Nuclear Science and Transmutation Research Division
Nuclear Many-Body Theory Laborarory

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 issues such as nuclear deformation, shell structure, and clustering of unstable nuclei, and nuclear reactions in the Universe where elements originate. In addition to fundamental research, we are also developing nuclear reaction database by combining the nuclear models and machine learning. The database will be used for various scientific and technological applications such as nuclear reactors, medicine and industry.

2. Major Research Subjects

(1) Structure and reactions of unstable nuclei
(2) Nuclear clustering and related nuclear reactions
(3) Nuclear reactions in the universe
(4) Research and development of the nuclear reaction database for applications

3. Summary of Research Activity

(1) Structure and reactions 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) Description of neutron-halo and resonances near and beyond dripline within the framework of molecular dynamics. We have developed the numerical technique to describe the neutron halos with heavier masses by the molecular dynamics models. Combining this technique with the method of analytical continuation of the coupling constant (ACCC), our model can also describe the resonances beyond the neutron dripline. As a benchmark calculation, the method has been successfully applied to a neutron halo nucleus ^{31}Ne and an unbound nucleus ^{25}O. This success opened the way to study nuclei beyond the drip line in a fully microscopic model. (2) Study of the total reaction cross sections of unstable nuclei. Combining the microscopic nuclear structure models and a reaction model (Glauber model), we have investigated how the ground-state structure of unstable nuclei affects the reaction cross section. In the study of the oxygen isotopes, the signature of the new shell closure and the growth of the neutron skin were found.

(2) Nuclear clustering and related nuclear reactions

The nuclear clustering, in which nucleons are confined into into several subunits (clusters), is an eligible research subject for understanding the correlation of nucleons interacting with strong force. 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 the formation probabilities of α cluster at the surface of unstable nuclei. Using the antisymmetrized molecular dynamics model, we have investigated how the α cluster formation probability in unstable Be and C isotopes changes as function of neutron skin thickness. We have demonstrated that the α cluster formation is hindered by the growth of the neutron skin, which is consistent with the experimental data reported for the Sn isotopes. (2) α cluster formation and total reaction cross section. The formation of α clusters should affect the density profile at the nuclear surface. Consequently, the signature of the clustering can be observed in the total reaction cross section. We have discussed such effect in the case of light stable nuclei.

(3) Nuclear reactions in the universe

Fusion reactions that occur in stellar and explosive astronomical events are key to understanding the origin of the elements. However, many reactions have extremely small cross sections, making direct experimental measurement difficult, and estimating reaction rates by theoretical calculation is critically important.

In this fiscal year, using the antisymmetrized molecular dynamics, we have provided an estimate of the reaction rate of ^{12}C +^{12} C fusion, which is a key reaction for understanding the steller evolution and superburst. We have shown that there are many resonances within the Gamow window, and hence, the reaction rate at steller temperatures are not hindered but are enhanced in contradiction to the estimation by a phenomenological model. Using several different nuclear density functionals, we have shown how the uncertainity of the nuclear models propages to the raction rate.

(4) Research and development of the nuclear reaction database for applications

Evaluated nuclear data are indispensable in the field of nuclear science and technology, and the demand of nuclear data is altering year by year with technical developments of nuclear science and technology. To meet such demands, an effective and accurate method that can regularly generate evaluated nuclear data has been highly desired.

The machine learning technologies can be an answer to this demand, and we are training nuclear reaction models by adopting the Bayesian optimization (BO) to effectively produce the nuclear data. In this fiscal year, we have improved a prototype system which combines the assembly of the nuclear reaction codes CCONE and BO with Gaussian regression. We have demonstrated that

the optical potentials at different incident energies can be predicted by using Gaussian Process (GP). Using this method, future RIBF experimental data can be used to determine optical potentials at arbitrary energies.

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List of Publications & Presentations

Publications

[Original Papers]

Q. Zhao, M. Kimura, B. Zhou, and S. Shin, "α formation probability in ^{10}Be and ^{12}Be within a microscopic cluster model," Phys. Rev. C **106**, 054313 (2022).

H. Motoki, Y. Suzuki, T. Kawai, and M. Kimura, "Cluster formation in neutron-rich Be and B isotopes," Prog. Theor. Exp. Phys. **2022**, 113D01 (2022).

T. Baba, Y. Taniguchi, and M. Kimura, "4α linear-chain state produced by ^{9}Be +^{9} Be collisions," Phys. Rev. C **105**, L061301 (2022).

H. Masui, W. Horiuchi, and M. Kimura, "Two-Neutron Halo Structure and Anti-halo Effect in ^{31}F," Few-Body Syst. **63**, 20 (2022).

S. Watanabe, F. Minato, M. Kimura, and N. Iwamoto, "Nuclear data generation by machine learning (I) application to angular distributions for nucleon-nucleus scattering," J. Nucl. Sci. and Technol. **59**, 1399 (2022).

Y. Suzuki, W. Horiuchi, and M. Kimura, "Erosion of $N = 28$ shell closure: Shape coexistence and monopole transition," Prog. Theor. Exp. Phys. **2022**, 063D02 (2022).

J. X. Han *et al*., "Observation of the $\pi^2\sigma^2$-bond linear-chain molecular structure in ^{16}C," Phys. Rev. C **105**, 044302 (2022).

Q. Zhao, B. Zhou, M. Kimura, H. Motoki, and S. Shin, "Microscopic calculations of ^{6}He and ^{6}Li with real-time evolution method," Eur. Phys. J. A **58**, 25 (2022).

M. Kimura, Y. Suzuki, T. Baba, and Y. Taniguchi, "Description of isospin mixing by a generator coordinate method," Phys. Rev. C **105**, 014311 (2022).

R. Takatsu, Y. Suzuki, W. Horiuchi, and M. Kimura, "Microscopic study of the deformed neutron halo of ^{31}Ne," Phys. Rev. C **107**, 024314 (2023).

T. Nakatsukasa, "Fermi operator expansion method for nuclei and inhomogeneous matter with a nuclear energy density functional," Phys. Rev. C **107**, 015802 (2023).

S. Kaur *et al*., "Proton distribuition radii of $^{16-24}$O: Signatures of new shell closures and neutron skin," Phys. Rev. Lett. **129**, 142502 (2022).

H. Tajima, H. Moriya, W. Horiuchi, K. Iida, and E. Nakano, "Resonance-to-bound transition of ^{5}He in neutron matter and its analogy with heteronuclear Feshback molecule," Phys. Rev. C **106**, 045807 (2022).

W. Horiuchi and N. Itagaki, "Density profiles near nuclear surface of ^{44,52}Ti: An indication of α clustering," Phys. Rev. C **106**, 044330 (2022).

W. Horiuchi and N. Itagaki, "Imprints of α clustering in the density profiles of ^{12}C and ^{16}O," Phys. Rev. C **107**, L021304 (2023).

H. Moriya, W. Horiuchi, J. Casal, and L. Fortunato, "Three-α configurations of the second $J^\pi = 2^+$ state in ^{12}C," Eur. Phys. J. A **59**, 37 (2023).

Presentations

[International Conferences/Workshops]

M. Kimura (invited) and Y. Taniguchi, "Astrophysical S-factor for ^{12}C + ^{12}C fusion reaction from a full-microscopic nuclear model," Annual Topical Meeting of IReNA - FA1 Nuclear reaction measurements in Underground Laboratories, Online, April 5–8, 2022.

M. Kimura (invited) and Y. Taniguchi, "Low energy monopole strength: A novel approach to the astrophysical fusion reactions," ECT* Workshop, Advances On Giant Nuclear Monopole Excitations And Applications To Multi-Messenger Astrophysics, Online, July 10–14, 2022.

M. Kimura (invited), "Monopole transitions as a probe for nuclear shape and clusters," Developments of Physics of Unstable Nuclei (YKIS2022b), Kyoto, Japan, May 23–27, 2022.

M. Kimura (invited), "Alpha cluster formation at the surface of stable and unstable nuclei," Korean Physical Society Spring meeting 2022, Online, April 4–8, 2022.

M. Kimura (invited), "Shape coexistence and electromagnetic moments/transitions," VI Topical Workshop on Modern Aspects in Nuclear Structure, Bormio, Italy, February 6–11, 2023.

Y. Taniguchi (invited) and M. Kimura, "Microscopic estimation of ^{12}C + ^{12}C fusion reaction rate at astrophysical energies," YIPQS long-term workshop Mean-field and Cluster Dynamics in Nuclear Systems 2022 (MCD2022), Kyoto, Japan, May 9–June 17, 2022.

F. Minato (invited), "Theoretical studies of beta-decay half-lives," JSPS/NSFC/NRF A3 Foresight Program Nuclear Physics in the 21st Century, Osaka, February 13–15, 2023.

F. Minato (invited), "Predictions of beta-decay half-lives and neutron capture cross sections of neutron-rich nuclei," RIKEN Workshop Physics of RI; Recent progress and perspectives, Wako, May, 2022.

K. Yoshida (invited), "Mean-field based approach for collective excitations in neutron-rich nuclei," YKIS2022b: Developments of Physics of Unstable Nuclei, Kyoto, Japan, May 23–27, 2022.

K. Yoshida (invited), "Pairing in neutron-rich nuclei investigated by responses," Physics of RI: Recent progress and perspectives, Wako, Japan, May 30–June 1, 2022.

K. Yoshida (invited),"Skyrme-QRPA for monopole modes of excitation," Advances on Giant Monopole Excitations and Applications to Multi-messenger Astrophysics, ECT*, Trento, Italy & Online, July 11–15, 2022.

K. Sato (invited), "Nuclear density functional calculation with proton-neutron mixing," YITP Workshop Fundamentals in Density Functional Theory (DFT2022), Kyoto University, December, 2022.

Y. Taniguchi (oral), "^{12}C + ^{12}C fusion reaction rate from a microscopic nuclear model," PANDORA Wrokshop, Onna, Japan, March 5–7, 2023.

Y. Taniguchi (oral), "^{12}C + ^{12}C fusion reaction rate from a full-microscopic nuclear model," The 16th International Symposium on Origin of Matter and Evolution of Galaxies, Hanoi, Vietnam, October 24–28, 2022.

Y. Taniguchi (oral), "^{12}C + ^{12}C fusion astrophysical S-factor from a full-microscopic nuclear model," Developments of Physics of Unstable Nuclei (YKIS2022b), Kyoto, Japan, May 23–27, 2022.

F. Minato (oral), "Evaluation of fission fragment yields and parameter optimization in CCONE code system," 2nd RCM on Updating Fission Yield Data for Applications, December, 2022.

F. Minato (oral), "Effects of continuum states on particle emissions from muon captures," YIPQS long-term workshop on Mean-field and Cluster Dynamics in Nuclear Systems 2022 (MCD 2022), Kyoto, May, 2022.

F. Minato (oral), "Study of particle emissions following beta-decays and muon captures," Shapes and Symmetries in Nuclei: from Experiment to Theory (SSNET'22 Conference), Orsay, May, 2022.

K. Sato (oral), "Large-amplitude collective dynamics with the adiabatic SCC theory including the second-order collective operator," YIPQS long-term workshop Mean-field and Cluster Dynamics in Nuclear Systems 2022 (MCD2022), Yukawa Institute for Theoretical Physics, Kyoto University, Japan, May 7–June 17, 2022.

S. Watanabe (oral), M. Kimura, F. Minato, S. Yoshida, and N. Iwamoto, "Nuclear data generation by machine learning," YIPQS long-term workshop "Mean-field and Cluster Dynamics in Nuclear Systems 2022 (MCD2022), Kyoto, Japan, May 9–June 17, 2022.

S. Watanabe, M. Kimura, F. Minato, S. Yoshida, and N. Iwamoto, "Generating nucleon-nucleus scattering data by Gaussian process regression," 15th International Conference on Nuclear Data for Science and Technology (ND2022), Online, July 24–29, 2022.

[Domestic Conferences/Workshops]

谷口億宇 (招待講演), 「基底および共鳴状態におけるクラスター相関と天体核反応」, おのころ戸隠夏合宿, JA 長野県ビル, 長野, 2022 年 7 月 29, 30 日.

谷口億宇 (招待講演), 木村真明, 「低エネルギー ^{12}C + ^{12}C 核融合反応率の微視的模型による評価」, 低エネルギー核物理と高エネルギー天文学で読み解く中性子星, 大阪大学核物理研究センター, 2022 年 8 月 3–5 日.

谷口億宇 (招待講演), 木村真明, 「X 線バーストを引き起こす ^{12}C + ^{12}C 分子共鳴状態」, 核反応シミュレーションと機械学習による核反応模型の発展, 北海道大学, 2022 年 12 月 13–15 日.

谷口億宇 (招待講演), 木村真明, 「^{12}C + ^{12}C molecular resonances that enhance the fusion reaction rate」, 星の進化と爆発天体における核反応の物理, 理化学研究所, 2023 年 2 月 20–21 日.

谷口億宇 (招待講演), 木村真明, 「天体核融合とノックアウト反応の微視的模型による研究」, 日本物理学会春季大会, オンライン, 2023 年 3 月 22–25 日.

湊太志 (招待講演), 「実験データからの拘束条件下での中性子捕獲断面積の理論予測」, 第 2 回 研究用原子炉を用いた原子核素粒子物理学（FPUR-II), 2023 年 3 月 16 日.

湊太志 (招待講演), 「中性子過剰核のベータ崩壊と遅発中性子」, 理化学研究所 RIBF ミニワークショップ「理論と実験で拓く中性子過剰核の核分裂」, 和光市, 2023 年 2 月 16–17 日.

湊太志 (招待講演), 「様々な拘束条件下での中性子過剰核の捕獲断面積の不定性」, 研究会「中性子捕獲反応で迫る宇宙の元素合成」, 東京, 2023 年 2 月 9–10 日.

湊太志 (招待講演), 「ミュオン捕獲後の粒子放出と半導体ソフトエラー」, 北大情報基盤セ萌芽型共同研究研究会「核反応シミュレーションと機械学習による核反応模型の発展」, 札幌, 2022 年 12 月.

湊太志 (招待講演), 「原子核構造モデルによるミュオン捕獲後の粒子放出計算」, ミューオンソフトエラー研究会, 九州大学筑紫キャンパス, 2022 年 11 月.

湊太志 (招待講演), 「Skyrme EDF+QRPA による beta 崩壊半減期の研究」, UKAKUREN-RCNP Conference on AstroNuclear Physics (ANP2022), 豊中, オンライン, 2022 年 7 月.

湊太志 (招待講演), 「中性子過剰核の keV 領域の中性子捕獲反応の理論予測」, RCNP 研究会「研究用原子炉を用いた原子核素粒子物理学」, 茨木, 2022 年 5 月.

谷口億宇 (口頭発表), 木村真明, 「クラスター共鳴による天体における ^{12}C + ^{12}C 核融合反応率の増大」, 原子核におけるクラスター物理の新展開, 大阪公立大学, 2022 年 10 月 19–20 日.

谷口億宇 (口頭発表), 木村真明, 「天体における ^{12}C + ^{12}C 核融合反応率の微視的評価」, 日本物理学会 2022 年秋季大会, 岡山理科大学, 2022 年 9 月 6–8 日.

谷口億宇 (口頭発表), 木村真明, 「^{12}C + ^{12}C fusion reaction rate at low temperature from a microscopic nuclear model」, UKAKUREN-RCNP Conference on AstroNuclear Physics (ANP2022), 大阪大学, 2022 年 7 月 20–21 日.

谷口億宇 (口頭発表), 木村真明, 「天体エネルギーにおける ^{12}C + ^{12}C 核融合反応率の微視的評価」, RCNP 研究会「原子核反応研究の最近の話題と展望」, 大阪大学核物理研究センター, 2022 年 7 月 8–9 日.

湊太志 (口頭発表), 「ミュオン捕獲後の粒子放出」, 日本物理学会 2022 年秋季大会, 岡山市, 2022 年 9 月.

堀内渉 (口頭発表), 板垣直之, 「原子核密度分布にみる α クラスター状態」, 大阪公立大研究会「原子核におけるクラスター物理の新展開」, 大阪公立大学杉本キャンパス, 2022 年 10 月 19–20 日.

堀内渉 (口頭発表), 鈴木宜之, M. Shalchi, L. Tomio, 「カルシウム 62, 72 のエキゾチックハロー構造発現の可能性について」, 日本物理学会 2022 年秋季大会, 岡山理科大学, 2022 年 9 月 6–8 日.

堀内渉 (口頭発表), 稲倉恒法, 「中性子過剰鉛同位体における芯核増大現象」, 日本物理学会 2022 年秋季大会, 岡山理科大学, 2022 年 9 月 6–8 日.

森谷元 (口頭発表), 堀内渉, Jeśus Casal, Lorenzo Fortunato, 「直交条件模型を用いた炭素 12 第二 2^+ 状態の研究」, 日本物理学会 2022 年秋季大会, 岡山理科大学, 2022 年 9 月 6–8 日.

槇口雄二 (口頭発表), 堀内渉, 「高エネルギー原子核衝突における不完全吸収反応」, 日本物理学会 2022 年秋季大会, 岡山理科大学, 2022 年 9 月 6–8 日.

堀内渉 (口頭発表), 板垣直之, 「陽子弾性散乱でみる原子核のクラスター構造」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.

山口雄紀 (口頭発表), 堀内渉, 板垣直之, 「ネオン 20 のクラスター構造と陽子弾性散乱断面積」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.

森谷元 (口頭発表), 堀内渉, Bo Zhou, 「パウリ原理を考慮した新しい多クラスター系の基底関数 II」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.

吉田賢市 (口頭発表), "Neutron stars tell us the shapes of nuclei," RCNP 研究会「低エネルギー核物理と高エネルギー天文学で読み解く中性子星」, 大阪大学核物理研究センター, 2022 年 8 月 3–5 日.

吉田賢市 (口頭発表), "Enhanced moments of inertia in neutron-rich nuclei: A role of pair correlations," 日本物理学会 2022 年秋季大会, 岡山理科大学, 2022 年 9 月 6–8 日.

吉田賢市 (口頭発表), "Collectivity of proton-neutron pairing," RCNP 研究会「微視的系と巨視的系における核子対凝縮相」, 大阪大学核物理研究センター, 2022 年 9 月 26–28 日.

吉田賢市 (口頭発表), "Linear-response TDDFT for rotating nuclei—Nuclear DFT for rovibrational motions—" Domestic Molecule Type Workshop Fundamentals in density functional theory, 京都大学基礎物理学研究所, 2022 年 12 月 7–20 日.

佐藤弘一 (口頭発表), 「高次の集団座標演算子を入れた大振幅集団運動への断熱的アプローチ II」, 日本物理学会 2022 年秋季大会, 岡山理科大学, 2022 年 9 月.

佐藤弘一 (口頭発表), 「ATDHF/ASCC 方程式における解の一意性の破れ」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月.

渡辺証斗 (口頭発表), 木村真明, 湊太志, 吉田聡太, 岩本信之, 「機械学習を用いた核データ生成」, 日本原子力学会 2022 年秋の年会大会, 茨城大学, 2022 年 8 月 6–9 日.

[Seminars]

W. Horiuchi, "What can we learn from nuclear density profiles ?," The 311th RIKEN RIBF nuclear physics seminar, RIKEN Nishina Center (Hybrid), Wako, Japan, November 17, 2022.

吉田賢市, "Shell effects in non-axial-shape excitations," 第 977 回九大原子核セミナー, 九州大学, 2023 年 1 月 24 日.