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1. Abstract

The Center for Nuclear Study (CNS) aims to elucidate the nature of nuclear system by producing the characteristic states where the Isospin, Spin and Quark degrees of freedom play central roles. These researches in CNS lead to the understanding of the matter based on common natures of many-body systems in various phases. We also aim at elucidating the explosion phenomena and the evolution of the universe by the direct measurements simulating nuclear reactions in the universe. In order to advance the nuclear science with heavy-ion reactions, we develop AVF upgrade, CRIB and SHARAQ facilities in the large-scale accelerators laboratories RIBF. The OEDO facility has been developed as an upgrade of the SHARAQ, where a RF deflector system has been introduced to obtain a good quality of low-energy beam. A new project for fundamental symmetry using heavy RIs has been starting to install new experimental devices in the RIBF. We promote collaboration programs at RIBF as well as RHIC-PHENIX and ALICE-LHC with scientists in the world, and host international meetings and conferences. We also provide educational opportunities to young scientists in the heavy-ion science through the graduate course as a member of the department of physics in the University of Tokyo and through hosting the international summer school.

2. Major Research Subjects

(1) Accelerator Physics
(2) Nuclear Astrophysics
(3) NUSPEQ/Low Energy Nuclear Reaction group
(4) Quark physics
(5) Nuclear Theory
(6) OEDO/SHARAQ project
(7) Exotic Nuclear Reaction
(8) Active Target Development
(9) Fundamental Physics

3. Summary of Research Activity

(1) Accelerator physics

One of the major tasks of the accelerator group is the development of ion sources and the optimization of the beam transport system to CRIB, E7B, and C12 in the E7 experiment room. In 2021, the operating time of HyperECR ion source was 1773 hours. The beam production methods for metallic ions such as Li, Mg, and Fe have matured. High brightness metallic ion beams to match the requirement for the experiments can now be achieved stably and sustainably. Together with undergoing studies on ECR plasma, further improvements in beam qualities are expected. For the development of the 4-dimensional emittance monitor for the extracted beam from AVF cyclotron, the design of an optical system with a digital camera equipped with a tele lens was completed. Then, it is expected that the monitor can be kept away from the beamline which was the radiation source caused by the ion beam.

(2) Nuclear astrophysics

The main activity of the nuclear astrophysics group is to study astrophysical reactions and special nuclear structure, such as clusters, using the low-energy RI beam separator CRIB. In 2021, two major experimental projects at CRIB were completed and final publications were made; One was on the study of the ^{7}Be destruction process in the Big-bang nucleosynthesis, to solve the cosmological ^{7}Li abundance problem. The other is on the precise determination of the ^{22}Mg(α, p) astrophysical reaction, relevant in X-ray bursts. In January 2022, we performed the first physics experiment at CRIB after the pandemic, which was to simultaneously study the ^{26}Si(α, α) scattering and the (α, p) reaction, relevant to the astrophysics.

(3) NUSPEQ/Low Energy Nuclear Reaction group

The NUSPEQ (NUclear SPectroscopy for Extreme Quantum system) and Low Energy Nuclear Reaction group study exotic structures in high-isospin and/or high-spin states in nuclei. The groups play a major role in the OEDO/SHARAQ project described below. In 2021, analysis of a new measurement of the ^{4}He(^{8}He, ^{8}Be)4n reaction for better statistics and better accuracy has been proceeding. A recoil particle detector for missing mass spectroscopy, named TiNA, at OEDO had been upgraded under the collaboration with RIKEN and RCNP. The original TiNA consisted of 6 sector telescopes and 12 CsI (Tl) crystals. Four TTT-type (1024 channels) doubly-sided silicon detectors and twenty-two CsI(Tl) were added to make a TiNA2 array. The production cross sections of ^{178m2}Hf were evaluated for the mass production in the future with a new and simple chemical separation method. The inelastic decays from the isobaric analog resonances of ^{97}Zr were studied for the single particle wave functions coupled to the second 0^{+} state in ^{96}Zr. The nature of the different shape of the second 0^{+} state from the ground state was revealed. The systematic studies of neutron-rich Zr isotopes are planned. The CNS GRAPE (Gamma-Ray detector Array with Position and Energy sensitivity) is also a major apparatus for high-resolution in-beam gamma-ray spectroscopy. The digital signal processing devices for the GRAPE are under development.

(4) Quark physics

Main goal of the quark physics group is to understand the properties of hot and dense nuclear matter created by colliding heavy nuclei at relativistic energies. The group has been involved in the ALICE experiment at Large Hadron Collider (LHC) at CERN. The group has led the global commissioning of the ALICE upgrades in 2021. The group has involved in the data analyses, which include the measurement of low-mass lepton pairs in Pb-Pb collisions, the measurement of long range two particle correlations in *p*-Pb collisions, searches for thermal photons in high multiplicity *pp* and *p*-Pb collisions. The group has involved in the ALICE-TPC upgrade using a Gas Electron Multiplier (GEM), where the group is very active in the development and benchmarking of the online space-charge distortion corrections using machine learning techniques running on the Graphical Processing Unit (GPU).

(5) Nuclear theory

The nuclear theory group participates in a project, "Program for Promoting Researches on the Supercomputer Fugaku," and has been promoting computational nuclear physics utilizing the Fugaku supercomputer. In FY2021, we performed large-scale shell-model calculations employing the Monte Carlo shell model and quasi-particle vacua shell model to investigate various exotic structures of unstable nuclei. By using the no-core Monte Carlo shell model, we successfully describe the Hoyle state of ^{12}C from the first principle without assuming any cluster structure. In the medium-heavy mass region, we successfully described the shape phase transition of Nd and Sm isotopes based on shell-model calculations and evaluated the nuclear matrix element of the neutrinoless double-beta decay of ^{150}Nd. The nuclear Schiff moment of ^{129}Xe was also investigated based on the shell model and we found an approximately linear correlation between the Schiff moment and the magnetic moment. In parallel, we promoted many research collaborations with experimental groups for investigating the structure of various nuclei such as ^{40}Ca, ^{32}Mg, ^{47,49}Cl, and ^{55}Cr.

(6) OEDO/SHARAQ project

The OEDO/SHARAQ group pursues experimental studies of RI beams by using the high-resolution beamline and the SHARAQ spectrometer, and the OEDO for the decelerated RI beams. SHARAQ11 experiment with a tritium-doped titanium target, which has been developed by Tohoku Univ., was successfully conducted. For SHARAQ13, a mass measurement by the TOF-Brho technique for very proton-rich nuclei, an active stopper detector has been developed. The optics study of OEDO is under way to improve the transmission of the ion beams. For the high intensity RIBs, the delay-line PPACs have been replaced with the strip-readout PPACs. The experimental study of 0^- strength in nuclei using the parity-transfer charge exchange (^{16}O, ^{16}F) will be reported soon. As for The OEDO beamline, the results of the first and second experiments for LLFPs will be finalised and reported soon. The profile of X ray from the RFD had been measured comprehensively, which finalised the design of the lead shield to enable us to conduct the in-beam gamma experiment at OEDO.

(7) Exotic nuclear reaction

The Exotic Nuclear Reaction group studies various exotic reactions induced by heavy-ion beams. We conducted a search of double Gamow-Teller resonance by a double charge exchange reaction (^{12}C, ^{12}Be) at BigRIPS.

(8) Active target development

Three gaseous active target TPCs called CAT-S, CAT-M and GEM-MSTPC are developed and used for the missing mass spectroscopies. The CAT's are employed for the study of equation of state of nuclear matter. The measurement of giant monopole resonance in ^{132}Sn at RIBF with CAT-S and the data analysis is ongoing. The CAT-M was employed for the systematic measurement of the deuteron inelastic scattering of the Xe and Kr isotopes. Newly developed permanent dipole magnet system was installed to reduce the background due to the delta rays. The GEM-MSTPC is employed for the nuclear astrophysics study. The data analysis of (α, p) reaction on ^{18}Ne and ^{22}Mg and the β-decay of ^{16}Ne followed by α emission are ongoing.

(9) Fundamental physics

The development of an optical lattice interferometer to search for a permanent electric dipole moment (EDM) with Francium (Fr) atoms is now in progress at RIKEN. The lattice-like potential with a standing wave of laser light, the so-called optical lattice, can realize a long interaction time of the trapped Fr atoms with external fields, which allows to measure the EDM with high precision. The experimental apparatus to produce the cold Fr atoms trapped in the magneto-optical trap (MOT) is ready at present. We have confirmed that the newly developed surface ionizer can produce approximately 10^6 Fr^+/s as a secondary beam via nuclear fusion reaction. We are now optimizing the experimental parameters to realize the high intensity cold Fr sources with 10^6 atoms to measure the EDM.

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[Original Papers]

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Presentations

[International Conferences/Workshops]

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H. Yamaguchi (oral), "Experimental studies on astrophysical reactions at the low-energy RI beam separator CRIB," The 16th International Symposium on Nuclei in the Cosmos (NIC-XVI), Web symposium hosted by JUNA, China, September 21–25, 2021.

H. Yamaguchi (oral), "Cluster states and astrophysical (α, p) reactionss," RCNP Workshop, "Cluster phenomena in knockout and astrophysical reactions," Web workshop hosted by RCNP, Osaka University, October 14–15, 2021.

T. Gunji (invited) for the ALICE collaboration, "Future measurements from ALICE Run3 and Run4," The 8th Asian Triangle Heavy-Ion Conference (ATHIC2021), Inha Univ. Incheon, South Korea, Hybrid, November 5–9, 2021.

D. Sekihata for the ALICE Collaboration, "Low-mass dielectron measurement in ALICE at the LHC," The 8th Asian Triangle Heavy-Ion Conference, Inha Univ. Incheon, South Korea, Hybrid, November 5–9, 2021.

K. Nakamura (oral), "Development of a laser frequency stabilization and an optical transmission system for the francium electric dipole moment search," 29th Annual International Laser Physics Workshop (LPHYS'21), Online, Jul 23, 2021.

N. Ozawa (oral), "Current status of the electron EDM search using laser-cooled francium atoms," 13th International Workshop on Fundamental Physics Using Atoms (FPUA2021), Online, August 4–5, 2021.

M. Sato (keynote talk), "Search for permanent EDM by using Fr atoms," SPIN2021, Kunibiki Messe, Shimane, Japan, Hybrid, October 18–22, 2021.

Y. Utsuno (oral), "Present status of large-scale shell-model calculations for photonuclear reactions," Second PANDORA Workshop, September 10, 2021.

N. Shimizu (oral), "Microscopic description of the collective motions of medium-heavy nuclei based on shell-model calculations," 13th symposium on Discovery, Fusion, Creation of New Knowledge by Multidisciplinary Computational Sciences, Online, October 8, 2021.

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N. Shimizu (poster), "Gamow-Teller transition of neutron-rich $N = 82, 81$ nuclei by shell-model calculations," 16th International Symposium on Nuclei in the Cosmos (NIC-XVI), Online, September 25, 2021.

[Domestic Conferences/Workshops]

S. Shimoura (invited): "High-resolution spectroscopy with SHARAQ and advice on HIHR," the 2nd J-PARC HEF-ex workshop, Online, February 16–18, 2022.

T. Chillery (oral): "Measurement of deuteron-induced pre-equilibrium reactions on ^{93}Zr at 30 MeV/u for the Treatment of Radioactive Waste," 2022 Annual (77th) Meeting of The Physical Society of Japan, Online, March 15–19, 2022.

R. Tsunoda (oral): "Observation of the isobaric analog resonances coupled to the excited state in Zr isotope," 2022 Annual (77th) Meeting of The Physical Society of Japan, Online, March 15–19, 2022.

J. T. Li (oral): "New project to explore neutron-deficient actinide nuclei," 2022 Annual (77th) Meeting of The Physical Society of Japan, Online, March 15–19, 2022.

S. Hanai (oral): "A fast-response tracking detector for high-intensity heavy ion beams," Workshop for radiation detector and their uses, KEK, January 24–26, 2022.

N. Imai (invited): "Nuclear Structure study with decelerated RI beams," RCNP future workshop, October 27–29, 2021.

川田敬太 (口頭発表), 「核破砕反応における角運動量移行」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

早川勢也（口頭発表）:「^{7}Be+n ビッグバン元素合成反応の測定と原始 ^{7}Li 生成量の検証」, 日本物理学会 秋季大会, オンライン,

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郡司卓 (招待講演), “Status of ALICE upgrade and commissioning for run3,” 第 7 回クラスター階層領域研究会, 東北大学, 2021 年 12 月 27–28 日.

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関畑大貴 (招待講演), 「光子・レプトン対・ハード測定」, 重イオン衝突の時空発展の理解に向けた理論・実験合同研究会, オンライン, 2021 年 9 月 24 日.

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中村 圭佑（口頭発表）:「波長計による光周波数安定化、光ファイバー伝送システム」, 第 82 回応用物理学会秋季学術講演会, オンライン, 2021 年 9 月 11–13 日.

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山根風樹（口頭発表）:「永久電気双極子能率探索に向けたアクチニウム-225 電着基板を用いたフランシウム-221 原子線源の開発」, 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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大塚孝治（口頭発表）, 清水則孝, 吉田聡太, 角田直文, 角田佑介, 「殻模型計算による中性子過剰 pf 殻核の構造」, 日本物理学会第 76 回年次大会, オンライン, 2022 年 3 月 17 日.

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吉永尚孝（口頭発表）, 柳瀬宏太, 清水則孝, 東山幸司, 「キセノン原子核のシッフモーメントと中性子 EDM 探索」, 日本物理学会第 77 回年次大会, 2022 年 3 月 17 日.

清水則孝（口頭発表）, 宇都野穣, 角田佑介, 「大規模殻模型計算による M1 バンドの解析」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 15 日.

宇都野穣（口頭発表）, 「非イラスト領域における原子核の秩序の探求」, RCNP での次期計画検討会, 2021 年 9 月 27 日.

宇都野穣（口頭発表）, “Cluster formation in nuclei from first-principles Monte Carlo shell model,” 第 7 回クラスター階層領域研究会, 2021 年 12 月 27 日.

[Seminar]

T. Otsuka, “What determines the driplines of atomic nuclei?,” CNS+RIBF NP seminar, Online, November 5, 2021.

Press Releases

山口英斉, 早川勢也, Hu Jun, 「X 線バースト天体における不安定マグネシウム燃焼の解明」, 2021 年 10 月 20 日.

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