for producing trans-uranium nuclei in transfer reactions within the improved dinuclear system model[J]. Journal of Physics G: Nuclear and Particle Physics, 2020, 47(6): 065107. DOI: 10.1088/1361-6471/ab871f.
31. Xu Siyu, Feng Zhaoqing. Cluster emission in massive transfer reactions based on dinuclear system model[J]. Nuclear Techniques, 2023, 46(3): 030501. DOI: 10.11889/j.0253-3219.2023.hjs.46.030501.
32. Zhang Fengshou, Ma Chunwang. Research progress in heavy ion collision transport theory and its application in superheavy nuclei synthesis[EB/OL]. (2022-07-15). https://www.koushare.com/video/videodetail/30562. DOI: 10.12351/ks.2207.1198.
33. Aichelin J. "Quantum" molecular dynamics—a dynamical microscopic n-body approach to investigate fragment formation and the nuclear equation of state in heavy ion collisions[J]. Physics Reports, 1991, 202(5–6): 233–360. DOI: 10.1016/0370-1573(91)90094-3.
34. Hartnack C, Oeschler H, Leifels Y, et al. Momentum dependence of nuclear collective flow in an isospin-dependent quantum molecular dynamics model[J]. Physical Review C, 1998, 58(4): 2283–2291. DOI: 10.1103/physrevc.58.2283.
35. Shi C Z, Ma Y G. α-clustering effect on flows of direct photons in heavy-ion collisions[J]. Nuclear Science and Techniques, 2021, 32(6): 66. DOI: 10.1007/s41365-021-00866-x.
36. Zhang Y H, Zhang G, Li J J, et al. Production cross sections of ^{248}No isotopes in fusion reactions[J]. Physical Review C, 2022, 106(1): 014625. DOI: 10.1103/physrevc.106.014625.
37. Li C, Zhang F, Li J J, et al. Multinucleon transfer in the ^{136}Xe+^{208}Pb reaction[J]. Physical Review C, 2016, 93(1): 014605. DOI: 10.1103/physrevc.93.014605.
38. Zhao K, Li Z X, Wang N, et al. Production mechanism of neutron-rich transuranium nuclei in ^{238}U+^{238}U collisions at near-barrier energies[J]. Physical Review C, 2015, 92(2): 024613. DOI: 10.1103/physrevc.92.024613.
39. Wu Z J, Guo L, Liu Z, et al. Production of proton-rich nuclei in the vicinity of ^{100}Sn via multinucleon transfer reactions[J]. Physics Letters B, 2022, 825: 136886. DOI: 10.1016/j.physletb.2022.136886.
40. Sun X X, Guo L, Umar A S. Microscopic study of the fusion reactions ^{40,48}Ca+^{78}Ni and the effect of the tensor force[J]. Physical Review C, 2022, 105(3): 034601. DOI: 10.1103/physrevc.105.034601.
41. Umar A S, Oberacker V E, Simenel C. Fusion and quasifission dynam-

ics in the reactions ^{48}Ca+^{249}Bk and ^{50}Ti+^{249}Bk using a time-dependent Hartree-Fock approach[J]. Physical Review C, 2016, 94(2): 024605. DOI: 10.1103/PhysRevC.94.024605.
42. Sun X X, Guo L. Microscopic study of compound-nucleus formation in cold-fusion reactions[J]. Physical Review C, 2022, 105(5): 054610. DOI: 10.1103/physrevc.105.054610.
43. Sekizawa K. Enhanced nucleon transfer in tip collisions of ^{238}U+^{124}Sn[J]. Physical Review C, 2017, 96(4): 041601. DOI: 10.1103/physrevc.96.041601.
44. Ayik S, Yilmaz B, Yilmaz O, et al. Merging of transport theory with the time-dependent Hartree-Fock approach: multinucleon transfer in U+U collisions[J]. Physical Review C, 2020, 102(2): 024619. DOI: 10.1103/physrevc.102.024619.
45. Novikov K V, Kozulin E M, Knyazheva G N, et al. Investigation of fusion probabilities in the reactions with ^{52},^{54}Cr, ^{64}Ni, and ^{68}Zn ions leading to the formation of Z=120 superheavy composite systems[J]. Physical Review C, 2020, 102(4): 044605. DOI: 10.1103/PhysRevC.102.044605.
46. Bertsch G F, Kruse H, Gupta S D. Erratum: Boltzmann equation for heavy ion collisions[J]. Physical Review C, 1986, 33(3): 1107. DOI: 10.1103/physrevc.33.1107.
47. Zhang Fengshou, Ge Lingxiao. Multiple fragmentation of nucleus[M]. Beijing: Science Press, 1998: 129–172.
48. Bertsch G F, Das Gupta S. A guide to microscopic models for intermediate-energy heavy-ion collisions[J]. Physics Reports, 1988, 160(4): 189–233. DOI: 10.1016/0370-1573(88)90170-6.
49. Li B A, Chen L W, Ko C M. Recent progress and new challenges in isospin physics with heavy-ion reactions[J]. Physics Reports, 2008, 464(4–6): 113–281. DOI: 10.1016/j.physrep.2008.04.005.
50. Chen L W, Ko C M, Li B A. Effects of isospin diffusion on isoscaling in heavy-ion collisions at intermediate energies[J]. Physical Review C, 2005, 72(6): 064309. DOI: 10.1103/physrevc.72.064309.
51. Colonna M, Toro G D. Boltzmann-Langevin equation for heavy-ion collisions[J]. Physical Review C, 1994, 49(3): 1410–1419. DOI: 10.1103/physrevc.49.1410.
52. Chomaz P, Colonna M, Randrup J. Nuclear spinodal fragmentation[J]. Physics Reports, 2004, 389(5): 263–440. DOI: 10.1016/j.physrep.2004.03.001.
53. Song Y D, Wei H L, Ma C W, et al. Improved FRACS parameterizations for cross sections of isotopes near the proton drip line in projectile fragmentation reactions[J]. Nuclear Science and Techniques, 2018, 29(7): 96. DOI: 10.1007/s41365-018-0439-4.
54. Ma C W, Wei H L, Liu X Q, et al. Nuclear fragments in projectile fragmentation reactions[J]. Progress in Particle and Nuclear Physics, 2021, 121: 103911. DOI: 10.1016/j.ppnp.2021.103911.
55. Crawford H L, Tripathi V, Allmond J M, et al. Crossing N=28 toward the neutron drip line: first measurement of half-lives at FRIB[J]. Physical Review Letters, 2022, 129(21): 212501. DOI: 10.1103/Phys-

RevLett.129.212501.
56. Thoennessen M. Exploring new neutron-rich nuclei with the facility for rare isotope beams[J]. Nuclear Data Sheets, 2014, 118: 85–90. DOI: 10.1016/j.nds.2014.04.025.
57. Xiao Guoqing, Xu Hushan, Wang Sicheng. HIAF and CiADS national research facilities: progress and prospect[J]. Nuclear Physics Review, 2017, 34(3): 275–283. DOI: 10.11804/NuclPhysRev.34.03.275.
58. Sakai H, Haba H, Morimoto K, et al. Facility upgrade for superheavy-element research at RIKEN[J]. The European Physical Journal A, 2022, 58(12): 238. DOI: 10.1140/epja/s10050-022-00888-3.
59. YANG Xiuxiu, ZHANG Gen, LI Jingjing, et al. Progress on synthesis of superheavy nuclei Z=119–122 with predictions from different theoretical models[J]. Nuclear Physics Review, 2020, 37(2): 151–159. DOI: 10.11804/NuclPhysRev.37.02.151.

Note: Figure translations are in progress. See original paper for figures.