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.

In this fiscal year, we mainly discussed the nuclear deformation and shape coexistence phenomena induced by the disappearance of the magic numbers in neutron-rich nuclei. One of the research highlights is the study of ^{44}S, in which we have found the onset of the large amplitude collective motion due to the disappearance of the magic number $N = 28$. We have shown that this nucleus does not have definite shape but is always fluctuating. We have also pointed out that the monopole transition strength is an experimental probe to this shape fluctuation. By using the obtained density distribution of unstable nuclei as an input to the Glauber model, we also investigated how the disappearance of magic number and the shape of the nuclei affect the reaction cross section and the angular distribution of elastic scattering.

(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.

In this year, we have studied the $3\alpha + n$ cluster structure in order to understand how the 3α cluster state (the 0_2^+ state of ^{12}C), known as the Bose-Einstein condensate (BEC) of α clusters, is influenced by the addition of a neutron as impurity. Using the real-time evolution method, we have identified the $3\alpha + n$ cluster state as an excited state of ^{13}C, and have shown that its matter radius is considerably reduced than that of the 3α BEC due to the attraction of the additional neutron. In addition, by 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.

(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 obtained an estimate of the reaction rate of ^{12}C +^{12} C fusion. It must be emphasized that this is a well-known key reaction which affects the steller evolution and superburst of neutron star, and that our result is the first estimates from a full-microscopic nuclear model. 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.

(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 catch up with the demands, an effective 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 developed a prototype system which combines the assembly of the nuclear reaction codes CCONE and BO with Gaussian regression. It is found that the optimization of the reaction model parameter works well to reproduce the observed angular distributions of neutron and proton elastic scatterings at various incident energies.

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List of Publications & Presentations

Publications

[Original Papers]

V. Choudhary, W. Horiuchi, M. Kimura, and R. Chatterjee, "Enormous nuclear surface diffuseness of Ne and Mg isotopes in the island of inversion," Phys. Rev. C **104**, 054313 (2021).

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[Review Article]

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Presentations

[International Conferences/Workshops]

H. Masui (oral), W. Horiuchi, and M. Kimura, "Two-neutron halo structure and anti-halo effect in ^{31}F," Yamada Conference LXXII: The 8th Asia-Pacific Conference on Few-Body Problems in Physics (APFB2020), Kanazawa bunka hall, Kanazawa, Japan, May 1–5, 2021.

S. Shin (oral), B. Zhou, and M. Kimura, "The shape of ^{13}C studied by the real-time evolution method," Yamada Conference LXXII: The 8th Asia-Pacific Conference on Few-Body Problems in Physics (APFB2020), Kanazawa bunka hall, Kanazawa, Japan, May 1–5, 2021.

H. Motoki (oral) and M. Kimura, "Research on the α condensate in ^{16}O using real time evolution method," Yamada Conference LXXII: The 8th Asia-Pacific Conference on Few-Body Problems in Physics (APFB2020), Kanazawa bunka hall, Kanazawa, Japan, May 1–5, 2021.

M. Kimura (oral), "Shape of $N = 28$ isotonesand monopole transitions," RIBF Users Meeting 2021, September 7–9, 2021.

H. Motoki (oral) and M. Kimura, "The structure of 0^+ states in ^{16}O using real-time evolution method," The 16th International Symposium on Nuclei in the Cosmos (NIC-XVI), Online, September 21–25 2021.

V. Choudhary (oral), W. Horiuchi, M. Kimura, and R. Chatterjee, "Exploring the bubble structure in ^{22}O," 65th DAE Symposium on Nuclear Physics, Bhabha Atomic Research Centre, Mumbai, India, December 1–5, 2021.

T. Baba (oral), Y. Taniguchi, and M. Kimura, "^{9}Be + ^{9}Be correlation in the 4α linear chain of ^{18}O," RCNP International Workshop on Cluster Phenomena in Knockout and Astrophysical Reactions, Online, October 14–15, 2021.

K. Sekizawa (invited), "Entrainment effects in neutron stars: Overview and progress," JSPS/NRF/NSFC A3 Foresight Program, "Nuclear physics in the 21st century," Joint Annual Meeting, Online, Feburary 17–18, 2022.

[Domestic Conferences/Workshops]

木村真明, 「光核反応からのクラスター崩壊の理論研究と最高エネルギー宇宙線への応用」, 新学術領域「量子クラスターで読み解く物質の階層構造」ワークショップ, オンライン, 2021 年 6 月 14, 19 日.

渡辺証斗, 湊太志, 木村真明, 岩本信之, 「チャネル結合光学模型を用いた核子–原子核散乱に対するポテンシャルの最適化 (2)」, 日本原子力学会 2021 年秋の大会, オンライン, 2021 年 9 月 8–10 日.

谷口億宇, 木村真明「天体において共鳴状態により誘発される ^{12}C +^{12} C 核融合反応」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

本木英陽, 鈴木祥輝, 川合毅, 木村真明「中性子過剰核でのクラスター形成と中性子スキンの相関」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

木村真明, 鈴木祥輝, 馬場智之「生成座標法によるアイソバリックアナログ状態とアイソスピン混合の記述」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

Vishal Choudhary, 堀内渉, 木村真明, Rajdeep Chatterjee, 「陽子弾性散乱でみる中性子過剰 Ne, Mg 同位体の核表面変化」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

鈴木祥輝, 木村真明, 堀内渉, 「中性子過剰 $N = 28$ 核での変形共存現象の研究」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

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本木英陽, 鈴木祥輝, 川合毅, 木村真明, 「軽い中性子過剰核におけるクラスター形成」, 「大規模シミュレーションと機械学習による原子核反応研究」, 北海道大学, 2021 年 11 月 17–19 日.

吉田賢市, "Anomalous quadrupole collectivity of neutron-rich Mg isotopes near the drip line," 基研研究会「核力に基づいた原子核の構造と反応」, 京都大学/オンライン, 2021 年 12 月 7–10 日.

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谷口億宇, 木村真明「低エネルギー ^{12}C +^{13} C 核融合の微視的模型による評価」, 日本物理学会 第 77 回年次大会, オンライン, 2022 年 3 月 15–19 日.

吉田賢市, "Anomalous quadrupole collectivity of Mg isotopes near the neutron drip line," 日本物理学会第 77 回年次大会, オンライン, 2022 年 3 月 15–19 日.

関澤一之, P. Magierski, A. Makowski, M. C. Barton, G. Wlazłowski, 「低エネルギー重イオン反応における新奇な超流動ダイナミクス」, 日本物理学会第 77 回年次大会, オンライン, 2022 年 3 月 15–19 日.

佐々木哲平, 関澤一之, 松尾正之, 「時間依存 Gross-Pitaevskii 方程式による量子渦のピン留め・ピン外れ機構の研究」, 日本物理学会第 77 回年次大会, オンライン, 2022 年 3 月 15–19 日.

佐藤弘一, 「日本物理学会第 77 回年次大会「2 次の集団演算子を入れた Adiabatic SCC 理論による集団経路の抽出」, 日本物理学会第 77 回年次大会, オンライン, 2022 年 3 月 15–19 日.

陳敬徳, 小野章, 木村真明, 石塚知香子, 千葉 敏, 「AMD による核分裂片のスピン, 相対軌道角運動量及びそれらの相関の研究」, 日本原子力学会 2022 年春の年会, オンライン, 2022 年 3 月 16–18 日.

[Seminars]

M. Kimura, Y. Suzuki, and W. Horiuchi, "Erosion of $N = 28$ shell gap: shape coexistence and monopole transitionsin the vicinity of ^{44}S," RIKEN RIBF Nuclear Physics Seminar, Online, January 8, 2022.

M. Kimura and Y. Taniguch, "Astrophysical S-factor for ^{12}C+^{12}C fusion reaction from a full-microscopic nuclear model," CINA/COSNAP Colloquium, October 19, 2022.