

Research Advances in Low-Energy Nuclear Reactions and Related Nuclear Structure (Postprint)

Authors: Yang Lei, Lin Chengjian, Jia Huiming, Ma Nanru, Wen Peiwei, Yang Feng, Zhang Huanqiao

Date: 2023-09-04T00:00:00+00:00

Abstract

The nuclear reaction group at the China Institute of Atomic Energy (CIAE), leveraging large-scale scientific facilities both domestically and internationally, has achieved numerous original accomplishments in heavy-ion fusion-fission mechanisms, sub-barrier fusion enhancement mechanisms, exotic nuclear reaction mechanisms, as well as exotic structures and decays. This paper briefly reviews the representative achievements, which mainly include: (1) a systematic investigation of coupled-channels effects in positive Q-value neutron transfer, the proposal of a self-consistent method for evaluating the contribution of transfer coupling, and the discovery of an anomalous isotopic effect; (2) the proposal of a high-precision backward-angle quasi-elastic scattering method to extract nuclear deformation parameters, confirming the existence of nuclear hexadecapole deformation; (3) the proposal of a surrogate capture reaction method using light charged particles, based on which the critical $^{239}\text{Pu}(n,2n)$ reaction cross-section was determined; (4) a systematic study of exotic decay spectroscopy in sd-shell proton-rich nuclei, including the discovery of β -delayed two-proton emission in ^{22}Si , the identification of extreme isospin asymmetry in the β decay of the mirror nuclei $^{22}\text{Si}/^{22}\text{O}$, and the discovery of the strongest isospin-mixed state to date in ^{26}Si ; (5) systematic investigations of reaction mechanisms for exotic nuclear systems in the near-barrier energy region, providing the first experimental evidence that the classical dispersion relation is not applicable to the neutron halo nucleus $^6\text{He}+^{209}\text{Bi}$ system, along with detailed examinations of the reaction mechanisms of proton drip-line nuclei ^8B and ^{17}F . This paper also outlines prospects for future research based on the heavy-ion time-of-flight spectrometer and the Beijing Radioactive Ion Beam Facility.

Full Text

Preamble

Vol. 46, No. 8

August 2023

Nuclear Techniques www.hjs.sinap.ac.cn Vol. 46, No. 8 August 2023 ChinaXiv
Partner Journal

Progress on Low-Energy Nuclear Reactions and Related Nuclear Structure

YANG Lei, LIN Chengjian, JIA Huiming, MA Nanru, WEN Peiwei, YANG Feng, ZHANG Huanqiao
(China Institute of Atomic Energy, Beijing 102413, China)

Abstract

The nuclear reaction group at the China Institute of Atomic Energy has achieved multiple original results in heavy-ion fusion-fission mechanisms, sub-barrier fusion enhancement mechanisms, exotic nuclear reaction dynamics, and related exotic nuclear structures and decays by utilizing major scientific facilities both domestically and internationally. This paper briefly reviews representative achievements, including: (1) systematic investigation of coupled-channel effects for positive Q-value neutron transfers and proposal of a self-consistent method to evaluate transfer coupling contributions, revealing anomalous isotopic effects; (2) development of a high-precision backward quasi-elastic scattering method to extract nuclear deformation parameters, confirming the existence of hexadecapole deformation; (3) proposal of a surrogate capture reaction method using light charged particles, which yielded the critical $^{239}\text{Pu}(n,2n)$ reaction cross section; (4) systematic investigation of exotic decay spectroscopy for sd-shell proton-rich nuclei, discovering β -delayed two-proton emission in ^{22}Si and revealing extreme isospin asymmetry in β decays of the mirror nuclei $^{22}\text{Si}/^{22}\text{O}$, while identifying the strongest isospin-mixed state to date in ^{26}Si ; and (5) systematic studies of reaction mechanisms for exotic nuclear systems near the barrier, providing the first experimental evidence that the classical dispersion relation does not apply to the neutron-halo $^6\text{He}+^{209}\text{Bi}$ system, along with detailed investigations of reaction mechanisms for proton-drip-line nuclei ^8B and ^{17}F . Future prospects for work based on the heavy-ion time-of-flight spectrometer and Beijing Radioactive Ion Beam Facility are also discussed.

Keywords: heavy-ion induced nuclear reactions, energies near the Coulomb barrier, exotic nuclear structure

The nuclear reaction team at the China Institute of Atomic Energy (CIAE) was formed in 1988 with the establishment of the National Laboratory of Tandem

Accelerator Nuclear Physics. In its early stage, the team primarily relied on tandem accelerators to investigate heavy-ion fusion and fission mechanisms at near-barrier and sub-barrier energies, achieving multiple innovative results in fusion-fission dynamics and barrier distributions that established the team's international academic standing in low-energy heavy-ion nuclear reactions. Around 2000, with the emergence of radioactive ion beams, the team expanded its research directions while continuing in-depth studies of heavy-ion fusion-fission mechanisms, incorporating exotic nuclear reaction mechanisms and related nuclear structure studies, including weakly-bound nuclear reaction dynamics, halo nuclear structure, and high-excitation-state proton emission mechanisms, yielding fruitful results. This paper briefly reviews representative research achievements over the past four decades from three aspects: heavy-ion nuclear reaction mechanisms, exotic nuclear structure and decay, and weakly-bound nuclear reaction mechanisms, and discusses future development directions.

Heavy-Ion Nuclear Reaction Mechanism Studies

1.1 Fusion-Fission Mechanism Research

Compound nuclei or composite systems produced in heavy-ion reactions exist in states of high excitation and angular momentum, exhibiting fission characteristics distinctly different from spontaneous fission or fission induced by light ions. Due to the extremely complex reaction pathways, heavy-ion fusion-fission mechanisms remain a challenging problem. In 1986, Vandenbosch et al. [1] discovered that the anisotropy of fission fragment angular distributions for $^{12}\text{C}+^{236}\text{U}$ and $^{16}\text{O}+^{232}\text{Th}$ systems at near-barrier and sub-barrier energies significantly exceeded predictions from the Saddle-Point Transition-State (SPTS) model, representing the anomalous angular distribution anisotropy phenomenon. For these actinide targets with relatively low fission barriers (5–6 MeV), besides fission from complete fusion, direct reactions such as inelastic excitation and nucleon transfer can also induce fission in the target or target-like nuclei. While fission from inelastic excitation does not produce anomalous anisotropy, transfer-induced fission, where only partial linear momentum from the projectile is transferred to the target, may lead to anomalous anisotropy in target-like fission angular distributions. Therefore, distinguishing between complete fusion-fission and transfer-followed fission is key to understanding this anomaly. To address this issue, Zhang Huanqiao and Liu Zuhua from the team further developed the folding angle technique to effectively differentiate various fission components. The folding angle typically refers to the angle between the emission directions of two fission fragments. For complete fusion-fission, the projectile's linear and angular momentum are fully transferred to the compound nucleus (full momentum transfer), resulting in different folding angle distributions compared to partial momentum transfer processes in transfer-induced fission. Figure 1 [Figure 1: see original paper] shows the folding angle distributions for $^{16}\text{O}+^{232}\text{Th}$ at 78 MeV and 86 MeV in different angular bins (10° intervals), where the main peak on the right corresponds to full-momentum-transfer

complete fusion-fission events, while the smaller peak on the left represents transfer-followed fission components.

Using the folding angle technique combined with double-velocity measurements, non-complete-fusion fission events can be effectively subtracted. Based on this approach, the team systematically measured fission fragment angular distributions for ^{11}B [3], ^{12}C [4] + ^{237}Np , ^{11}B [4], ^{16}O [2] + ^{238}U , and ^{16}O [3,5], ^{19}F [2,6] + ^{232}Th , further confirming the existence of anomalous anisotropy in complete fusion-fission fragment angular distributions at near-barrier and sub-barrier energies, which attracted significant international attention [7]. Fusion-fission is a complex process where various non-equilibrium fission processes, non-compound-nucleus mechanisms, and nuclear structure effects in initial states can all contribute to anomalous fragment anisotropy, and no consistent explanation has yet emerged.

In 1995, Liu Zuhua and Zhang Huanqiao et al. [3] proposed a low angular momentum-dependent pre-equilibrium fission model: at near-barrier and sub-barrier energies, the orbital angular momentum transferred to the composite system is small, resulting in low total spin J , and the relaxation of the K -distribution (projection of total spin on the symmetry axis) depends on J . This low angular momentum increases the K -relaxation time, leading to fission before K -equilibration, i.e., K pre-equilibrium fission. Compared with the standard SPTS model, this low angular momentum-dependent pre-equilibrium fission model better describes experimentally observed fission fragment angular distributions and represents one of two internationally recognized models (the other being the deformation-dependent quasi-fission model proposed by Hinde et al. [8]).

Additionally, besides complete fusion-fission, fast fission and quasi-fission processes occur in heavy-ion collisions. Quasi-fission refers to situations where mass and K degrees of freedom have not equilibrated before a compound nucleus forms. In 1983, Back et al. [9] observed significant anisotropy in fission fragment angular distributions for $^{16}\text{O}+^{238}\text{U}$, interpreted as evidence for quasi-fission. Zhang Huanqiao et al. [10] measured fusion-fission excitation functions for $^{32,34}\text{S}+^{182,184}\text{W}$ systems at near-barrier energies and, using angular and mass distribution measurements, successfully resolved quasi-fission components in medium-mass systems for the first time—a significant advance in quasi-fission research.

To understand nuclear deformation effects on fission mechanisms, Lin Chengjian et al. [11] systematically studied fission fragment mass distributions for $^{48}\text{Ti}+^{144,154}\text{Sm}$, ^{162}Dy , ^{174}Yb , ^{186}W , ^{192}Os , ^{196}Pt , ^{200}Hg , ^{208}Pb systems at near-barrier energies. Figure 2 [Figure 2: see original paper] shows the width of mass distributions (σ_M) versus energy for different targets. For light or spherical targets, σ_M increases with incident energy, consistent with fusion-fission behavior. However, for heavy or deformed targets, σ_M increases rapidly with decreasing energy. This work also examined the complex relationships between fissility, nuclear deformation, and incident energy, laying

a foundation for further understanding quasi-fission dynamics.

1.2 Fusion Reaction and Coupled-Channel Effects

A distinctive feature of near-barrier nuclear reactions is strong coupled-channel effects, causing orders-of-magnitude enhancement in sub-barrier fusion cross sections. While existing coupled-channel theories successfully describe collective motion couplings (vibrational or rotational) from inelastic excitation, they cannot properly account for transfer channel couplings, particularly for positive Q-value neutron transfer channels. The team conducted systematic experimental studies, measuring fusion excitation functions using electrostatic deflector systems for $16,18\text{O}+50,52\text{Cr}$, 54Fe , 58Ni , $74,76\text{Ge}$ [12] and $32\text{S}+90,94,96\text{Zr}$ [13], $112,116,120,124\text{Sn}$, $144,154\text{Sm}$ systems, from which barrier distributions were extracted. The 18O system has positive Q-value neutron stripping channels (denoted by “-”), contrasting sharply with 16O systems, while 32S with neutron-rich targets has positive Q-value $+xn$ pickup channels (where “+” denotes pickup and “x” indicates neutron number) up to $+6n$. Combined with full coupled-channel model analysis, results show no significant fusion enhancement associated with positive Q-value transfer channels in 18O systems, whereas 32S systems exhibit strong fusion enhancement correlated with positive Q-value transfer channels, revealing the complexity of transfer reactions themselves and their couplings, including nucleon migration, rearrangement, energy dissipation, and nucleon correlations. To accurately evaluate transfer channel coupling contributions, the team proposed the concept of Residual Enhancement (RE) to subtract collective motion coupling contributions, self-consistently incorporating nuclear structure information in coupled-channel model calculations. Results show fusion enhancement correlates with $+xn$ Q-values but reveal anomalous isotopic effects in Zr systems [14], as shown in Figure 3 [Figure 3: see original paper], which existing coupled-channel models cannot explain and whose underlying physics requires further exploration.

1.3 Extraction of Key Actinide Nuclear Reaction Cross Sections

Actinide $(n,2n)$ reaction cross sections are crucial nuclear data for nuclear energy (fast reactors, thorium-based reactors, etc.) and defense applications, with $239\text{Pu}(n,2n)$ being particularly critical. However, China previously lacked independent measurement data and relied on foreign data. Measurement difficulties include: (1) direct $2n$ measurement is limited by strong neutron beam background; (2) activation methods require extremely high target purity (typically better than 10^{-10}); and (3) in-beam γ measurement requires complete branching ratio information limited by nuclear structure data. To meet national needs, the team proposed a surrogate reaction method using light charged particles (p , d , ^3He , α , etc.) to replace neutron capture, enabling $(n,2n)$ cross-section measurements over wide energy ranges.

This method overcomes spin-correction challenges faced by traditional surrogate reactions. First, method validation was performed using $232\text{Th}(\alpha,2n)$ to surro-

gate $^{235}\text{U}(n,2n)$, as both produce the same compound nucleus ^{236}U with identical excitation energies and spins, yielding identical $2n$ evaporation channel cross sections. By measuring fission cross sections for $\alpha+^{232}\text{Th}$ between 18–36 MeV and α activity of $2n$ evaporation residue ^{234}U , 14 energy points for $^{235}\text{U}(n,2n)$ between 6–19 MeV were obtained, showing good agreement with direct measurements and evaluated library data, validating the method. Subsequently, $^{236}\text{U}(\alpha,2n)$ was used to surrogate $^{239}\text{Pu}(n,2n)$, obtaining 15 energy points for $^{239}\text{Pu}(n,2n)$ between 6–20 MeV [15], as shown in Figure 4 [Figure 4: see original paper]. This represents China's first independently measured $^{239}\text{Pu}(n,2n)$ excitation function. The proposed surrogate capture reaction method opens a new pathway for measuring actinide $(n,2n)$ reaction cross sections.

Exotic Nuclear Structure and Decay

2.1 High-Order Nuclear Deformation

Nuclear deformation is a topic of broad interest. While low-order deformation parameters such as quadrupole and octupole (β_2 and β_3) can be determined through in-beam γ spectroscopy, precise measurement of high-order deformation like hexadecapole parameters (β_4) has long been challenging. The team proposed using low-energy backward quasi-elastic scattering to study nuclear deformation. At sub-barrier energies, backward quasi-elastic angular distributions are highly sensitive to coupled-channel effects, particularly deformation parameters, enabling β_4 extraction through fitting. To validate this method, three typical deformed nuclei in the rare-earth region— ^{152}Sm , ^{170}Er , and ^{174}Yb —were selected as targets, and high-precision backward quasi-elastic scattering excitation functions were measured for $^{16}\text{O}+^{152}\text{Sm}$, ^{170}Er , ^{174}Yb systems from above-barrier to deep sub-barrier energies [16]. Using χ^2 analysis of sub-barrier data to fit barrier distributions, high-precision β_4 values for the three targets were extracted, as shown in Figure 5 [Figure 5: see original paper]. These results agree well with those from other experimental methods (Coulomb excitation, Coulomb-nuclear interference, electron scattering) and theoretical calculations, providing direct experimental evidence for nuclear hexadecapole deformation.

2.2 Excited Halo Structure Studies

When nuclei far from the β -stability line exhibit extremely diffuse halo structures. The regions where halo nuclei appear, their structural properties, and their reaction mechanisms are hot topics in nuclear physics. Most discovered halo nuclei are near the drip lines. Can halo structures exist in nuclei on or near the β -stability line? The answer is affirmative based on halo formation conditions. Otsuka et al. [17] pointed out that halo phenomena are universal, and many excited states of nuclei on or near the β -stability line may possess halo structures.

To search for new halo states near the β -stability line, we measured angular distributions of outgoing channels ^{12}B and ^{13}C in $^{11}\text{B}(d,p)$ and $^{12}\text{C}(d,p)$ reactions

for several states of interest [18]. Based on forward-angle cross-section data, the Distorted-Wave Born Approximation (DWBA) method and Asymptotic Normalization Coefficient (ANC) method were used to extract valence neutron density distributions, root-mean-square (RMS) radii, and contributions from outer-shell nucleons. Due to its model independence, ANC results are more reliable. The extracted ANC coefficients for ^{13}C ground, first, and third excited states are $(1.93 \pm 0.17) \text{fm}^{-1/2}$, $(0.15 \pm 0.01) \text{fm}^{-1/2}$, and $(0.94 \pm 0.08) \text{fm}^{-1/2}$, respectively; RMS radii are $(3.39 \pm 0.17) \text{fm}$; and corresponding probabilities of valence neutrons outside the potential well are 14.3%, 50.3%, and 25.2%. These results confirm that the first excited state of ^{13}C is a halo state, representing the first experimental verification of an excited halo state on the β -stability line. For ^{12}B ground, second, and third excited states, ANC coefficients are $(1.16 \pm 0.10) \text{fm}^{-1/2}$, $(1.34 \pm 0.12) \text{fm}^{-1/2}$, and $(1.84 \pm 0.16) \text{fm}^{-1/2}$; RMS radii are $(3.16 \pm 0.32) \text{fm}$, $(4.01 \pm 0.15) \text{fm}$, and $(4.01 \pm 0.15) \text{fm}$; with outer neutron probabilities of 19.9%, 53.6%, and 66.8%. The second and third excited states of ^{12}B are identified as halo states, representing the second new halo nucleus discovered near the β -stability line.

The team also improved the single-particle potential model based on the nuclear core + valence particle picture originally proposed by Hansen and Jonson for halo nuclei. The original model only described neutron halo structure using a square-well potential, which differs from realistic conditions. Using a more realistic Woods-Saxon potential with Coulomb and spin-orbit coupling terms, the team investigated conditions for proton halo existence. Based on this improved model, RMS radii of valence protons in different orbitals of proton-drip-line nuclei ^8B and ^{17}F were calculated as functions of binding energy, as shown in Figure 6 [Figure 6: see original paper]. The calculated points clearly distribute along three lines, indicating distinct patterns for different orbital angular momentum l values. For $l=2$ states, only three points make reliable fitting difficult (shown as dashed lines), and halo formation in d-states is highly unlikely. Due to the Coulomb barrier, some resonant states with energies above zero but below the Coulomb barrier height V_B have finite lifetimes and may become proton halo resonant states. Therefore, the necessary condition for proton halo formation is: $0.511/R_{cn} < E_p < V_B$, where R_{cn} is the interaction potential radius, E_p is the valence proton energy, and V_B is the Coulomb barrier height. This work first established necessary conditions for proton halo formation and identified possible regions where proton halos may exist, providing practical guidance for discovering new halo and skin states.

2.3 Two-Proton Exotic Emission Mechanism

Two-proton emission is a unique decay mode of nuclei near the proton drip line, related to nucleon pairing correlations and nuclear astrophysical ($2p, \gamma$) processes, representing a frontier in research on proton-rich nuclei. High-excitation-state two-proton emission provides information on nucleon configurations and structures within nuclei, offering important insights into exotic nuclear structure, nucleon correlations, and quantum many-body theory.

Using proton-rich nuclei $^{28,29}\text{S}$ and $^{27,28}\text{P}$ produced by the Radioactive Ion Beam Line in Lanzhou (RIBLL) at the Institute of Modern Physics, Chinese Academy of Sciences, we systematically studied two-proton emission mechanisms and intrinsic correlations through Coulomb excitation to high-lying states [20–22]. Experimentally, silicon strip detectors were arranged in arrays to establish kinematically complete measurement methods. Data analysis employed relativistic kinematic reconstruction to obtain invariant masses of three-body final states, relative opening angles, relative momenta, and relative energies of the two protons. A Monte Carlo method incorporating three emission mechanisms (three-body uncorrelated emission, two-body sequential emission, and correlated two-proton emission) was developed. Correlated two-proton emission (i.e., 2He cluster emission) was observed in high-excitation states of $^{28,29}\text{S}$ [20], with ^{29}S representing the second case of excited-state 2He emission observed internationally, as shown in Figure 7 [Figure 7: see original paper]. Comparing $^{28,29}\text{S}$ with $^{27,28}\text{P}$ revealed that two-proton halo structure, rather than previously assumed high-deformation orbitals, is the primary cause of correlated two-proton emission [21].

2.4 Proton Drip-Line Nuclear Decay Spectroscopy

Nuclei far from the β -stability line have large decay energies and typically populate high-excitation states in daughter nuclei after β decay, which can subsequently decay via nucleon or cluster emission and fission, such as βn , βp , $\beta^2\text{n}$, $\beta^2\text{p}$, $\beta\alpha$, etc. These exotic decays serve as sensitive probes of nuclear structure near drip lines, providing knowledge of effective interactions (pairing, three-body forces, isospin asymmetry, etc.) and fundamental symmetries. Building upon high-excitation-state two-proton emission studies, the team shifted focus to exotic decays of ground states in drip-line nuclei, systematically conducting decay spectroscopy of extremely proton-rich nuclei in the sd shell.

Experiments were performed at RIBLL1. To address weak secondary beam intensities and improve beam utilization efficiency for higher statistics, the team developed three sets of stop-decay detector arrays based on silicon strip detectors, achieving detection efficiencies $>50\%$ for protons and $>15\%$ for double protons, energy resolution better than 50 keV, and detection thresholds below 150 keV. A continuous-beam implantation measurement method was developed, enabling identification of decay events with probabilities as low as one in a million [23]. Based on this system, decay properties of $^{20,21}\text{Mg}$, $^{22,23}\text{Al}$, $^{22,23,24,25}\text{Si}$, $^{26,27}\text{P}$, $^{27,28,29}\text{S}$, and $^{36,37}\text{Ca}$ were precisely measured [24], yielding high-precision data on masses, half-lives, and decay branching ratios, and discovering several exotic βp and $\beta^2\text{p}$ decays.

^{22}Si has neutron number $N=8$ and a Borromean structure, being the only nucleus with $T_z = 3$ in the light nuclear region. Previous experiments at GANIL observed only one βp decay. Using high-efficiency detection, we observed nine peaks in the decay proton spectrum of ^{22}Si , identifying the 5700 keV peak as $\beta^2\text{p}$ decay through position-energy correlations. The mass of ^{22}Si was derived

using isobaric analog state (IAS) Coulomb displacement energy relations, yielding a 2p separation energy of 108(125) keV, suggesting possible ground-state 2p emission [25]. Further, three β p decays were identified through p- γ coincidences, constructing the decay scheme shown in Figure 8 [Figure 8: see original paper]. Comparison with β decay of the mirror nucleus ^{22}O revealed extreme isospin asymmetry in decay to the first 1+ state, with $\delta = 209\%$ (where δ is the percentage difference between $\beta+$ and $\beta-$ decay probabilities). Shell model calculations including isospin-nonconserving forces reproduced experimental results, indicating this large asymmetry originates from the halo structure of the ^{22}Al s1/2 orbital [26]. This result provides a new experimental method for identifying halo structure and new insights into the origin of isospin violation.

In ^{27}S decay, 13 proton peaks were observed. After γ coincidence, their energy levels and branching ratios were determined, constructing the decay scheme shown in Figure 9 [Figure 9: see original paper], where starred levels are newly observed. This experiment first simultaneously measured low-excitation-state β p and $\beta\gamma$ decays, obtaining thermonuclear reaction rates for $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ of interest to nuclear astrophysics, and combined with $^{26}\text{Si}(p,\gamma)^{27}\text{P}$ from ^{27}S to study the ^{26}Al overabundance problem in the galaxy. The six lower-energy peaks (p1–p6) represent ^2p decay, with angular correlation analysis determining the sequential two-proton emission mechanism. Near the IAS state of daughter nucleus ^{26}Si ($E_x = 13055$ keV, $T = 2$), two states at 11912 keV and 13380 keV were discovered, with the 13380 keV ($T = 1$) state forming an isospin-mixed doublet with the IAS state having mixing matrix element $V = 130(21)$ keV and level spacing $\Delta E = 325(13)$ keV, representing the strongest isospin mixing discovered to date [28]. Isospin-mixed states involve both Fermi and Gamow-Teller (GT) transitions, where Fermi transitions relate to CKM matrix unitarity and GT transitions involve isospin symmetry breaking. Investigating the origin of this extremely strong isospin mixing in ^{26}Si will significantly advance understanding of these two important issues.

Weakly-Bound Nuclear Reaction Mechanisms

3.1 Energy Dependence of Optical Potentials

The nucleus-nucleus interaction potential is the most fundamental physical quantity needed to study nuclear reaction mechanisms. Due to its close connection with nuclear structure, optical potentials for halo nuclear systems typically exhibit properties different from tightly-bound nuclei, particularly their energy dependence in deep sub-barrier regions—a key unresolved question. Limited radioactive beam quality makes direct extraction of optical potential parameters from elastic scattering angular distributions difficult. Therefore, the team proposed an original method using transfer reactions with stable beams as probes to extract optical potential parameters for exit-channel exotic nuclear systems by fitting transfer reaction angular distributions [29]. This method offers advantages: (1) high-quality stable beams enable relatively high precision in statistics, energy, and angular resolution; (2) transfer reactions can populate different ex-

cited states in final channels, facilitating studies of potential parameter energy dependence and enabling dedicated investigations of specific nuclear states.

Based on this method, multiple transfer reaction measurements were performed at the Beijing HI-13 tandem accelerator to study optical potential properties of exit-channel exotic nuclear systems [30–35]. Particularly, through the single-proton transfer reaction $^{208}\text{Pb}(^7\text{Li},^6\text{He})^{209}\text{Bi}$, the reaction threshold for the neutron-halo $^6\text{He}+^{209}\text{Bi}$ system was determined for the first time, completely revealing anomalous “threshold anomaly” phenomena and demonstrating that the dispersion relation cannot describe the correlation between optical potential imaginary and real parts [34], as shown in Figure 10 [Figure 10: see original paper]. The dispersion relation is derived from causality, making its inapplicability a highly anomalous phenomenon whose underlying physics urgently requires further exploration.

Additionally, we applied Bayesian methods to extract optical potentials for exotic nuclear systems [36]. First, the influence of prior distributions on Bayesian analysis results was investigated. For $^6\text{Li}+^{209}\text{Bi}$ elastic scattering data, two previously reported imaginary depth trends from literature were adopted as prior distributions, along with a uniform distribution over a certain range for comparison. Results showed that Bayesian analysis conclusions strongly depend on the chosen prior distribution, indicating that due to ambiguities in phenomenological optical models, elastic scattering data cannot sufficiently constrain posterior distributions of optical potential parameters. In such cases, conclusions from uniform or unbiased frequentist methods can serve as prior distributions for Bayesian analysis of elastic scattering data. This work lays the foundation for further application of Bayesian methods to optical potential analysis of exotic nuclear systems.

3.2 Reaction Mechanisms of Proton Drip-Line Nuclei

With improvements in radioactive beam intensity/quality and detection capabilities, studies of nuclear reaction mechanisms induced by exotic nuclei in the Coulomb barrier energy region have become a hot topic. Weakly-bound nuclei readily break up due to low binding energies, and breakup channels couple to elastic scattering and fusion channels, affecting the entire reaction dynamics. For the proton-rich region, only a few experimental results exist, making reaction mechanisms of proton-rich nuclei near the barrier an unexplored frontier. Current research focuses on ^8B and ^{17}F nuclei. ^8B is a proton-halo nucleus with proton separation energy of only 138 keV. ^{17}F is a proton-drip-line nucleus with proton breakup threshold of 600 keV, and its first excited state is believed to have proton halo structure. We conducted complete kinematic measurements for both nuclei using the Center for Nuclear Study Radioactive Ion Beam separator (CRIB) at the University of Tokyo [37].

For the $^{17}\text{F}+^{58}\text{Ni}$ system, measurements were performed at four near-barrier energies (43.6 MeV, 47.5 MeV, 55.7 MeV, and 63.1 MeV) [38]. To identify

low-energy heavy reaction products, a Multilayer Ionization-chamber Telescope Array (MITA) [39] was designed, consisting of 10 quadruple telescopes covering approximately 8% of 4π solid angle. Based on MITA's powerful particle identification capability, complete identification of reaction products for $17\text{F}+58\text{Ni}$ was achieved for the first time at near-barrier energies, enabling extraction of quasi-elastic scattering angular distributions, breakup reaction angular distributions, and total fusion excitation functions—data covering nearly all reaction channels. Excitation functions for each channel are shown in Figure 11 [Figure 11: see original paper]. Results indicate that fusion dominates at above-barrier energies, decreasing exponentially with energy. At near-barrier and sub-barrier energies, direct processes like breakup/transfer dominate. Compared with $16\text{O}+58\text{Ni}$, $17\text{F}+58\text{Ni}$ shows enhanced total fusion cross sections at sub-barrier energies. Detailed calculations using different reaction models reveal that non-elastic breakup is the main mechanism producing 16O , while sub-barrier fusion enhancement primarily results from strong coupling to continuum states. This represents the first attempt to understand complex reaction mechanisms of exotic nuclei from a complete reaction channel perspective and provides crucial experimental data for advancing relevant nuclear reaction models.

For the proton-halo nucleus $8\text{B}+120\text{Sn}$ system, measurements were performed at two near-barrier energies of 38.7 MeV and 46.1 MeV [40]. Since reaction products are relatively light, silicon detector telescopes suffice for identification. To improve detection efficiency for breakup fragment coincidence measurements, the Silicon Telescope Array for Reactions induced by Exotic nuclei (STARE) [41] was developed, consisting of 10 silicon telescopes with compact geometry covering 40% of 4π solid angle. Based on this array, correlated breakup fragment measurements for proton-halo nucleus 8B were achieved for the first time. Breakup angular distributions indicate that elastic breakup is the dominant mechanism producing 7Be , providing definitive evidence that breakup is the main direct reaction process. Through energy and angular correlations of breakup fragments (Figure 12 [Figure 12: see original paper]), the complete breakup process was reconstructed. Data analysis employed Continuum-Discretized Coupled Channels (CDCC) calculations combined with Markov Chain Monte Carlo methods for microscopic description of breakup and continuum coupling effects. Results show that breakup through the $1+$ resonance state accounts for only 4% of the total breakup cross section, with 8B breakup dominated by prompt breakup in the exit channel.

Summary and Outlook

Over the past four decades, the CIAE nuclear reaction team has achieved multiple original results in heavy-ion fusion-fission mechanisms, sub-barrier fusion enhancement, exotic nuclear reaction mechanisms, and exotic structures and decays. Future work will continue deepening existing research while exploring new directions, such as multi-nucleon transfer reaction mechanisms using the newly constructed Heavy-ion Time of Flight (HiTOF) spectrometer to provide

new approaches for superheavy element synthesis, and unstable nuclear reaction mechanisms and exotic structure studies using the newly commissioned Beijing Radioactive Ion beam Facility (BRIF).

Author Contributions: Yang Lei collected data and wrote the manuscript; Lin Chengjian, Jia Huiming, Ma Nanru, and Wen Peiwei provided relevant data and figures; Yang Feng and Zhang Huanqiao provided guidance. All authors reviewed and revised the manuscript.

References

- [1] Vandenbosch R, Murakami T, Sahm C, et al. Anomalously broad spin distributions in sub-barrier fusion reactions[J]. *Physical Review Letters*, 1986, 56(12): 1234–1236. DOI: 10.1103/PhysRevLett.56.1234.
- [2] Zhang H Q, Liu Z H, Xu J C, et al. Anomalous anisotropy of fission fragments in near- and sub-barrier complete fusion-fission reactions of $^{16}\text{O}+^{232}\text{Th}$, $^{19}\text{F}+^{232}\text{Th}$, and $^{16}\text{O}+^{238}\text{U}$ [J]. *Physical Review C, Nuclear Physics*, 1994, 49(2): 926–931. DOI: 10.1103/physrevc.49.926.
- [3] Liu Z H, Zhang H Q, Xu J C, et al. Preequilibrium fission at low angular momentum[J]. *Physics Letters B*, 1995, 353(2–3): 173–178. DOI: 10.1016/0370-2693(95)00461-s.
- [4] Zhang H Q, Liu Z H, Xu J C, et al. Experimental evidence against a model incorporating fission before K equilibration[J]. *Physical Review C, Nuclear Physics*, 1993, 47(3): 1309–1310. DOI: 10.1103/physrevc.47.1309.
- [5] Zhang H Q, Xu J C, Liu Z H, et al. Anomalous anisotropies of fission fragment angular distributions in sub-barrier fusion-fission reaction[J]. *Physics Letters B*, 1989, 218(2): 133–136. DOI: 10.1016/0370-2693(89)91407-X.
- [6] Kailas S. Heavy-ion induced fission at near-barrier energies[J]. *Physics Reports*, 1997, 284(6): 381–416. DOI: 10.1016/S0370-1573(96)00044-0.
- [7] Hinde D J, Dasgupta M, Leigh J R, et al. Fusion-fission versus quasifission: effect of nuclear orientation[J]. *Physical Review Letters*, 1995, 74(8): 1295–1298. DOI: 10.1103/PhysRevLett.74.1295.
- [8] Back B B, Betts R R, Cassidy K, et al. Experimental signatures of quasifission reactions[J]. *Physical Review Letters*, 1983, 50(11): 818–821. DOI: 10.1103/physrevlett.50.818.
- [9] Zhang C L, Zhang H Q, Lin C J, et al. Competition between fusion-fission and quasifission processes in $^{32}\text{S}+^{184}\text{W}$ reaction[J]. *Nuclear Physics A*, 2010, 834(1–4): 201c–204c. DOI: 10.1016/j.nuclphysa.2009.12.040.
- [10] Lin C J, du Rietz R, Hinde D J, et al. Systematic behavior of mass distributions in ^{48}Ti -induced fission at near-barrier energies[J]. *Physical Review C*, 2012, 85: 014611. DOI: 10.1103/physrevc.85.014611.

- [11] Jia H M, Lin C J, Yang F, et al. Fusion of the $^{16}\text{O}+^{76}\text{Ge}$ and $^{18}\text{O}+^{74}\text{Ge}$ systems and the role of positive Q-value neutron transfers[J]. *Physical Review C*, 2012, 86: 044621. DOI: 10.1103/PhysRevC.86.044621.
- [12] Jia H M, Lin C J, Yang F, et al. Fusion of $^{32}\text{S}+^{94}\text{Zr}$: further exploration of the effect of the positive Q_{xn} value neutron transfer channels[J]. *Physical Review C*, 2014, 89(6): 064605. DOI: 10.1103/physrevc.89.064605.
- [13] Jia H M, Lin C J, Yang L, et al. A self-consistent method to analyze the effects of the positive Q-value neutron transfers on fusion[J]. *Physics Letters B*, 2016, 755: 43–46. DOI: 10.1016/j.physletb.2016.01.058.
- [14] Lin C J. Optical potentials of exotic nuclear systems extracted from transfer reactions[C]//AIP Conference Proceedings. San Servolo, Venezia (Italy). AIP, 2006, 853: 81. DOI: 10.1063/1.2338359.
- [15] An G P, Lin C J, Zhang H Q, et al. Optical potential parameters of weakly bound nuclear System $^{17}\text{F}+^{13}\text{C}$ [J]. *Chinese Physics Letters*, 2008, 25(12): 4237–4239. DOI: 10.1088/0256-307x/25/12/014.
- [16] Yang L, Lin C J, Jia H M, et al. Extracting the hexadecapole deformation from backward quasi-elastic scattering[J]. *Physical Review C*, 2014, 90(3): 031601. DOI: 10.1103/physrevc.90.031601.
- [17] Otsuka T, Fukunishi N, Sagawa H. Structure of exotic neutron-rich nuclei[J]. *Physical Review Letters*, 1993, 70(10): 1385–1388. DOI: 10.1103/physrevlett.70.1385.
- [18] Liu Z H, Lin C J, Zhang H Q, et al. Asymptotic normalization coefficients and neutron halo of the excited states in ^{12}B and ^{13}C [J]. *Physical Review C*, 2001, 64: 034312. DOI: 10.1103/PhysRevC.64.034312.
- [19] Lin C J, Zhang H Q, Liu Z H, et al. Single-particle potential model for halo nuclei[J]. *Chinese Physics Letters*, 2002, 19(11): 1645–1647. DOI: 10.1088/0256-307x/19/11/327.
- [20] Xu X X, Lin C J, Jia H M, et al. Experimental study of two-proton correlated emission from ^{29}S excited states[J]. *Physical Review C*, 2009, 80: 014310. DOI: 10.1103/physrevc.80.014310.
- [21] Xu X X, Lin C J, Jia H M, et al. Correlations of two protons emitted from excited states of ^{28}S and ^{27}P [J]. *Physics Letters B*, 2013, 727(1–3): 126–129. DOI: 10.1016/j.physletb.2013.10.029.
- [22] Xu X X, Lin C J, Jia H M, et al. Investigation of two-proton emission from excited states of the odd-Z nucleus ^{28}P by complete-kinematics measurements[J]. *Physical Review C*, 2010, 81(5): 054317. DOI: 10.1103/physrevc.81.054317.
- [23] Sun L J, Xu X X, Lin C J, et al. A detection system for charged-particle decay studies with a continuous-implantation method[J]. *Nuclear Instruments and*

Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2015, 804: 1–7. DOI: 10.1016/j.nima.2015.09.039.

[24] Lin Chengjian, Xu Xinxing, Sun Lijie, et al. Progress on decays of extremely proton-rich nuclei based on the HIRFL-RIBLL1 facility[J]. Chinese Science Bulletin, 2021, 66(27): 3527–3536. DOI: 10.1360/TB-2020-1679.

[25] Xu X X, Lin C J, Sun L J, et al. Observation of β -delayed two-proton emission in the decay of ^{22}Si [J]. Physics Letters B, 2017, 766: 312–316. DOI: 10.1016/j.physletb.2017.01.023.

[26] Lee J, Xu X X, Kaneko K, et al. Large isospin asymmetry in $^{22}\text{Si}/^{22}\text{O}$ mirror gamow-teller transitions reveals the halo structure of ^{22}Al [J]. Physical Review Letters, 2020, 125(19): 192503. DOI: 10.1103/physrevlett.125.192503.

[27] Liang P F, Sun L J, Lee J, et al. Simultaneous measurement of β -delayed proton and γ emission of ^{26}P for the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ reaction rate[J]. Physical Review C, 2020, 101: 024305. DOI: 10.1103/PhysRevC.101.024305.

[28] Liu J J, Xu X X, Sun L J, et al. Observation of a strongly isospin-mixed doublet in ^{26}Si via β -delayed two-proton decay of ^{26}P [J]. Physical Review Letters, 2022, 129: 122501. DOI: 10.1103/physrevlett.129.122501.

[29] Lin C J. Optical potentials of exotic nuclear systems extracted from transfer reactions[C]//AIP Conference Proceedings. San Servolo, Venezia (Italy). AIP, 2006, 853: 81. DOI: 10.1063/1.2338359.

[30] An G P, Lin C J, Zhang H Q, et al. Optical potential parameters of weakly bound nuclear System $^{17}\text{F}+^{13}\text{C}$ [J]. Chinese Physics Letters, 2008, 25(12): 4237–4239. DOI: 10.1088/0256-307x/25/12/014.

[31] Zhang H Q, Lin C J, Jia H M, et al. Optical model parameters for halo nucleus system $^6\text{He}+^{12}\text{C}$ from transfer reaction $^{11}\text{B}(^7\text{Li}, ^6\text{He})^{12}\text{C}$ [J]. Chinese Physics Letters, 2009, 26(2): 022503. DOI: 10.1088/0256-307x/26/2/022503.

[32] Yang L, Lin C J, Jia H M, et al. Optical potential parameters for $^6\text{He}+^{64}\text{Zn}$ from $^{63}\text{Cu}(^7\text{Li}, ^6\text{He})^{64}\text{Zn}$ reactions[J]. Physical Review C, 2017, 95: 034616. DOI: 10.1103/PhysRevC.95.034616.

[33] Yang L, Lin C J, Jia H M, et al. Abnormal behavior of the optical potential for the halo nuclear system $^6\text{He}+^{209}\text{Bi}$ [J]. Physical Review C, 2017, 96(4): 044615. DOI: 10.1103/physrevc.96.044615.

[34] Yang L, Lin C J, Jia H M, et al. Is the dispersion relation applicable for exotic nuclear systems? The abnormal threshold anomaly in the $^6\text{He}+^{209}\text{Bi}$ system[J]. Physical Review Letters, 2017, 119(4): 042503. DOI: 10.1103/physrevlett.119.042503.

[35] Yang L, Lin C J, Zhang Y X, et al. Bayesian analysis on interactions of exotic nuclear systems[J]. Physics Letters B, 2020, 807: 135540. DOI: 10.1016/j.physletb.2020.135540.

- [36] Yang L, Lin C J, Ma N R, et al. Reaction dynamics of proton drip line nuclei at energies around the Coulomb barrier[J]. Science Bulletin, 2023, 68(8): 775–778. DOI: 10.1016/j.scib.2023.03.026.
- [37] Yang L, Lin C J, Yamaguchi H, et al. Insight into the reaction dynamics of proton drip-line nuclear system $^{17}\text{F}+^{58}\text{Ni}$ at near-barrier energies[J]. Physics Letters B, 2021, 813: 136045. DOI: 10.1016/j.physletb.2020.136045.
- [38] Yao Y J, Lin C J, Yang L, et al. The effects of beam drifts on elastic scattering measured by the large solid-angle covered detector array[J]. Nuclear Science Techniques, 2021, 32(2): 14. DOI: 10.1007/s41365-021-00844-5.
- [39] Yang L, Lin C J, Yamaguchi H, et al. Breakup of the proton halo nucleus ^8B near barrier energies[J]. Nature Communications, 2022, 13: 7193. DOI: 10.1038/s41467-022-34931-0.
- [40] Yao Y J, Lin C J, Yang L, et al. Multilayer ionization-chamber Telescope Array for low-energy reactions with exotic nuclei[J]. The European Physical Journal A, 2019, 55(6): 87. DOI: 10.1140/epja/i2019-12784-8.

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

Source: ChinaXiv — Machine translation. Verify with original.