Nuclear Science Research Division
Nuclear Many-Body Theory Laboratory

1. Abstract

The nuclear many-body theory laboratory aims to understand various aspects of nuclear structure and reactions due to the assembly and disassembly of protons and neutrons in the nuclear many-body systems. For this purpose, we construct theoretical models and conduct numerical calculations to describe them. Our research topics include nuclear structure problems such as exotic nuclear deformation, shell structure, clustering of unstable nuclei, and nuclear reactions in the Universe where elements originate. In addition to the ordinary research, we are also participating in the RIKEN TRIP project, where we are conducting fundamental research of quantum computing and machine learning for nuclear physics.

2. Major Research Subjects

(1) Structure and reactions of unstable nuclei
(2) Nuclear clustering and related nuclear reactions
(3) Quantum computing and machine learning for nuclear physics

3. Summary of Research Activity

(1) Structure and reaction of unstable nuclei

The study of the structure and reactions of unstable nuclei is an important subject of the Nishina Center, as well as one of the core issues in modern nuclear physics. Our group approaches this problem by performing numerical calculations using theoretical models such as antisymmetrized molecular dynamics and density functional theory. The research highlights in this fiscal year are as follows:

(1) Study of Nuclear Radii and Proton-Neutron Correlations: We have calculated the radii of tin and lead isotopes using various relativistic and non-relativistic density functionals, and investigated the influence of tensor force. The results showed that tensor force is crucial for reproducing the observed kink near magic numbers. Additionally, we extended the HFB model to describe spin-singlet and spin-triplet proton-neutron pairing, examining the coexistence of these two correlations in the ground states of $N = Z$ nuclei.
(2) Exotic Deformations in Neutron-Rich Nuclei: Zirconium is a unique isotope that exhibits an abrupt transition from spherical to quadrupole deformation. We systematically calculated this shape coexistence using the quasiparticle vacuua shell model. We demonstrated that this shape transition occurs due to an interchange between spherical and deformed bands. Additionally, zirconium- 106 and 108 show triaxial deformation, evidenced by gamma bands observed in recent gamma-ray spectroscopy experiments at RIKEN RIBF. This study further extended similar analyses to neighboring isotopes of krypton, strontium, molybdenum, and ruthenium.
(3) Study of $2p$ Decay Process: We investigated the two-proton decay process of ^{10}C by applying the ACCC (Analytic Continuation in the Coupling Constant) to the $2\alpha + 2p$ system. We demonstrated that the $2p$ decay process becomes dominant despite the open $1p$ decay channel. Additionally, we conducted real-time evolution calculations for the two-proton decay of ^{16}Ne (^{14}O + $2p$), revealing that the two-proton decay process significantly varies depending on the position of the s-wave resonance.
(4) Study of Radii and Diffuseness in Island of Inversion: We systematically investigated the radii and surface diffuseness of neutron skin and neutron halo nuclei such as ^{29}Ne and ^{31,33,35}Mg using antisymmetrized molecular dynamics (AMD). We quantitatively demonstrated that the increase in radius and diffuseness occurs when the system becomes weakly bound and the low angular momentum $p_{3/2}$ orbital intrudes. Furthermore, by performing Glauber calculations, we evaluated the total reaction cross-sections and angular distributions of elastic scattering, showing that the increase in radius and diffuseness can be detected through these measurements.

(2) Nuclear clustering in structure and reaction problems

Nuclear clustering, in which nucleons are confined into several subunits (clusters), is an eligible research subject for understanding the correlation of nucleons. Since the clusters are linked to the nuclear reaction channels, they also appear as the intermediate states of various nuclear reaction dynamics. The research highlights in this fiscal year are as follows:

(1) Study of stellar fusion reaction rate Using various density functionals combined with AMD, we have investigated how the uncertainty in the nuclear models propagetes to the reaction rate of ^{12}C + ^{12}C fusion, which is a key reaction for the steller evolution and superburst. We have shown that Skyrme functionals systematically smaller reaction rates than the Gongy functionals.
(2) Shape of ^{12}C While various shapes of ground-state rotational bands are discussed, their direct experimental verification is challenging as they are not directly observable. We proposed a method to reconstruct nuclear shapes in an almost model-independent manner using transition densities measured by electron scattering. Applying this method to experimental data for ^{12}C, we demonstrated that ^{12}C has a shape where α clusters are arranged in an equilateral triangle configuration.
(3) di-neutron correlation and clusters We investigated the structure of the excited state (2nd 0^+) of ^{8}He using the real-time evolution method. By comparing with experimental data from RIKEN, we pointed out that this state exhibits relatively strong dineutron correlations and may contain a component of di-neutron condensation.

(3) Quantum computing and AI for nuclear physics

We are participating in the RIKEN TRIP project, advancing fundamental research in Quantum computing and AI for nuclear physics. Quantum computers may enable large-scale calculations impossible with classical computers, potentially allowing for exact calculations of nuclear structure and reactions. Additionally, AI could optimize and estimate parameters in theories based on vast amounts of experimental data. The research highlights in this fiscal year are as follows:

(1) Quantum computing for nuclear shell model The shell model is a promising application for quantum computers. However, noise in current NISQ devices makes accurate calculations challenging. We attempted to reduce errors by refining the qubit representation of wave functions and qubit connectivity. First, we proposed a pair-wise representation of the wave function, halving the required number of qubits. Furthermore, we significantly reduced errors (from a few percent to less than 1%) by implementing circuit designs that consider the physical connectivity of qubits.

(2) Machine learning for nuclear database Evaluated nuclear data are indispensable in the field of nuclear science and technology, and an effective and accurate method that can regularly generate evaluated nuclear data has been highly desired. To answer such demand, we are training nuclear reaction models by adopting the Bayesian optimization (BO). In this fiscal year, we have improved a prototype system that combines the nuclear reaction codes CCONE and BO. Using this system, By estimating the particle number dependence of the optical potential, we predicted cross-sections for unknown target nuclei from known data.

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List of Publications & Presentations

Publications

[Original Papers]

M. Kimura and Y. Taniguchi, "Shape of ^{12}C," Eur. Phys. J. A **60**, 77 (2024).

Q. Zhao, M. Kimura, B. Zhou, and S. Shin, "Microscopic investigation of one- and two-proton decay from the excited states of ^{10}C," Phys. Lett. B **850**, 138511 (2024).

Y. Taniguchi and M. Kimura, "Impact of the molecular resonances on the ^{12}C + ^{12}C fusion reaction rate," Phys. Lett. B **849**, 138434 (2024).

H. Utsunomiya *et al*., "Photoneutron emission cross sections for ^{13}C," Phys. Rev. C **109**, 014617 (2024).

E. Kido *et al*., "Evaluations of uncertainties in simulations of propagation of ultrahigh-energy cosmic-ray nuclei derived from microscopic nuclear models," Astropart. Phys. **152**, 102866 (2023).

Z. H. Yang *et al*., "Observation of the exotic 0^+ cluster state in ^{8}He," Phys. Rev. Lett. **131**, 242501 (2023).

A. Tamii *et al*., "PANDORA Project for the study of photonuclear reactions below $A = 60$," Eur. Phys. J. A **59**, 208 (2023).

T. Naito, T. Oishi, H. Sagawa, and Z. Wang, "Comparative study on charge radii and their kinks at magic numbers," Phys. Rev. C **107**, 054307 (2023).

N. Hinohara, T. Oishi, and K. Yoshida, "Triplet-odd pairing in finite nuclear systems: Even-even singly closed nuclei," Phys. Rev. C **109**, 034302 (2024).

K. Yanase, N. Shimizu, K. Higashiyama, and N. Yoshinaga, "Correlations between nuclear Schiff moment and electromagnetic measurement," Phys. Lett. B **841**, 137897 (2023).

B. K. Sahoo, N. Yamanaka, and K. Yanase, "Revisiting theoretical analysis of the electric dipole moment of ^{129}Xe," Phys. Rev. A **108**, 042811 (2023).

E. Senapati, S. Mondal, S. Bhattacharya, D. Pandit, N. D. Dang, N. N. Anh, L. T. Q. Huong, R. Santra, N. Q. Hung, and B. Dey, "Pairing phase transition in an odd-even hot ^{69}Zn nucleus," J. Phys. G: Nucl. Part. Phys. **50**, 075104 (2023).

T. V. Dong, L. T. Phuc, N. Q. Hung, N. D. Dang, T. D. Huyen, and N. L. A. Tuan, "Pairing reentrance in odd nuclei at finite temperature," Phys. Rev. C **107**, 064319 (2023).

Le. T. Phuc, T. V. Dong, N. D. Dang, B. M. Hue, L. T. Q. Huong, B. Dey, N. N. Anh, and N. Q. Hung, "Imprint of pairing correlation in (n, γ) and Maxwellian-averaged cross sections of an odd-odd ^{166}Ho nucleus," Phys. Lett. B **849**, 138421 (2024).

S. Amano, Y. Aritomo, and M. Ohta, "Nuclear viscosity estimated by dynamics of neck formation in the early stage of nuclear collision," Mod. Phys. Lett. A **38**, 2350136 (2023).

S. Amano, Y. Aritomo, and M. Ohta, "Dynamical mechanism of fusion hindrance in heavy ion collisions," Phys. Rev. C **108**, 014612 (2023).

S. Tanaka, N. Nishimura, F. Minato, and Y. Aritomo, "Postfission properties of uranium isotopes: A hybrid method with Langevin dynamics and the Hauser-Feshbach statistical model," Phys. Rev. C **108**, 054607 (2023).

C. Song, C. Lee, I. Shin, Y. Kim, and Y. Aritomo, "The $p + ^{238}$U reaction for the RI beam based on the Langevin Method," New Physics: Sae Mulli **74**, 35–39 (2024).

S. Amano, Y. Aritomo, and M. Ohta, "Effects of neck and nuclear orientations on the mass drift in heavy ion collisions," Phys. Rev. C **109**, 034603 (2024).

L. Coraggio, G. De Gregorio, T. Fukui, A. Gargano, Y. Z. Ma, Z. H. Cheng, and F. R. Xu, "The role of three-nucleon potentials within the shell model: past and present," Prog. Part. Nucl. Phys. **134**, 104079 (2024).

W. Horiuchi, T. Inakura, S. Michimasa, and M. Tanaka, "Enlarged deformation region in neutron-rich Zr isotopes promoted by the second intruder orbit," Phys. Rev. C **107**, L041304 (2023).

Y. Yamaguchi, W. Horiuchi, and N. Itagaki, "Evidence of bicluster structure in the ground state of ^{20}Ne," Phys. Rev. C **108**, 014322 (2023).

W. Horiuchi, T. Sato, Y. Uesaka, and K. Yoshida, "Electron wave functions in beta-decay formulas revisited (II): Completion including recoil-order and induced currents," Prog. Theor. Exp. Phys. **2023**, 073D02 (2023).

Y. Yamaguchi, W. Horiuchi, T. Ichikawa, and N. Itagaki, "Dineutron-dineutron correlation in ^{8}He," Phys. Rev. C **108**, L011304 (2023).

J. T. Zhang *et al*., "Matter radius of ^{78}Kr from proton elastic scattering at 153 MeV," Phys. Rev. C **108**, 014614 (2023).

H. Moriya, W. Horiuchi, and B. Zhou, "Novel approach to the removal of Pauli-forbidden states in the orthogonality condition model: a case of multi-α systems," Eur. Phys. J. A **59**, 197 (2023).

T. Furumoto, K. Tsubakihara, S. Ebata, and W. Horiuchi, "Global density-dependent α-nucleon interaction for α-nucleus elastic scattering," Prog. Theor. Exp. Phys. **2024**, 013D01 (2024).

H. Tajima, H. Moriya, W. Horiuchi, E. Nakano, and K. Iida, "Intersections of ultracold atomic polarons and nuclear clusters: how is a chart of nuclides modified in dilute nuclear matter?," Association of Asia Pacific Physical Societies Bulletin **34**, 9 (2024).

H. Tajima, H. Moriya, W. Horiuchi, E. Nakano, and K. Iida, "Polaronic proton and diproton clustering in neutron-rich matter," Phys. Lett. B **851**, 138567 (2024).

K. Yoshida, Y. Niu, and F. Minato, "β-decay half-lives as an indicator of shape-phase transition in neutron-rich Zr isotopes with particle-vibration coupling effects," Phys. Rev. C **108**, 034305 (2023).

F. Minato, T. Naito, and O. Iwamoto, "Nuclear many-body effects on particle emission following muon capture on ^{28}Si and ^{40}Ca," Phys. Rev. C **107**, 054314 (2023).

T. Nakatsukasa and N. Hinohara, "Local α-removal strength in the mean-field approximation," Phys. Rev. C **108**, 014318 (2023).

Y. Taniguchi and M. Kimura, "Impact of the molecular resonances on the ^{12}C + ^{12}C fusion reaction rate," Phys. Lett. B **849**, 138434 (2024).

K. Washiyama, S. Ebata, and K. Yoshida, "Evolution of giant monopole resonance with triaxial deformation," Phys. Rev. C **109**, 024317 (2024).

N. Hizawa, K. Hagino, and K. Yoshida, "Analysis of a Skyrme energy density functional with deep learning," Phys. Rev. C **108**, 034311 (2023).

H. Gil, N. Hinohara, C. H. Hyun, and K. Yoshida, "Nuclear mass table in density functional approach inspired by neutron-star observations," Phys. Rev. C **108**, 044316 (2023).

W. Washiyama, S. Ebata, and K. Yoshida, "Triaxial-shape dynamics in the low-lying excited 0^+ state: Role of the collective mass," Phys. Rev. C **108**, 014323 (2023).

Presentations

[International Conferences/Workshops]

M. Kimura (invited) and Y. Suzuki, "Investigation of N = 20, 28 shapeless nuclei," The Workshop on Frontier Nuclear Studies with Gamma-ray Spectrometer Arrays, Osaka, Japan, March 27, 2024.

M. Kimura (invited), "Shape of nuclei and knockout reactions," Reimei Workshop, "Intersection of nuclear structure and direct reaction," Tokai, Japan, February 28, 2024.

M. Kimura (invited), "Nuclear structure and reaction of exotic nuclei," The 3rd RIKEN-IBS Joint Conference on Nuclear Physics, Wako, Japan, January 26, 2024.

M. Kimura (invited), "Nuclear reaction data generation by machine learning," 15th Symposium on Discovery, Fusion, Creation of New Knowledge by Multidisciplinary Computational Sciences, Tsukuba, Japan, October 3, 2023.

M. Kimura (invited), "Cluster formation around the neutron drip-line," Direct Reactions and Spectroscopy with Hydrogen Targets: past 10 years at the RIBF and future prospects, York, UK, August 4, 2023.

T. Oishi (invited), "Time-dependent Dirac equation applied to one-proton radioactivity," PROCON2023, University of Warsaw, Poland, June 26–30, 2023.

T. Oishi (invited), "Two-proton radioactivity and its sensitivity to the nuclear structure," The 3rd International Conference on Nuclear Physics in Astrophysics, Tokyo, Japan, March 20–24, 2023.

K. Yanase (invited), "Shell-model study for describing neutron-rich medium-heavy & heavy nuclei," RIBF Workshop: ADRIB2024, RIKEN Wako, Japan, January 2024.

K. Yanase (invited), "Shell-model study for describing octupole correlation towards revealing CP violation beyond the standard model," The Workshop on Frontier Nuclear Studies with Gamma-ray Spectrometer Arrays (gamma24), Osaka University, Japan, March 2024.

Y. Aritomo (invited), A. Iwamoto, K. Nishio, and M. Ohta, "Dynamical effects in fission process by the langevin equation," 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.

Y. Aritomo (invited), R. Yamasaki, S. Takagi, S. Tanaka, K. Hirose, K. Nishio, K. Hirose, S. Tanaka, and M. Ohta, "Effect of neutron evaporations in fission process with dynamical model and mass distribution of fission fragments," 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.

Y. Aritomo (invited), "New development and perspectives on fission process by dynamical model," Symposia of the 30th Anniversary of the Advanced Science Research Center, Tokai (Central Community Center), Japan, December 7, 2023.

Y. Aritomo (invited), "Extensive systematic study of fission process in heavy and superheavy mass regions (2095 nuclei) related to r-process nucleosynthesis," ASRC International Workshop "Nuclear astrophysics with stable beams," Tokai (Tokai Village Museum), Ibaraki, Japan, February 20–22, 2024.

T. Fukui (invited), "Deuteron-Xi correlation function studied with three-body model," WPCF 2023—XVI Workshop on Particle Correlations and Femtoscopy & IV Resonance Workshop 2023, Catania, Italy, November 10, 2023.

W. Horiuchi (invited), "Probing nuclear cluster structure with proton-nucleus elastic scattering," The international Symposium on Physics of Unstable Nuclei 2023 (ISPUN23), Phu Quoc Island, Vietnam, May 4–8, 2023.

W. Horiuchi (invited), "Nuclear structure revealed in density profiles near nuclear surface," The International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7), Catania (Dipartimento di Fisca e Astronomia "Ettore Majorana" of Catania University), Italy, June 11–16, 2023.

W. Horiuchi (invited), "Nuclear structure study using proton-nucleus scattering," The 5th International Workshop on Quasi-Free Scattering with Radioactive-Ion Beams: QFS-RB 2023, Lefkada (Porto Galini Seaside Resort & Spa), Greece, October 1–6, 2023.

W. Horiuchi (invited), "Probing alpha-cluster structure by proton-nucleus scattering," Workshop on Nuclear Cluster Physics (WNCP2023), Toyonaka (Osaka University), Japan, November 27–29, 2023.

W. Horiuchi (invited), "Visualizing nuclear structure with proton scattering," Advancing physics at next RIBF (ADRIB24), Wako (RIKEN), Japan, January 23–24, 2024.

F. Minato (invited), "Nuclear structures observed from global beta-decay predictions and measurements," Advancing physics at next RIBF (ADRIB24), Wako (RIKEN), Japan, January 23–24, 2024.

K. Sekizawa, "Time-dependent microscopic approaches for low-energy heavy-ion reactions: Recent progress and discussion," The Workshop on Frontier Nuclear Studies with Gamma-ray Spectrometer Arrays (Gamma24), Osaka (Osaka University Minoh Campus), Japan, March 26–28, 2024.

K. Sekizawa, "Current status and perspectives of time-dependent mean-field theories: Going beyond TDHF," A Workshop on Low-Energy Heavy-Ion Reactions and Chemistry of Superheavy Elements, Tokyo (Gakushikaikan), Japan, March 3, 2024.

K. Sekizawa, "Time-dependent superfluid band theory for the inner crust of neutron stars," A Workshop on "Microscopic approach from pair correlation to pair condensation," Osaka, Japan, August 28–30, 2023.

K. Sekizawa, "Microscopic description of neutron star crustal matter based on time-dependent density functional theory," KEK Workshop, "Thermal quantum field theory and its applications," Ibaraki, Japan, August 28–30, 2023.

Y. Taniguchi (invited), "^{12}C + ^{12}C fusion reaction rate from a microscopic nuclear model," Nuclear Astrophysics with Stable Beams (NAPS2024), Tokai, Japan, February 20–22, 2024.

Y. Taniguchi (invited), "Microscopic estimation of nuclear reaction rate in astrophysical phenomena," 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.

Y. Taniguchi and M. Kimura, "Real-time evolution of Gaussian wave packets: its application to the nuclear cluster problems," 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.

K. Yoshida (invited), "Spin-isospin modes of excitation in a Skyrme energy-density functional approach: Roles of neutron excess and deformation," International Symposium on Physics of Unstable Nuclei 2023 (ISPUN23), Phu Quoc Island, Vietnam, May 4–8, 2023.

K. Yoshida (invited), "Spin-isospin modes of excitation in a Skyrme energy-energy-density approach to unveil the *r*-process nucleosynthesis," DNA Workshop on Nuclear Structure, Reaction and Astrophysics, Daegu University, Korea, May 26, 2023.

K. Yoshida (invited), "Electromagnetic multipole excitations," RIKEN Workshop on "Giant monopole resonance and related topics," Wako (RIKEN), Japan, May 18, 2023.

K. Yoshida (invited), "Density dependence of pairing functionals for the rotational excitation in neutron-rich nuclei," 7th International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7), Catania (Dipartimento di Fisica e Astronomia, "Ettore Majorana"), Italy, June 11–16, 2023.

K. Yoshida (invited), "Nuclear shapes in spin-isospin excitations," DNA-OMEG Workshop on Nuclear structure, reaction and astrophysics, Busan (Pukyong National University), Korea, November 9–11, 2023.

K. Yoshida (invited), "Unraveling the nuclear secrets: Exploration of responses of exotic nuclei," Advancing Physics at Next RIBF (ADRIB24), Wako (RIKEN), Japan, January 23–24, 2024.

K. Yoshida (invited), "Exploring collective states in actinides for insights into the structure of superheavies," The Workshop on Frontier Nuclear Studies with Gamma-ray Spectroscopic Array (Gamma24), Osaka University, Japan, March 26–28, 2024.