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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) Nuclear spectroscopy of exotic nuclei
(4) Quark physics
(5) Nuclear Theory
(6) OEDO/SHARAQ project
(7) Exotic Nuclear Reaction
(8) Low Energy Nuclear Reaction Group
(9) Active Target Development
(10) Fundamental Physics

3. Summary of Research Activity

(1) Accelerator physics

One of the major tasks of the accelerator group is the AVF upgrade project that includes development of ion sources, upgrading the AVF cyclotron of RIKEN and the beam transport system to CRIB, E7B, and C12 in the E7 experiment room. In 2020, the operating time of the HyperECR was 1146 hours. The beam extraction system of the HyperECR is developed to realize a high intensity and low emittance beam and the study of mixing gas is started for heavy ionization. The calculation model of injection beam orbit of the AVF cyclotron was completed and the study of the optimization of injection beam orbit was started. For the detailed studies on ion optics of the beamline to CRIB and experiment device of Fr-EDM measurement from AVF cyclotron, the development of 4-dimensional emittance monitor for high power ion beams was started. the prototype was completed and evaluated for performance.

(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. To produce RI beams at CRIB with higher intensity, a project to improve the heat durability of the cryogenic gas target is in progress. In 2020, we used a high-current oxygen beam to test the heat durability of the gas target. Sealing foils of several materials and copper extention parts were employed in the test, and we found the target can stand for the beam heat much exceeding the previous limit of 2 Watts per foil. The secondary beam development is also on going. A ^{6}He RI beam was first produced at CRIB in March 2021, as the lightest RI beam ever created at CRIB. We successfully produced a ^{6}He beam at the intensity more than 105 pps, which is to be used for the approved ^{6}He + p scattering measurement, as well as other future experiments.

(3) Nuclear structure of exotic nuclei

The NUSPEQ (NUclear SPectroscopy for Extreme Quantum system) group studies exotic structures in high-isospin and/or high-spin states in nuclei. The CNS GRAPE (Gamma-Ray detector Array with Position and Energy sensitivity) is a major apparatus for high-resolution in-beam gamma-ray spectroscopy. Missing mass spectroscopy using the SHARAQ is used for another approach on exotic nuclei. The group plays a major role in the OEDO/SHARAQ project described below. In 2020, analysis of a new measurement of the ^{4}He(^{8}He, ^{8}Be)4n reaction for better statistics and better accuracy has been proceeding.

(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 PHENIX experiment at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, and the ALICE experiment at Large Hadron Collider (LHC) at CERN. As for ALICE, 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 and for strangeness dibaryons. 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 promotes computational nuclear physics utilizing the Fugaku supercomputer. In FY2020, we proposed a new framework called the "quasi-particle vacua shell model," which is an extension of the Monte Carlo shell model, and promoted its code developments. Based on these methodological developments, we investigated the exotic structure of nuclei, especially neutron-rich Mg isotopes, and discussed the mechanism to determine the neutron drip line. In addition, the nuclear Schiff moments of ^{129}Xe and ^{199}Hg were theoretically evaluated by large-scale shell-model calculations to contribute to the experimental search of time-reversal breaking. In parallel, we promoted the collaborative researches with experimental groups for investigating the exotic structure of unstable nuclei, such as ^{35}S, ^{30}Mg, ^{64}Ni, ^{75}Ni, ^{112}Sn and ^{137}Ba.

(6) OEDO/SHARAQ project

The OEDO/SHARAQ group pursues experimental studies of RI beams by using the high-resolution beamline and the SHARAQ spectrometer. A mass measurement by TOF-$B\rho$ technique for very neutron-rich nuclei successfully reaches titanium isotopes at $N = 40$, ^{62}Ti, of which the report was published in 2020. The experimental study of 0^- strength in nuclei using the parity-tansfer 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 finalized and reported soon. Since experimental studies using OEDO were newly proposed, we continue developments to improve the performance for coming these beam times, such as the intensity of low-energy RI beams and the suppression of X rays from RF deflector.

(7) Exotic nuclear reaction

The Exotic Nuclear Reaction group studies various exotic reactions induced by beams of unstable nuclei. One subject is inverse-kinematics (p, n) measurement by using the neutron counter array PANDORA. Candidate nuclei to study are high spin isomers such as ^{52}Fe(12^+). Study of the production mechanism of high-spin isomer beams was in progress. Another is search of double Gamow-Teller resonance by a double charge exchange reaction (^{12}C, ^{12}Be). Preparations including the development of MWDCs were ongoing.

(8) Low energy nuclear reaction group

A recoil particle detector for missing mass spectroscopy, named TiNA, 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 commissioning experiment of the TiNA2 was conducted at Kyushu University in March 2021. The production cross sections of ^{178m2}Hf were evaluated for the mass production in the future and will be reported soon. The digital signal processing devices for the GRAPE are under development. For the SHARAQ11 experiment which uses a tritium-doped titanium target, the safety devices has been developed with Tohoku University.

(9) 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 measurements of the proton inelastic scattering on ^{136}Xe at HIMAC and the proton elastic scattering on ^{132}Sn. The development for the reduction of space charge due to the ion backflow and the reduction of delta-ray background is ongoing. 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.

(10) Fundamental physics

In order to investigate the origin of matter-antimatter symmetry (CP) violation, we focused on the fact that the permanent electric dipole moment (EDM) of heavy elements such as Francium (Fr) is greatly enhanced by the relativistic effect and octupole deformation of the nucleus. The development of the laser cooled Fr source is in progress at RIBF. In particular, we have established a technique for a high-intensity Fr source by using the nuclear fusion reaction with a surface ionization ion source using a non-contact heating method with an infrared heater. Also the frequency stabilization with an iodine molecule and a high-precision wavemeter are ready at present. Furthermore, by establishing a coexistence trapping technique for two types of Rb isotopes, we have established a co-magnetometer for an accurate EDM measurement.

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List of Publications & Presentations

Publications

[Original Papers]

Z. H. Yang, Y. Kubota, A. Corsi, K. Yoshida, X. -X. Sun, J. G. Li, M. Kimura, N. Michel, K. Ogata, C. X. Yuan, Q. Yuan, G. Authelet, H. Baba, C. Caesar, D. Calvet, A. Delbart, M. Dozono, J. Feng, F. Flavigny, J. -M. Gheller, J. Gibelin, A. Giganon, A. Gillibert, K. Hasegawa, T. Isobe, Y. Kanaya, S. Kawakami, D. Kim, Y. Kiyokawa, M. Kobayashi, N. Kobayashi, T. Kobayashi, Y. Kondo, Z. Korkulu, S. Koyama, V. Lapoux, Y. Maeda, F. M. Marqúes, T. Motobayashi, T. Miyazaki, T. Nakamura, N. Nakatsuka, Y. Nishio, A. Obertelli, A. Ohkura, N. A. Orr, S. Ota, H. Otsu, T. Ozaki, V. Panin, S. Paschalis, E. C. Pollacco, S. Reichert, J. -Y. Roussé, A. T. Saito, S. Sakaguchi, M. Sako, C. Santamaria, M. Sasano, H. Sato, M. Shikata, Y. Shimizu, Y. Shindo, L. Stuhl, T. Sumikama, Y. L. Sun, M. Tabata, Y. Togano, J. Tsubota, F. R. Xu, J. Yasuda, K. Yoneda, J. Zenihiro, S. -G. Zhou, W. Zuo, and T. Uesaka, "Quasifree neutron knockout reaction reveals a small *s*-orbital component in the borromean nucleus ^{17}B," Phys. Rev. Lett. **126**, 082501 (2021).

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Presentations

[International Conferences/Workshops]

N. Imai (invited), "Preparation status of NP1912-SHARAQ18," OEDO/SHARAQ Collabotration Meeting 2020, On-line, September 7, 2020.

S. Michimasa (invited), "Mapping background X-rays from OEDO RFD," OEDO/SHARAQ Collabotration Meeting 2020, On-line, September 7, 2020.

M. Dozono (invited), "Probing exotic structures of highly excited nuclei: OEDO-SHARAQ activities," RIBF User Meeting, On-line, September 8–10, 2020.

S. Michimasa (invited), "Development of energy-degraded RI beam and expansion of nuclear reaction studies," Symposium of Nuclear Data 2020 (hybrid), Saitama, Japan, November 26–27, 2020.

S. Ota (invited), "Study of nuclear matter property via nuclear scattering and reactions," JPS/NRF/NSFC A3 Foresight Program "Nuclear Physics in the 21st Century" Joint Annual Meeting, Huizhou, China and On-line, November 18–19, 2020.

H. Yamaguchi (oral), "Activities at the low-energy RI beam separator CRIB," RIBF Users Meeting 2020 (on-line), Saitama, Japan, Sepember 8–10, 2020.

H. Yamaguchi (oral), "Overview of alpha resonant scattering experiments at CRIB," International mini-workshop on "Physics in resonant reaction induced by low-energy RI beam", Web Meeting Hosted by CNS, the University of Tokyo/IBS Center for Exotic Nuclear Studies/Department of Pure and Applied Physics, Kansai University/Research Center for Nuclear Physics (RCNP), Osaka, Japan, February 22, 2021.

N. R. Ma (oral), "Primary result of $^{14}O + \alpha$ clustering study at CRIB," International mini-workshop on "Physics in resonant reaction induced by low-energy RI beam", Web Meeting Hosted by CNS, the University of Tokyo/IBS Center for Exotic Nuclear Studies/Department of Pure and Applied Physics, Kansai University/Research Center for Nuclear Physics (RCNP), Osaka, Japan, February 22, 2021.

D. Sekihata (oral) for the ALICE Collaboration, "Low-mass dielectron measurements in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC," 10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Online, June 2020.

T. Hayamizu (oral), "Development of ultracold francium atomic sources towards the permanent EDM search," Yamada Conference LXXII: The 8th Asia-Pacific Conference on Few-Body Problems in Physics (APFB2020), Kanazawa, Japan, March 4, 2021.

N. Shimizu (oral), "Data-driven approaches in nuclear shell-model calculations," Nuclear Data Symposium 2020 (RIKEN Nishina Cen-

ter), Saitama, Japan, November 27, 2020.

Y. Tsunoda (invited), "Structure of medium-mass nuclei studied by Monte Carlo shell model calculations," The RIBF Users Meeting 2020, Online, September 9, 2020.

Y. Tsunoda (oral), "Nuclear shapes and collective motions in the region of Sm," 12th Symposium on Discovery, Fusion, Creation of New Knowledge by Multidisciplinary Computational Sciences, Online, October 6, 2020.

K. Yanase (oral), "Large-scale shell-model calculations of nuclear Schiff moments of 129Xe and 199Hg," Beyond-the-Standard-Model Physics with Nucleons and Nuclei (INT 20-2b), online, July 23, 2020.

[Domestic Conferences/Workshops]

今井伸明 (招待講演), 「不安定核の中性子捕獲率測定プロジェクト」, 研究会「星の錬金術から銀河考古学へ」, 東京都三鷹市（国立天文台）, 2020 年 10 月 26–29 日.

下浦亨（招待講演）, "Direct reactions as quantum probes of nuclear system," Symposium on "JPS nuclear physics and physical review C," 日本物理学会 2020 年秋季大会, オンライン, 2020 年 9 月 14 日–17 日.

花井周太郎 (口頭発表), 「分割電極型 PPAC(SR-PPAC) における位置較正手法の開発」, 日本物理学会 2020 年秋季大会, on-line, 2020 年 9 月 14 日–17 日.

道正新一郎（口頭発表）, 「中性子過剰 ^{62}Ti 核および近傍核の質量測定」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

堂園昌伯（口頭発表）, 「(^{4}He, ^{6}He) 反応による錫同位体の対振動状態の研究」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

郡司卓（招待講演）, "ALICE upgrade and physics topics (II)," 第 4 回クラスター階層領域研究会, オンライン講演, 2020 年 5 月 28 日.

関畑大貴（口頭発表）, 「機械学習を用いた ALICE-TPC 検出器内部の空間電荷効果補正」, MPGD & Active 媒質 TPC 研究会 2020, 兵庫県神戸市（神戸大学+オンライン）, 2020 年 12 月.

関畑大貴 for the ALICE Collaboration（口頭発表）, 「機械学習を用いた ALICE-TPC 検出器内部の空間電荷効果補正」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

関畑大貴（基調講演）, 「核子対あたり重心系エネルギー 5.02 における中性中間子と直接光子測定」(受賞記念企画公演), 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

関口裕子（口頭発表） for the ALICE Collaboration, 「LHC-ALICE 実験を用いた小さな衝突系における方位角異方性の擬ラピディティ依存性測定」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

清水夏樹（口頭発表） for the ALICE Collaboration, 「ALICE 実験における Run2 全統計を用いたエキゾチックハドロン探索」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

佐藤幹（口頭発表）, 「高効率フランシウム原子線のための吸着防止コーティング材の評価」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

君塚大樹（口頭発表）, 「狭線幅光会合を用いた極低温 Sr_2 分子生成のための高安定な光源開発」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

池田英彦（口頭発表）, 「電場の量子センシングに向けた Sr リドベルグ原子の分光」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

小澤直也（口頭発表）, 「フランシウム原子の電気双極子能率探索のための表面電離イオン源の開発」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

清水則孝（口頭発表）, 「準粒子真空基底によるモンテカルロ殻模型の拡張」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

角田佑介（口頭発表）, 「モンテカルロ殻模型による二重ベータ崩壊の核行列要素の計算」, 新学術領域「地下宇宙」2020 年度領域研究会, オンライン講演, 2020 年 6 月 2 日.

角田佑介（口頭発表）, 「モンテカルロ殻模型による二重ベータ崩壊の核行列要素の計算」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

柳瀬宏太（口頭発表）, 「原子核殻模型による電気双極子モーメントの精密計算」, 「富岳で加速する素粒子・原子核・宇宙・惑星」シンポジウム, オンライン講演, 2021 年 1 月 28 日.

柳瀬宏太（口頭発表）, 「清水則孝, 原子核殻模型による電気双極子モーメントの精密計算」, 日本物理学会 第 76 回年次大会, オンライン講演, 2021 年 3 月 12–15 日.

[Seminars]

N. Kitamura (oral), "In-beam spectroscopy of ^{30}Mg: structural evolution approaching the island of inversion," CNS Seminar, On-line, July 29, 2020.

S. Koyama (oral), "Spectroscopy of resonance states in light proton-rich nuclei via missing mass method," CNS Seminar, On-line, August 7, 2020.

鎌倉恵太 (oral), 「東大 HyperECR イオン源の現状」, 第 19 回 AVF 合同打ち合わせ, 宮城県仙台市（東北大学）, 2021 年 3 月 10 日.

小高康照 (oral), 「理研 AVF のビーム輸送系最適化の現状」, 第 19 回 AVF 合同打ち合わせ, 宮城県仙台市（東北大学）, 2021 年 3 月 10 日.

Awards

関畑大貴, 第 15 回日本物理学会若手奨励賞 (実験核物理領域).

関畑大貴, 第 27 回原子核談話会新人賞.

Press Releases

道正新一郎, 小林幹, 下浦享, 上坂友洋, 井手口栄治, 西村太樹, 「チタン同位体でおこる新たな安定化現象を発見—質量測定で迫る原子核存在限界」, 2020 年 9 月 16 日.

大塚孝治, 角田直文, 高柳和雄, 清水則孝, 鈴木俊夫, 宇都野穣, 吉田聡太, 上野秀樹, 「原子核の存在限界（中性子ドリップライン）の新たなメカニズム」, 2020 年 11 月 5 日, https://www.s.u-tokyo.ac.jp/ja/press/2020/7074/.

Others

[東京大学理学部ニュース]

道正新一郎, 「質量から探る原子核の秩序と存在限界」, 学部生に伝える研究最前線, 東京大学理学部ニュース 2021 年 1 月号.