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 resulting from the assembly and disassembly of protons and neutrons in 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, we are also participating in the RIKEN TRIP project, where we are conducting fundamental research on 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) Spin correlation is a typical evidence of quantum entanglement. In the nuclear physics, one of possible examples to observe the nuclear spin correlation is the two-proton ($2p$) radioactive emission. By numerical computations based on the time-dependent three-body model, we showed that a strong spin entanglement can exist in the $2p$ emission from ^{6}Be. This entanglement is suggested as sensitive to the pairing correlation inside finite systems. The $2p$ emitters can provide a testing field for the identical-particle entanglement.
(2) Another possible example to measure the nuclear-entangled state is the deuteron. In the ^{102}Sb nucleus, for the valence proton and neutron around the ^{100}Sn core, we calculated the strength and effect of the deuteron (pn) correlation. As the result, the one-proton ($1p$) emission is suggested as remarkably sensitive to this pn correlation. The prediction of pn-entanglement based on the present model is in progress now.
(3) 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. The results were published in PRC.

(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, showing the uncertainity originating in the nuclear models. The results were published in PLB.
(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. The results were published in EPJA, and further applied to the high-energy heavy ion collision calculations.

(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. The results were published in PRC.

Members

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List of Publications & Presentations

Publications

[Original Papers]

Y. Taniguchi, T. Baba, T. Suhara, M. Kimura, and Y. Kanada-En'yo, "Progress in the studies of cluster resonances by antisymmetrized molecular dynamics," Eur. Phys. J. A **61**, 25 (2025).

S. Watanabe, Y. Suzuki, M. Kimura, and K. Ogata, "Uncovering the sign of nuclear deformations: Determination of prolate or oblate shape via low-energy α inelastic scattering," Phys. Rev. C **110**, 034618 (2024).

Y. Suzuki, W. Horiuchi, and M. Kimura, "Isospin-forbidden electric dipole transition of the 9.64 MeV state of ^{12}C," Phys. Rev. C **109**, 014617 (2024).

M. Isaka, T. Tada, M. Kimura, and Y. Yamamoto, "Excitation spectra of $^{15}_{\Xi}$C and $^{12}_{\Xi}$Be calculated with a ΞN interaction from lattice QCD," Phys. Rev. C **109**, 044317 (2024).

Z. H. Yang *et al.*, "The ^{19}N$(n,\gamma)^{20}$N capture rate in light of the probable bubble nature of ^{20}N," Eur. Phy. J. A **60**, 184 (2024).

M. Kimura, and Y. Taniguchi, "An implementation of nuclear many-body wave functions by the superposition of localized Gaussians," Prog. Theor. Exp. Phys **2024**, 093D01 (2024).

T. Naito, T. Oishi, H. Sagawa, and Z. Wang, "^{164}Pb: A possible heaviest $N = Z$ doubly magic nucleus," Phys. Rev. R **7**, 013050 (2024).

S. Yoshida, T. Sato, T. Ogata, T. Naito, and M. Kimura, "Accurate and precise quantum computation of valence two-neutron systems," Phys. Rev. C **109**, 064305 (2024).

T. Oishi, "Spin correlation in two-proton emission from ^{6}Be," Phys. Lett. B **862**, 139361 (2025).

T. Oishi, M. Kimura, and L. Fortunato, "One-proton emission from ^{102}Sb and its sensitivity to the proton-neutron interaction," Phys. Rev. C **111**, 034307 (2025).

M. J. Yang, H. Sagawa, C. L. Bai, and H. Q. Zhang, "Study of magnetic dipole excitations in magic nuclei with subtracted second random-phase approximation," Phys. Phys. C **109**, 054319 (2024).

E. Ha, M. Cheoun, and H .Sagawa, "Residual tensor force effects on the Gamow-Teller states in magic nuclei, ^{48}Ca, ^{90}Zr, ^{132}Sn, and ^{208}Pb," Prog. Theor. Exp. Phys. **2024**, 063D02 (2024).

M. -H. Mun, E. Ha, M. -K. Cheoun, H. Sagawa, and G. Colò, "Symmetry energy from two-nucleon separation energies from Pb and Ca isotopes," Phys. Phys. C **110**, 014314 (2024).

E. Ha, M. -K. Cheoun, H. Sagawa, and G. Colò, "Gamow-Teller strength distributions of ^{18}O and well-deformed nuclei ^{24,26}Mg by deformed QRPA," Phys. Phys. C **110**, 034617 (2024).

H. -T. Xue, J. -W. Cui, Q. B. Chen, X. -R. Zhou, and H. Sagawa, "Shape coexistence in Ne isotopes and hyperon impurity effect in hypernuclei," Phys. Phys. C **110**, 044310 (2024).

K. Uzawa, N. Hinohara, and T. Nakatsukasa, "Generator coordinate method with proton-neutron pairing fluctuations and magnetic properties of $N = Z$ odd-odd nuclei," Prog. Theor. Exp. Phys. **2024** 053D02 (2024).

K. Washiyama, N. Hinohara, and T. Nakatsukasa "'Five-dimensional collective Hamiltonian with improved inertial functions," Phys. Rev. C **109** L051301 (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).

J. Singh, J. Casal, W. Horiuchi, N. R. Walet, and W. Satu la, "Prediction of two-neutron halos in the $N = 28$ isotones ^{40}Mg and ^{39}Na," Phys. Lett. B **853**, 138694 (2024).

M. Okada, W. Horiuchi, and N. Itagaki, "Shell-cluster transition in ^{48}Ti," Phys. Rev. C **109**, 054324 (2024).

T. Moriguchi *et al*., "Investigation of total reaction cross sections for proton-dripline nuclei ^{17}F and ^{17}Ne on a proton target," Phys. Rev. C **110**, 014607 (2024).

S. Watanabe, T. Furumoto, W. Horiuchi, T. Suhara, and Y. Taniguchi, "Investigation of the determination of nuclear deformation using high-energy heavy-ion scattering," Phys. Rev. C **110**, 024604 (2024).

S. Ebata and W. Horiuchi, "Global analysis of the nonuniformity of nucleon density distributions," Phys. Rev. C **111**, 014313 (2025).

H. Tajima, H. Moriya, T. Naito, W. Horiuchi, E. Nakano, and K. Iida, "Polaronic neutron in dilute alpha matter: A p-wave Bose polaron," Phys. Rev. C **111**, 025302 (2025).

S. Yoshida, "Surrogate model for in-medium similarity renormalization group method using dynamic mode decomposition," Particles **8**, 13 (2025).

T. Fukui, G. De Gregorio, and A. Gargano, "Uncovering the mechanism of chiral three-nucleon force in driving spin-orbit splitting," Phys. Lett. B **855**, 138839 (2024).

Q. Zhao, Z. Ren, P. W. Zhao, and K. Yoshida, "Exact-exchange relativistic density functional theory in three-dimensional coordinate space," Phys. Lett. B **860**, 13916 (2025).

D. Rochman *et al*., "An introduction to spent nuclear fuel decay heat for light water reactors: A review from the NEA WPNCS," Eur. Phys. J. N **10**, 9 (2024).

F. Minato and O. Iwamoto, "Fission fragment yields of U235(nth,f) evaluated with the CCONE code system," Phys. Rev. C **110**, 054311 (2024).

H. Kawashimo, R. Sawada, Y. Suwa, T. J. Moriya, A. Tanikawa, and N. Tominaga, "Impacts of the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate on ^{56}Ni nucleosynthesis in pair-instability supernovae," MNRAS **531**, 2786 (2024).

K. Yoshimura and K. Sekizawa, "Superfluid extension of the self-consistent time-dependent band theory for neutron star matter: Anti-entrainment versus superfluid effects in the slab phase," Phys. Rev. C **109**, 065804 (2024).

Presentations

[International Conferences/Workshops]

M. Kimura (invited), "Investigation of $N = 20$, 28 shapeless nuclei," International Workshop on Nuclear Physics Related to HIAF, Huizhou, China, April 17, 2024.

M. Kimura (invited), "Theoretical approaches for nuclear clustering," Exploring Nuclear Physics Across Energy Scales 2024, Beijing, China, April 22, 2024.

M. Kimura (invited), "Nuclear structure and reaction of exotic nuclei," EIC で展開する新たな原子核・素粒子物理 Tokyo, Japan, May 29, 2024.

M. Kimura (keynote talk), "State of the art of the nuclear cluster theory," State of the Art of the Nuclear Cluster Physics 2024 (SOTANCP2024), Hvar, Croatia, June 10, 2024.

M. Kimura (invited), "Shape of light clustered nuclei," A3 Foresight Program: Nuclear Physics in the 21st Century, Daejeon, Korea, July 17, 2024.

M. Kimura (invited), "原子核構造・反応計算への量子コンピューティングの応用," RCNP 研究会「量子情報と原子核物理の交差点を探る」, Osaka, Japan, September 09, 2024.

M. Kimura (invited), "Nuclear theory activities at RIKEN Nishina Center," Nuclear Physics Workshop, Roorkee, India, November 6, 2024.

M. Kimura (invited), "Theoretical nuclear physics at RIKEN-RIBF," RIKEN-CAS Workshop, Wako, Saitama, November 11, 2024.

M. Kimura (invited), "Shape of light clustered nuclei," ENST Workshop: Light Nuclei between Single-Particle and Clustering Features, Paris, France, December 4, 2024.

T. Oishi (invited), "Nuclear spin degrees of freedom and related phenomena," Workshop on Advancing Physics at Next RI, Saitama, Japan, January 23, 2025.

K. Yanase (invited), "Shape coexistence of Zr and the neighboring isotopes described by nuclear shell model," VII-th Topical Workshop on Modern Aspects in Nuclear Structure, Bormio, Italy, February 6, 2025.

K. Yanase (invited), "CP-odd nuclear moments evaluated by nuclear shell model," Single-Particle and Collective Motions from Nuclear Many-Body Correlation (PCM2025), Aizu, Japan, March 6, 2025.

Y. Aritomo (invited) *et al*., "Evaluation of the synthesis of new superheavy elements using dynamical model," NuSRAP2024, RCNP-CENuM-OMEG Symposium on Nuclear Structure, Reaction, and Astrophysics, Osaka University, Japan, December 18–20, 2024.

Y. Aritomo (invited), "Dynamical aspects of nuclear fission in phenomenological approaches," Workshop on Dynamical Aspects of Nuclear Fission, Bordeaux Univ., France, January 14–15, 2025.

W. Horiuchi (invited), "Exploring exotic nuclear structure by medium- and high-energy nuclear collisions," 14th International Conference on Nucleus-Nucleus Collision (NN2024), Whistler, Canada, August 18–23, 2024.

W. Horiuchi (invited), "Complete Glauber model analysis for total reaction and elastic scattering cross sections," International Symposium: TRIP Usecase: Nuclear Transmutation 2025, Wako, Japan, March 10–12, 2025.

S. Yoshida (invited), "Quantum computation of valence two-neutron systems towards solving full nuclear Hamiltonians," Joint N3AS - iTHEMS Meeting on Quantum Information Science in Multimessenger Astrophysics, Wako, Saitama, Japan, June 16–18, 2024.

S. Yoshida (invited), "Towards quantum computation of nuclear many-body problems," RIKEN—LBNL Workshop on Quantum Information Science, LBNL, US, September 3–6, 2024.

S. Yoshida (invited), "Surrogate models for quantum many-body systems," Recent Progress in Many-Body Theories (RPMBT22), Tsukuba, Japan, September 23–27, 2024.

S. Yoshida (invited), "Surrogate models for In-medium Similarity Renormalization Group method," Information and Statistics in Nuclear Experiment and Theory (ISNET)-10, Fudan University, China, November 10–15, 2024.

S. Yoshida (invited), "Collaborations through TRIP: Emulators and quantum computing as examples," International Symposium: TRIP Usecase: Nuclear Transmutation 2025, Wako, Saitama, Japan, March 10–12, 2025.

T. Fukui (invited), "Three-nucleon force and its antisymmetric spin-orbit properties," Advancing Physics at Next RIBF (ADRIB25), Saitama, Japan, January 22, 2025.

T. Fukui (invited), "Tensorial structure of chiral three-nucleon force," Workshop on Tomoe Project, Tohoku University, Sendai, Japan, January 9, 2024.

T. Fukui (invited), "Uncovering the mechanism of chiral three-nucleon force in driving spin-orbit splitting," Universality of Strongly Correlated Few-body and Many-body Quantum Systems, Tohoku University, Sendai, Japan, September 4, 2024.

T. Fukui (invited), "Chiral three-nucleon force in many-nucleon systems," The 11th International Workshop on Chiral Dynamics (CD2024), Ruhr University Bochum, Germany, August 27, 2024.

T. Fukui (invited), "Uncovering the mechanism of chiral three-nucleon force in driving spin-orbit splitting," International Workshop on Nuclear Physics Related to HIAF, Huizhou, China, April 18, 2024.

K. Yoshida (invited), "Proton-neutron pairing in neutron-rich nuclei," Kyoto-Soongsil Nuclear Physics Joint Workshop (75th OMEG SSANPworkshop), Soongsil University, Seoul, Korea June 7–8, 2024.

K. Yoshida (invited), "Nuclear density functional theory for microscopic physics of the *r*-process," 2024 Annual Meeting of NRF/NSFC/JSPS A3 Foresight Program "NuclearPhysics in the 21st Century," Daejeon, Korea July 17–20, 2024.

K. Yoshida (invited), "Shell effects in the proton-neutron pairing," TOMOE Theory Wokshop, Tohoku University, Sendai, Miyagi, January 6–10, 2025.

K. Yoshida (invited), "beta-decay half-life as an indicator of shap-phase transition in neutron-rich Zr isotopes," Nucleosynthesis and Evolution of Neutron Stars, YITP, Kyoto University, Kyoto, January 27–30, 2025.

K. Yoshida (invited), "From superdeformation to hyperdeformation," Physics Opportunities Using the 8pi Spectrometer at RCNP, RCNP, OsakaUniversity, Osaka, February 4–5, 2025.

F. Minato (invited), "Predictions of beta-decay half-lives and beta-delayed neutron emissions within Skyrme-QRPA," International symposium: TRIP Usecase: Nuclear Transmutation 2025, Wako, March 10–12, 2025.

F. Minato (invited), "Particles in continuum studied within second random phase approximation," The 8th International Workshop on DRHBc Mass Table, March 15–16, 2025.

F. Minato (invited), "Evolutions from 1p-1 hours to 2p-2 hours states studied within second random phase approximation," Single-Particle and Collective Motions from Nuclear Many-Body Correlation (PCM2025), March 4–7, 2025.

F. Minato (invited), "Weak interactions in nuclei and door-way states to many-particle many-hole configurations," VIIth Topical Workshop on Modern Aspects in Nuclear Structure, February 3–7, 2025.

F. Minato (invited), "Beta-Delayed Neutron Branching Ratios calculated by proton-neutron QRPA and statistical model," Fifth Gogny Conference, December 11–13, 2024.

F. Minato (invited), "Muon capture rates considering microscopic nuclear structure," Future on Muon Elemental Analysis (FUME), October 19–20, 2024.

F. Minato (invited), "Perspectives for next beta-decay and delayed-neutron data table," Structure of the Neutron-rich Matter Revealed by Beta Decay, July 29–30, 2024.

F. Minato (invited), "Transitions to door-way states and nuclear responses against 2-body external fields," Compound Nuclear Reactions and Related Topics (CNR*24), July 8–12, 2024.

Y. Taniguchi (invited), "Triaxiality and molecular resonances induced by clustering in deformed states," Physics Opportunities Using the 8pi Spectrometer at RCNP, Toyonaka, Japan, February 4–5, 2025.

Y. Taniguchi (invited), "Impact of cluster resonances on low-energy nuclear fusion reactions," Nucleosynthesis and Evolution of Neutron Stars, Kyoto, Japan, January 27–30, 2025.

Y. Taniguchi (invited), "Low-energy fusion reactions enhanced by resonance states," Advancing Physics at Next RI Beam Factory (ADRIB25), Wako, Japan, January 22–25, 2025.

K. Sekizawa, "Neutron star studies at science Tokyo," RCNP-CENuM-OMEG Symposium on Nuclear Structure, Reaction, and Astro-Physics (NuSRAP2024), RCNP, Osaka, Japan, December 18–20, 2024.

K. Sekizawa, "Microscopic approaches for multinucleon transfer reactions beyond TDHF: Future perspective," A Workshop on Exploring the Heavy Exotic Neutron-rich Nuclides via Multinucleon Transfer Reactions (MNT2024), RIKEN, Saitama, Japan, July 3, 2024.

K. Sekizawa, "Prospects of superheavy formation in terrestial and stellar environments," FRIB-TA Topical Program: The Path to Superheavy Isotopes, Michigan State University, East Lansing, Michigan, USA, June 3–7, 2024.