1. Organization

1.1 Organization Chart as of March 31, 2019 (End of FY2018)

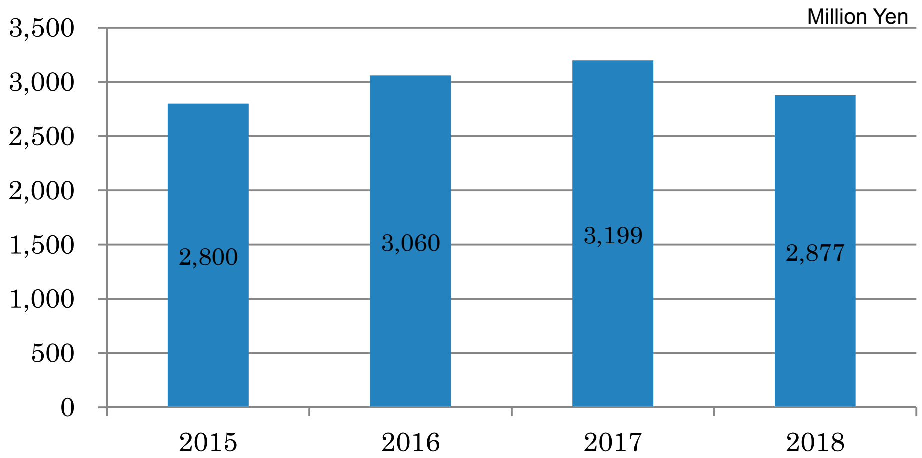
1.2 Topics in FY2018

In FY2018, the RNC reorganized the former three division system consisting of the Theory Research Division, the Subnuclear System Research Division and the RIBF Research Division into a four division system.

Year	Date	Topics in Management
2018	Apr. 1	Newly appointed: Team Leader of the SLOWRI Team: Hironobu ISHIYAMA
2018	Apr. 1	Newly appointed: Team Leader of the Computing and Network Team: Hidetada BABA
2018	May. 1	Newly appointed: Team Leader of the Plant Genome Evolution Research Team: Yusuke KAZAMA
2019	Jan. 11	Interim Review of the Chief Scientist, Tomohiro UESAKA

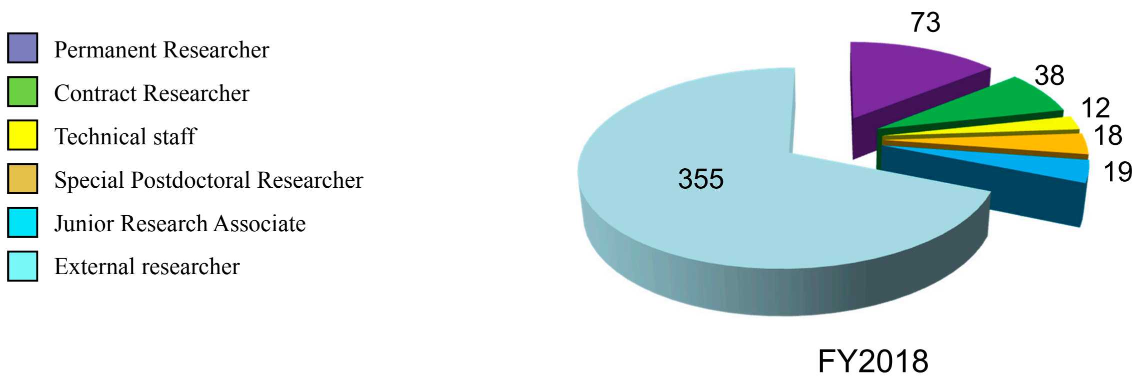
2. Finances

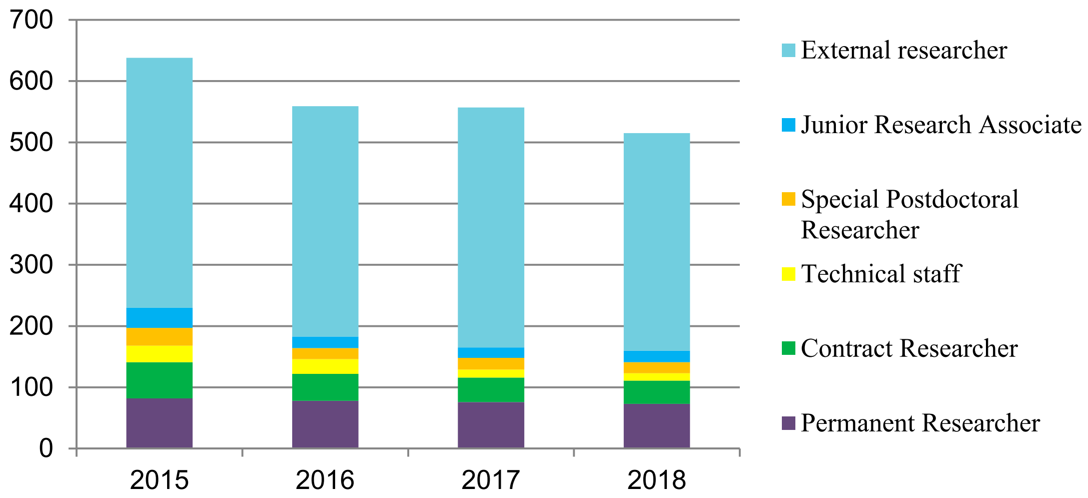
A transition of the RNC budget for the past five years is shown in following graph.



3. Staffing

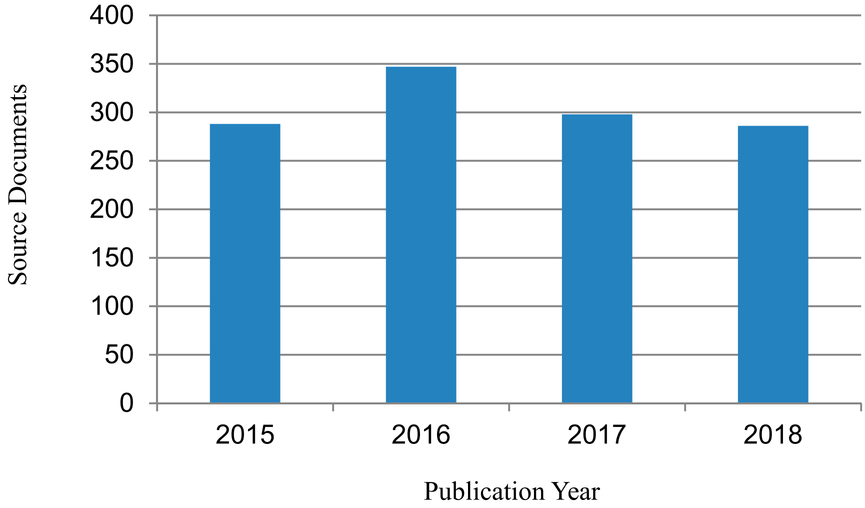
At the start of FY 2018, there were 160 personnel affiliated with RNC and 355 researchers visiting RNC for research purpose. The following graphs show a breakdown of personnel into six categories as of April 1, 2018, and a transition of the number of each category.





4. Research publication

The number of papers published annually from RNC is shown graphically using the data obtained from Clarivate Analytics' Web of Science Documents.



Citation analysis for the past four years

As of March 2019

Indicators \ Year	2015	2016	2017	2018
Total number of papers	288	347	298	286
Percentage of papers in top 10%	17.01	15.85	16.78	20.63
Percentage of papers in top 1%	1.39	1.44	2.68	4.20

5. Management

Headed by the RNC Director Hideto En'yo, the RIKEN Nishina Center for Accelerator-Based Science (RNC) consists of:

- 9 Laboratories
- 10 Groups with 27 Teams
- 2 overseas research centers with 3 Groups

as of the end of FY2018. There are also two 'Partner Institutes' which conduct research in the laboratories set up in RNC. RNC is managed by its Director who takes into consideration the majority decision of the RNC Coordination Committee. The management of RNC is supported by the following committees:

- Program Advisory Committee
- Safety Review Committee
- RIBF Machine Time Committee
- Public Relations Committee

There are also committees to support the President of RIKEN and/or the Director of RNC such as:

- Nishina Center Advisory Council with three subcommittees:
  - ・RBRC Scientific Review Committee (SRC)
  - ・International Advisory Committee for the RIKEN-RAL Muon Facility
  - ・RBRC Management Steering Committee (MSC)

Nishina Center for Accelerator-based Science

Executive Members (as of March 31, 2019)

Hideto EN'YO	Director RNC, Chief Scientist, Director of Radiation Laboratory
Hiroyoshi SAKURAI	Deputy Director (Nuclear Science and Transmutation Research Division)
Osamu KAMIGAITO	Deputy Director (Research Facility Development Division)
Tomoko ABE	Deputy Director (Accelerator Application Division)
Yasushige YANO	Senior Advisor
Tohru MOTOBAYASHI	Senior Advisor
Hideyuki SAKAI	Senior Advisor

RNC Coordination Committee

The following subjects relevant to the RNC management are deliberated under the chairmanship of the RNC Director:

- Establishment of the new organization or reorganization in RNC
- Personnel management of RNC researchers
- Research themes and research budget
- Approval of the Partner Institutes
- Evaluation of the management of RNC and the response to the recommendations by external evaluation

The RNC Coordination Committee is held monthly.

Members (as of March 31, 2019)

Hideto EN'YO	Director, RNC, Director, Radiation Laboratory
Hiroyoshi SAKURAI	Deputy Director, RNC; Group Director, Radioactive Isotope Physics Laboratory and Nuclear Transmutation Data Research Group; Team Leader, Muon Date Team
Osamu KAMIGAITO	Deputy Director, RNC; Group Director, Accelerator Group and High-Intensity Accelerator R&D Group; Team Leader, Infrastructure Management Team
Tomoko ABE	Deputy Director, RNC; Group Director, Beam Mutagenesis Group; Team Leader, Ion Beam Breeding Team
Yasushige YANO	Senior Advisor, RNC
Tohru MOTOBAYASHI	Senior Advisor, RNC
Hideyuki SAKAI	Senior Advisor, RNC
Tomohiro UESAKA	Group Director, Spin Isospin Laboratory and Research Instruments Group
Hideki UENO	Group Director, Nuclear Spectroscopy Laboratory and User Liaison Group; Team Leader, Outreach Team
Toru TAMAGAWA	Group Director, High Energy Astrophysics Laboratory
Kosuke MORITA	Group Director, Superheavy Element Research Group
Yuko MOTIZUKI	Group Director, Astro-Glaciology Research Group
Hiroki OKUNO	Deputy Group Director, Accelerator Group; Team Leader, Accelerator R&D Team, Cryogenic Technology Team, and High-Power Target R&D Team
Nobuhisa FUKUNISHI	Deputy Group Director, Accelerator Group; Team Leader, Beam Dynamics & Diagnostics Team
Masanori WAKASUGI	Group Director, Instrumentation Development Group; Team Leader, Rare RI-Ring Team and SCRIT Team
Hiromitsu HABA	Group Director, RI Application Research Group; Team Leader, RI Application Team and Superheavy Element

	Production Team
Tetsuo HATSUDA	Group Director, Quantum Hadron Physics Laboratory
Emiko HIYAMA	Group Director, Strangeness Nuclear Physics Laboratory
Masahiko IWASAKI	Group Director, Meson Science Laboratory
Kanenobu TANAKA	Group Director, Safety Management Group
Koji MORIMOTO	Team Leader, Superheavy Element Device Development Team
Hideaki OTSU	Team Leader, SAMURAI Team and Fast RI Data Team
Toshiyuki SUMIKAMA	Team Leader, Slow RI Data Team
Naruhiko SAKAMOTO	Team Leader, Cyclotron Team and High-Gradient Cavity R&D Team
Takahide NAKAGAWA	Team Leader, Ion Source Team
Eiji IKEZAWA	Team Leader, RILAC Team
Hironobu ISHIYAMA	Team Leader, SLOWRI Team
Koichi YOSHIDA	Team Leader, BigRIPS Team
Hidetada BABA	Team Leader, Computing and Network Team
Hiromi SATO	Team Leader, Detector Team
Yusuke KAZAMA	Team Leader, Plant Genome Evolution Research Team
Atsushi YOSHIDA	Team Leader, Industrial Application Research Team
Yasuyuki AKIBA	Group Leader, Experimental Group, RIKEN BNL Research Center
Taku IZUBUCHI	Group Leader, Computing Group, RIKEN BNL Research Center
Ken-ichiro YONEDA	Team Leader, RIBF User Liaison Team
Tsukasa TADA	Vice Chief Scientist, Quantum Hadron Physics Laboratory
Yutaka WATANABE	Deputy Team Leader, Infrastructure Management Team
Yasushi WATANABE	Deputy Team Leader, RIBF User Liaison Team
Teruo NAYUKI	Director, Nishina Center and iTHEMS Promotion Office

Program Advisory Committee

The Program Advisory Committee reviews experimental proposals submitted by researchers and reports the approval/disapproval of the proposals to the RNC Director. The Committee also reports to the RNC Director the available days of operation at RIBF or the Muon Facility at RAL allocated to researchers. The Committee is divided into three categories according to the research field.

- Nuclear Physics Experiments at RIBF (NP-PAC): academic research in nuclear physics
- Materials and Life Science Researches at RNC (ML-PAC): academic research in materials science and life science
- Industrial Program Advisory Committee (In-PAC): non-academic research

Program Advisory Committee for Nuclear Physics Experiments at RI Beam Factory (NP-PAC)

The 19th NP-PAC was held on November 29−December 1, 2018 at RIBF.

Members (as of March 31, 2019)

Angela BRACCO (Chair)	INFN
Dieter ACKERMANN	GANIL
Andrei ANDREYEV	University of York
Ikuko HAMAMOTO	Lund University
Robert V.F. JANSSENS	University of North Carolina at Chapel Hill
Augusto O. MACCHIAVELLI	Lawrence Berkeley National Laboratory
David J. MORRISSEY	Michigan State University
Tomofumi NAGAE	Kyoto University
Hitoshi NAKADA	Chiba University
Alexandre OBERTELLI	Technische Universität Darmstadt
Kazuyuki OGATA	RCNP, Osaka University
Tomas RAUSCHER	University of Basel
Kimiko SEKIGUCHI	Tohoku University
Haik SIMON	GSI
Piet VAN DUPPEN	K.U.Leuven
Yuhu ZHANG	Institute of Modern Physics, CAS

Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)

The 16th and 17th ML-PAC was held on July 20, 2018 and January 2019 at RIBF, respectively.

Members (as of March 31, 2019)

Adrian HILLIER (Chair)	ISIS, RAL (UK)
Toshiyuki AZUMA	RIKEN Cluster for Pioneering Research
Ryosuke KADONO	Institute of Materials Structure Science (KEK)
Atsushi KAWAMOTO	Hokkaido University
Norimichi KOJIMA	Toyota RIKEN
Kenya KUBO	ICU
Philippe MENDELS	Universite Paris-SUD(France)

Atsushi SHINOHARA	Osaka University
Shukri SULAIMAN	Universiti Sains Malaysia (Malaysia)
Hiroyuki YAMASE	NIMS
Shigeo YOSHIDA	Thera-Projects
Xu-Guang ZHENG	Saga University

Industrial Program Advisory Committee (In-PAC)

The 8th In-PAC was held on June 29, 2018 at RNC.

Safety Review Committee

The Safety Review Committee is composed of two sub committees, the Safety Review Committee for Accelerator Experiments and the Hot-Lab Safety Review Committee. These Committees review the safety regarding the usage of radiation generating equipment based on the proposal submitted to the RNC Director from the spokesperson of the approved experiment.

Safety Review Committee for Accelerator Experiments

Members (as of March 31, 2019)

Hiromi SATO (Chair)	Team Leader, Detector Team
Kouji MORIMOTO	Team Leader, Superheavy Element Device Development Team
Eiji IKEZAWA	Team Leader, RILAC Team
Hiromitsu HABA	Team Leader, RI Application Team
Shinichiro MICHIMASA	Assistant Prof., Center for Nuclear Study, University of Tokyo
Hidetoshi YAMAGUCHI	Lecturer, Center for Nuclear Study, University of Tokyo
Yutaka WATANABE	Associate Professor, High Energy Accelerator Research Organization, KEK
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Koichi YOSHIDA	Team Leader, BigRIPS Team
Naoki FUKUDA	Nishina Center Research Scientist, BigRIPS Team
Naruhiko SAKAMOTO	Team Leader, Cyclotron Team
Daisuke SUZUKI	Research Scientist, Radioactive Isotope Physics Laboratory
Juzo ZENIHIRO	Research Scientist, Spin Isospin Laboratory
Yuichi ICHIKAWA	Research Scientist, Nuclear Spectroscopy Laboratory

Ex officio members

Kanenobu TANAKA	Group Director, Safety Management Group
Hisao SAKAMOTO	Technical Scientist, Safety Management Group

Hot-Lab Safety Review Committee

Members (as of March 31, 2019)

Masako IZUMI (Chair)	Senior Research Scientist, Ion Beam Breeding Team
Kanenobu TANAKA	Group Director, Safety Management Group
Hisao SAKAMOTO	Safety Management Group
Hiroki MUKAI	Technical Staff I, Assigned Employee, Safety Management Group
Eriko HIGURASHI	Technical Scientist, Safety Management Group
Hiromitsu HABA	Team Leader, RI Application Team

RIBF Machine Time Committee

Upon request of the RNC Director, the RIBF Machine Time Committee deliberates on the machine time schedule of RIBF and reports the results to the Director.

Members (as of March 31, 2019)

Hideki UENO (Chair)	Group Director, User Liaison and Industrial Cooperation Group and Nuclear Spectroscopy Laboratory
Osamu KAMIGAITO	Group Director, Accelerator Group
Masanori WAKASUGI	Group Director, Instrumentation Development Group
Tomohiro UESAKA	Group Director, Research Instruments Group and Spin Isospin Laboratory
Nobuhisa FUKUNISHI	Deputy Group Director, Accelerator Group
Hiroki OKUNO	Deputy Group Director, Accelerator Group
Hiroyoshi SAKURAI	Group Director, Radioactive Isotope Physics Laboratory
Tomoko ABE	Group Director, Beam Mutagenesis Group
Hiromitsu HABA	Group Director, RI Application Research Group
Kanenobu TANAKA	Group Director, Safety Management Group
Ken-ichiro YONEDA	Team Leader, RIBF User Liaison Team

Kouji MORIMOTO	Team Leader, Superheavy Element Research Device Development Team
Koichi YOSHIDA	Team Leader, BigRIPS Team

External members

Kentaro YAKO	Associate Professor, Center for Nuclear Study, University of Tokyo
Hidetoshi YAMAGUCHI	Lecturer, Center for Nuclear Study, University of Tokyo
Michiharu WADA	Professor, High Energy Accelerator Research Organization, KEK

Observers

Hideto EN'YO	Director, RNC
Susumu SHIMOURA	Director, Center for Nuclear Study, University of Tokyo
Hiroari MIYATAKE	Director, KEK Wako Nuclear Science Center
Kosuke MORITA	Group Director, Superheavy Element Research Group
Hideaki OTSU	Team Leader, SAMURAI Team
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Tohru MOTOBAYASHI	Senior Advisor, RNC
Kazushige FUKUSHIMA	Manager, Nishina Center and iTHMES Promotion Office

Public Relations Committee

Upon request of the RNC Director, the Public Relations Committee deliberates and coordinates the following matters:

- Creating public relations system for RNC
- Prioritization of the public relations activities for RNC
- Other general and important matters concerning the public relations of RNC

Members (as of March 31, 2019)

Teruo NAYUKI	Director, Nishina Center and iTHEMS Promotion Office
Hiroyoshi SAKURAI	Deputy Director, RNC; Group Director, Radioactive Isotope Physics Laboratory
Osamu KAMIGAITO	Deputy Director, RNC; Group Director, Accelerator Group
Tomoko ABE	Deputy Director, RNC; Group Director, Beam Mutagenesis Group
Tetsuo HATSUDA	Group Director, Quantum Hadron Physics Laboratory
Masahiko IWASAKI	Group Director, Meson Science Laboratory
Tomohiro UESAKA	Group Director, Spin Isospin Laboratory and Research Instruments Group
Hideki UENO	Group Director, Nuclear Spectroscopy Laboratory and User Liaison Group
Toru TAMAGAWA	Group Director, High Energy Astrophysics Laboratory
Emiko HIYAMA	Group Director, Strangeness Nuclear Physics Laboratory
Kosuke MORITA	Group Director, Superheavy Element Research Group

RBRC Management Steering Committee (MSC)

RBRC MSC is set up according to the Memorandum of Understanding between RIKEN and BNL concerning the collaboration on the Spin Physics Program at the Relativistic Heavy Ion Collider (RHIC). The 24^{th} MSC was held on June 12, 2018.

Members (as of June 12, 2018)

Motoko KOTANI	Executive Director, RIKEN
Shoji NAGAMIYA	Senior Visiting Scientist, RNC
Tetsuo HATSUDA	Program Director, RIKEN Interdisciplinary Theoretical and Mathematical Sciences Program
Robert TRIBBLE	Deputy Director for Science and Technology, BNL
David LISSAUER	Deputy Chair, Physics Department, BNL
Berndt MUELLER	Associate Laboratory Director for Nuclear and Particle Physics, BNL

6. International Collaboration

Country	Partner Institute	Objects	RNC contact person
China	China Nuclear Physics Society	Creation of the council for China -Japan research collaboration on nuclear physics	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
	Peking University	Nuclear Science	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory

	Institute of Modern Physics, Chinese Academy of Science	Physics of heavy ions	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
	School of Nuclear Science and Technology, Lanzhou University	Framework	Masahiko IWASAKI, Director, Meson Science Laboratory
	School of Physics, Nanjing University	Framework	Emiko HIYAMA, Director, Strangeness Nuclear Physics Laboratory
	Department of Physics, Faculty of Science, The University of Hong Kong	Experimental and educational research collaboration in experimental nuclear physics	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
	School of physics, Nankai University	Framework	Emiko HIYAMA, Director, Strangeness Nuclear Physics Laboratory
Finland	University of Jyvaskyla	Basic nuclear physics and related instrumentation	Hironobu ISHIYAMA, Team Leader, SLOWRI Team
France	National Institute of Nuclear Physics and Particle Physics (IN2P3)	Physics of heavy ions	Tohru MOTOBAYASHI, Senior Advisor, RNC
Germany	Technische Universität München	Nuclear physics, hadron physics, nuclear astrophysics	Emiko HIYAMA, Director, Strangeness Nuclear Physics Laboratory
	GSI	Physics of heavy ions and accelerator	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
	Department of Physics, Technische Universität Darmstadt	Framework	Emiko HIYAMA, Director, Strangeness Nuclear Physics Laboratory
Hungary	The Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI)	Nuclear physics, Atomic Physics	Tomohiro UESAKA, Director, Spin Isospin Laboratory
Indonesia	ITB, UNPAD, ITS, UGM, UI	Material science using muons at the RIKEN-RAL muon facility	Masahiko IWASAKI, Director, Meson Science Laboratory
Italy	Applied Physics Division, National Institute for New Technologies, Energy and Environment (ENEA)	Framework	Tohru MOTOBAYASHI, Senior Advisor, RNC
	European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*)	Theoretical physics	Tetsuo HATSUDA, Director, Quantum Hadron Physics Laboratory
	Istituto Nazionale di Fisica Nucleare (INFN)	Physics of heavy ions	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory

Country	Partner Institute	Objects	RNC contact person
Korea	Seoul National University	Nishina School	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
	College of Natural Science, Ewha Women’s University	Framework	Tomohiro UESAKA, Director, Spin Isospin Laboratory
	College of Natural Sciences, INHA University	Framework	Emiko HIYAMA, Director, Strangeness Nuclear Physics Laboratory
Malaysia	Universiti Sains Malaysia	Muon Science	Masahiko IWASAKI, Director, Meson Science Laboratory
Norway	Faculty of Mathematics and Natural Science, University of Oslo（UiO MN）	Framework	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
Poland	The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences(IFPAN)	Framework	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
Romania	“Horia Hulubei” National Institute of Physics and Nuclear Engineering Bucharest-Magurele, Romania	Framework	Tomohiro UESAKA, Director, Spin Isospin Laboratory
Russia	Joint Institute for Nuclear Research (JINR)	Framework	Tomohiro UESAKA, Director, Spin Isospin Laboratory
	Russian Research Center “Kurchatov Institute”	Framework	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory

Switzerland	Paul Scherrer Institute	Improve the performance and reliability of accelerator systems	Osamu KAMIGAITO, Director, Accelerator Group
UK	The Science and Technology Facilities Council	Muon science using the ISIS Facility at the Rutherford Appleton Laboratory	Masahiko IWASAKI, Director, Meson Science Laboratory
USA	BNL	The Spin Physics Program at the Relativistic Heavy Ion Collider (RHIC)	Hideto EN'YO, Director, Radiation Laboratory
	Columbia University	The development of QCDCQ	Hideto EN'YO, Director, Radiation Laboratory
	Michigan State University	Comprehensive The use of TPC (Time Projection Chamber)	Tomohiro UESAKA, Director, Spin Isospin Laboratory
Vietnam	Vietnam Atomic Energy Commission	Framework	Tohru MOTOBAYASHI Senior Advisor, RNC
	Institute of Physics, Vietnam Academy of Science and Technology	Framework	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
Europe	European Nuclear Science and Application Research2	Framework	Tomohiro UESAKA, Director, Spin Isospin Laboratory

7. Awards

Awardee, Laboratory / Team	Award	Organization	Date
Hiroki OKUNO, Deputy Group Director, Accelerator Group Kensuke KUSAKA, Nishina Center Research Scientist, BigRIPS Team	The 22nd Superconductivity Science and Technology Award	Forum of Superconductivity Science and Technology	Apr. 16
Hideaki OTSU, Team Leader, Fast RI Data Team Hiroyoshi SAKURAI, Team Leader, Muon Date Team Teiichiro MATSUZAKI, Contract Researcher, Muon Data Team	The 21st Century Invention Prize	Japan Institute Invention and Innovation	Jun. 12
Minjung KIM, Intern, Radiation Laboratory	2018 Gertrude Scharff-Goldhabor Prize	Brookhaven Woman in Science (BWIS)	Jul. 17
Yuya TANIZAKI, Special Postdoctoral Researcher, Theory Group, RIKEN BNL Research Center	The 13th Particle Physics Medal(FY2018): Young Scientist Award in Theoretical Particle Physics	Particle Theory Committee	Sep. 16
Taku IZUBUCHI, Group Leader, Computing Group, RIKEN BNL Research Center	APS Fellow	American Physical Society	Sep. 11
Naoki KIMURA, Student Trainee, SLOWRI Team	The 2018 International Conference Presentation Incentive Award	The Atomic Collision Society of Japan	Jun. 18
Masato NAKAMURA, Senior Technical Scientist, Cryogenic Technology Team	The Saitama prefecture High-pressure Gas Chairman Commendation	The Saitama prefecture High-pressure Gas Committee	Oct. 16
Takahiro NISHI, Postdoctoral Researcher, Spin Isospin Laboratory	The 13th Young Scientist Award of the Physical Society of Japan in the field of experimental physics/The 25th Award for Outstanding Young Physicists-Experimental Nuclear Physics	The Physical Society of Japan	Mar. 15

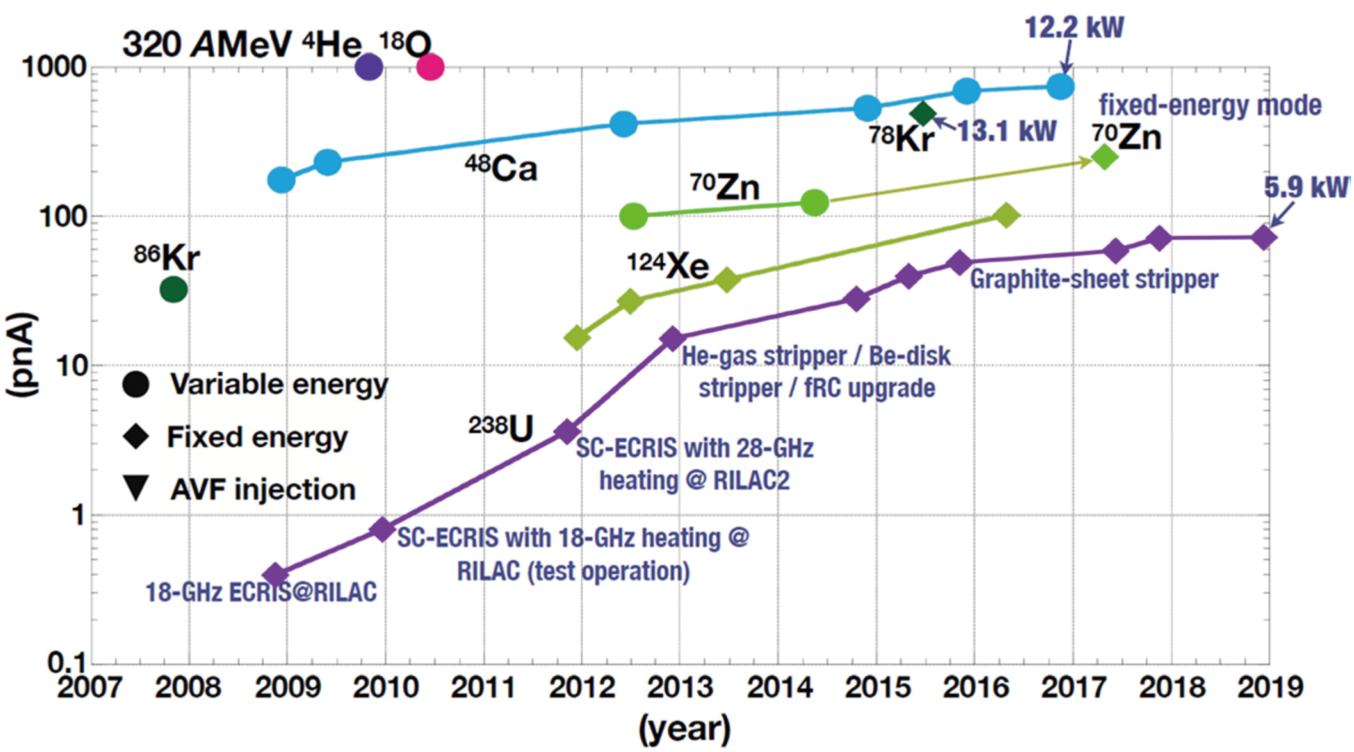
8. Brief overview of the RI Beam Factory

Intensity of Primary Beams

Achieved beam intensities (as of March 2018)

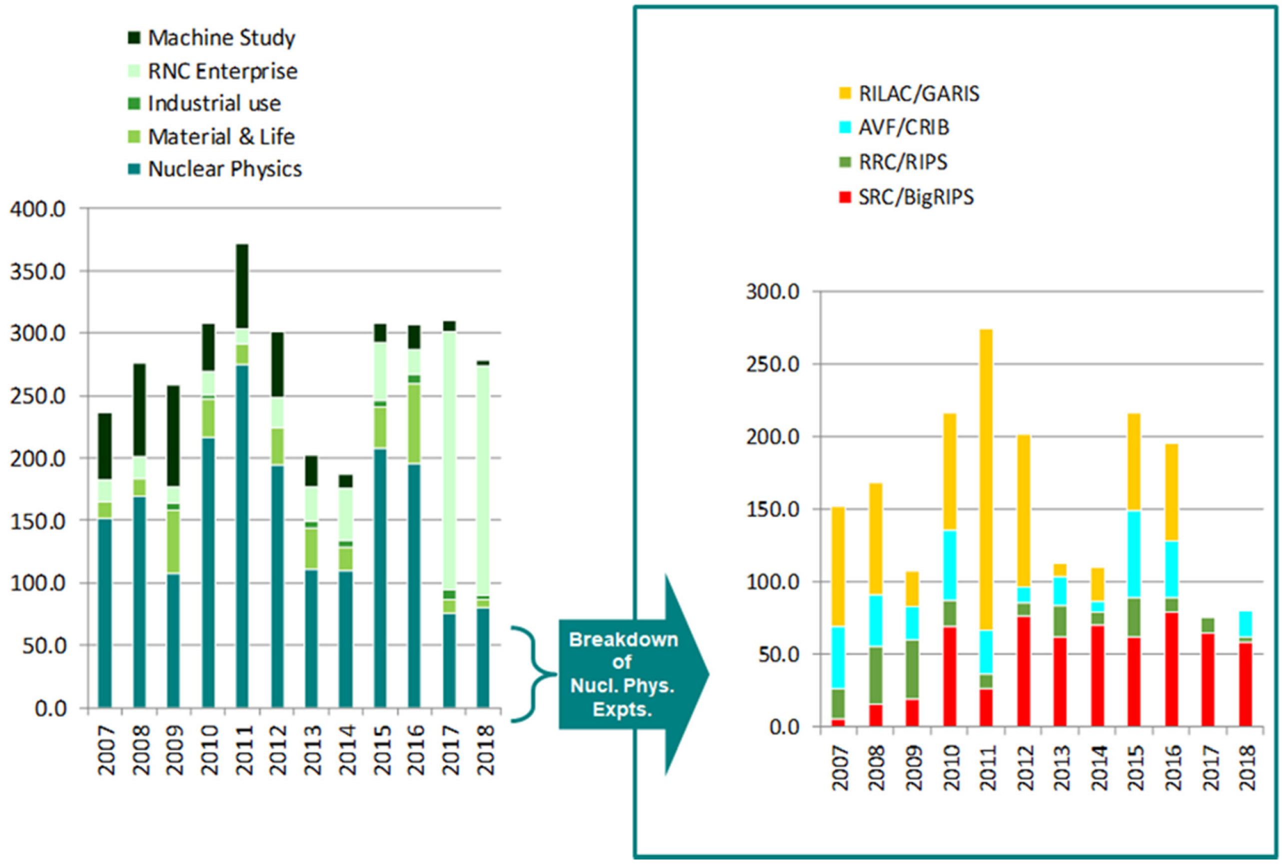
^{238}U	70 pnA (345 MeV/nucleon, Nov. 2017)
^{124}Xe	102 pnA (345 MeV/nucleon, Apr. 2016)
^{86}Kr	30 pnA (345 MeV/nucleon, Nov. 2007)
^{78}Kr	486 pnA (345 MeV/nucleon, May. 2015)
^{70}Zn	250 pnA (345 MeV/nucleon, May 2017)
^{48}Ca	730 pnA (345 MeV/nucleon, Nov. 2016)
^{18}O	1000 pnA (345 MeV/nucleon, Jun. 2010)
^{14}N	400 pnA (250 MeV/nucleon, Oct. 2010)
^{4}He	1000 pnA (250 MeV/nucleon, Oct. 2009)
d	1000 pnA (250 MeV/nucleon, Oct. 2010)
pol. d	120 pnA, *P*~80% (250 MeV/nucleon, May 2015)

History of Beam Intensity Upgrade

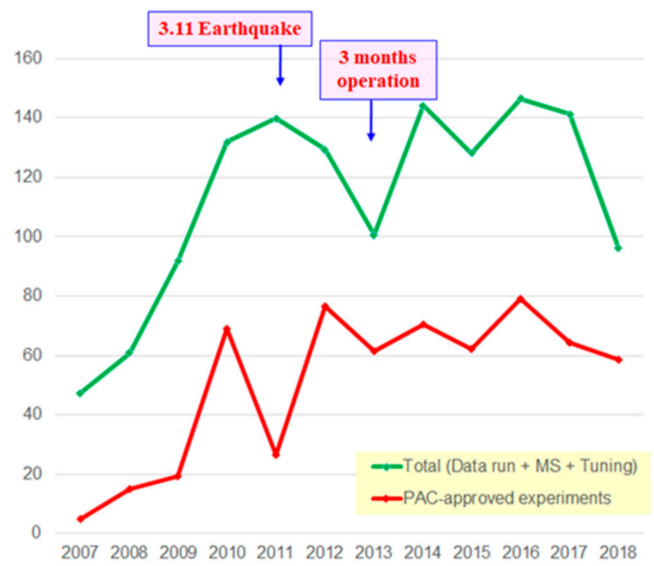


Beam energies of the beams without explicitly indicated are 345 AMeV.

Total beam time for experiments



Total beam time allocated to BigRIPS experiments



Nuclear Science and Transmutation Research Division
Radioactive Isotope Physics Laboratory

1. Abstract

This Laboratory works as one of core research groups conducting programs at the world-premiere heavy-ion accelerator facility of RIKEN "RI Beam Factory (RIBF)," The Laboratory explores exotic nuclear structures and dynamics in exotic nuclei that have never been investigated before, such as those with largely imbalanced proton and neutron numbers. Our aim is to develop new experimental techniques utilizing fast radioactive isotope (RI) beams at RIBF, to discover new phenomena and properties in exotic nuclei. The Laboratory is focusing three major subjects; shell evolution of very neutron-rich nuclei, the r-process path and equation-of-state in asymmetric nuclear matter. The Laboratory has initiated international collaborations for in-beam gamma spectroscopy, decay spectroscopy and heavy-ion induced reactions, and has formed a discussion forum for next generation gamma detectors.

2. Major Research Subjects

(1) Study of structure and dynamics of exotic nuclei through developments of new tools in terms of reaction- and technique-based methodology
(2) Research on EOS in asymmetric nuclear matter via heavy-ion induced reactions
(3) Detector developments for spectroscopy and reaction studies

3. Summary of Research Activity

(1) In-beam gamma spectroscopy

In the medium and heavy mass region explored at RIBF, collective natures of nuclei are one of important subjects, which are obtained through production and observation of high excited and high spin states. To populate such states, heavy-ion induced reactions such as fragmentation, fission are useful. So far, we have developed two-step fragmentation method as an efficient method to identify and populate excited states, and lifetime measurements to deduce transition strength.

Devices utilized for the in-beam gamma spectroscopy are ZeroDegree Spectrometer (ZDS) and a NaI array DALI2. Since the end of 2008, the first spectroscopy on nuclei island-of-inversion region was performed, we have explored step-by-step new and unknown regions in the nuclear chart. The second campaign in 2009 was organized to study background components originating from atomic processes in a heavy target. Neutron-rich nuclei at $N = 20$ to 28 were studied in 2010. In 2011–2013, we conducted experiment programs for Ca-54, Ni-78, neutron-rich nuclei at $N = 82$ and neutron-deficient nuclei at $Z = 50$.

A multitude of data obtained with inelastic, nucleon knock-out, fragmentation channels have been analyzed and published. In 2011–2013, collective natures of Mg-36, 38 and Si-42 were both published in PRL. Excited states firstly observed in Ca-54 were reported in Nature to demonstrate a new nuclear magic number of 34. Fragmentation reaction has been found efficient for nuclei with $A > 100$ and low-lying excited state in Pd-126 has been successfully observed and reported in PRC.

To further strengthen the in-beam gamma spectroscopy at RIBF, we have proposed a new setup of MINOS + DALI2 to search for the 1st excited states in even-even neutron-rich nuclei with $Z \sim 20$ to 40. The program was submitted to the PAC 2013 as a new category of proposal, "proposal for scientific program" and was S-ranked. A dedicated collaboration "SEASTAR" has been established as a subset of in-beam gamma collaboration "SUNFLOWER." The three campaigns were organized in 2014, 2015 and 2017 to study very neutron-rich isotopes, and were very productive to access very neutron-rich nuclei such as Ar-52, Ca-56, Ni-78, Kr-100, Zr-110.

A new project of high resolution gamma spectroscopy with fast beams has been proposed at PAC 2018 and the campaign programs are scheduled in 2020. MINIBALL and several Ge tracking detectors from Japan, Europe and the USA are being combined to form an array of germanium detectors. The new setup aims to accelerate researches of the nuclear structure by observing gamma-lines in even-odd nuclei and measuring lifetimes of excited states. The first workshop will be organized in April, 2019, and having 55 participants.

Concerning a next generation detector, a discussion forum has been established to write up a white paper on tracking germanium detectors and high-efficient crystal detectors such $LaBr_3$ and GAGG.

(2) Decay spectroscopy

Beta- and isomer-spectroscopy is an efficient method for studying nuclear structure, especially for non-yrast levels. We had accumulated experimental techniques at the RIPS facility to investigate nuclear structure in light mass region via beta-gamma and beta-p coincidence. Concerning the medium and heavy mass region available at RIBF, we have developed two position-sensitive active-stoppers, strip-silicon detectors and a cylindrical active stopper called CAITEN, to achieve a low-background measurement by taking correlation between heavy ion stop position and beta-ray emission position. A site of decay-spectroscopy at the new facility of RIBF is the final focal plane of ZDS, where high precision of TOF in particle identification is obtained due to a long flight path from BigRIPS to ZDS.

At the end of 2009, the first decay spectroscopy was organized with a minimum setup of four clover gamma detectors and silicon strip detectors, to study neutron-rich nuclei with $A \sim 110$. The first campaign was found successful and efficient to publish four letter articles in 2011, two PRL's and two PLB's. One of the PRL papers is associated to the r-process path where half-lives for 18 neutron-rich nuclei were determined for the first time. The other PRL paper reported a finding of deformed magic number 64 in the Zr isotopes.

The success of the first decay-spectroscopy campaign stimulated to form a new large-scale collaboration "EURICA," where a twelve Euroball cluster array is coupled with the silicon-strip detectors to enhance gamma efficiency by a factor of 10. A construction proposal of "EURICA" was approved in the PAC 2011, and the commissioning was successfully organized in spring 2012. Since then, physics runs have been conducted for programs approved to survey nuclei of interest as many as possible, such as Ni-78, Pd-128, Sn-100. So far, 44 papers including 12 PRL's and 10 PLB's were published. One of the highlights is discovery of a seniority isomer in Pd-128, of which cascade gamma decay gives the energy of first excited state and robustness of N = 82 magic number, and the other is a half-life measurement for 110 neutron-rich nuclei across the N = 82 shell gap, which shows implications for the mechanism and universality of the r-process path. The EURICA collaboration finished its physics programs in summer 2016.

Beta-delayed neutron emission probability of medium and heavy neutron-rich nuclei is important to understand nuclear structure and the r-process path. In 2013, a new collaboration "BRIKEN" has been established to form a He-3 detector array. A present design of the array has neutron efficiency as high as 70% up to 3 MeV. The array was coupled with the AIDA silicon strip system. A construction proposal was approved at the PAC 2013 and three physics proposals have been approved. The commissioning run was conducted in autumn 2016. The major physics runs were conducted in 2017 and 2018.

The CAITEN detector was successfully tested with fragments produced with a Ca-48 beam in 2010.

(3) Equation-of-state via heavy-ion central collisions

Equation-of-state in asymmetric nuclear matter is one of major subjects in physics of exotic nuclei. Pi-plus and pi-minus yields in central heavy ion collisions at the RIBF energy are considered as one of EOS sensitive observables at the RIBF energy. To observe charged pions, a TPC for the SAMURAI spectrometer is being constructed under an international collaboration "SπRIT," Construction proposal was submitted at the PAC 2012, and physics proposals were approved at the PAC 2012 and 2013. The physics runs were successfully conducted in spring 2016. The data analysis is in progress to produce the first physics results.

An international symposium "NuSYM" on nuclear symmetry energy was organized at RIKEN July 2010 to invite researchers in three sub-fields, nuclear structure, nuclear reaction and nuclear astrophysics, and to discuss nuclear symmetry energy together. Since then, the symposium series have been held every year and been useful to encourage theoretical works and to strengthen the collaboration.

(4) Nucleon correlation and cluster in nuclei

Nucleon correlation and cluster in nuclei are matters of central focus in a "beyond mean-field" picture. The relevant programs with in-beam gamma and missing-mass techniques are to depict nucleon condensations and correlations in nuclear media as a function of density as well as temperature. Neutron-halo and –skin nuclei are objects to study dilute neutron matter at the surface. By changing excitation energies in neutron-rich nuclei, clustering phenomena and role of neutrons are to be investigated.

In 2013, two programs were conducted at the SAMURAI spectrometer. One is related to proton-neutron correlation in the C-12 nucleus via p-n knockout reaction with a carbon target. The other is to search for a cluster state in C-16, which was populated via inelastic alpha scattering. The data is being analyzed. In 2018 a program to find out proton-cluster states was organized by utilizing low-energy radioactive isotope beams at GANIL-LISE, where the RIKEN liquid hydrogen target was installed.

A new project based on missing mass spectroscopy was launched to investigate an exotic cluster state in a very proton-rich nucleus. The experiment will be organized at GANIL with combination of RIKEN liquid hydrogen target CRYPTA and the MUST2 detector array in 2018.

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Publications

[Journal]

(Original Papers) *Subject to Peer Review

H. L. Crawford, P. Fallon, A. O. Macchiavelli, P. Doornenbal, N. Aoi, F. Browne, C. M. Campbell, S. Chen, R. M. Clark, M. L. Cortes, M. Cromaz, E. Ideguchi, M. D. Jones, R. Kanungo, M. MacCormick, S. Momiyama, I. Murray, M. Niikura, S. Paschalis, M. Petri, H. Sakurai, M. Salathe, P. Schrock, D. Steppenbeck, S. Takeuchi, Y. K. Tanaka, R. Taniuchi, H. Wang, K. Wimmer, "First spectroscopy of the near drip-line nucleus ^{40}Mg," Phys. Rev. Lett. **122**, 052501 (2019).

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H. Sakurai (invited), "Recent highlights and future programs at RIBF," The 10th China-Japan Joint Nuclear Physics Symposium, Huizhou, China, November, 2018.

H. Sakurai (invited), "Recent activities and highlights at the RIBF," International Conference on Simplicity, Symmetry and Beauty of Atomic Nuclei, Shanghai, China, September, 2018.

H. Sakurai (invited), "The RIBF Facility and Its Future," 20th Northeastern Asian Symposiu-2018 on Nuclear Physics in the 21st Century, Nagoya, September, 2018.

H. Sakurai (invited), "Recent activities and perspectives," 1st Symposium on Intermediate-energy Heavy Ion Collisions (iHIC2018), Beijing, China, April, 2018.

S. Nishimura (invited), "Experimental challenges relevant to the r-process," EMMI Rapid Reaction Task Force: The physics of neutron star mergers at GSI/FAIR Symposium GSI, Darmstadt, Germany, June 4–15, 2018.

S. Nishimura (invited), "Decay spectroscopy of exotic nuclei at RIBF," International workshop on Physics at HIAF High-Energy Beam Lines and Nuclear Astrophysics, Beihang Univ., China, December 13–15, 2018.

S. Nishimura (invited), "Experiments Relevant to r-Process Nucleosynthesis at RIBF," 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, October 23, 2018.

S. Nishimura (invited), "Experiments related to r-process nucleosynthesis at RIBF," Nuclear Physics in Stellar Explosions, Debrecen, Hungary, September 12–14, 2018.

S. Nishimura (invited), "Experiments related to astrophysical nucleosynthesis," 20th Northeastern Asian Symposiu-2018 on Nuclear Physics in the 21st Century, Nagoya, September, 2018.

T. Isobe (invited), "The SπRIT and pion detectors in RIKEN for the experimental study of symmetry energy with heavy ion collisions," International Workshop on Multi facets of Eos and Clustering, Catania, Italy, May 22–25, 2018.

T. Isobe (invited), "Implementation of GET readout system for heavy RI collision experiment with SπRIT-TPC at RIBF," GET Workshop: General Electronic for Physics, Haut Carre, France, October 10–12, 2018.

T. Isobe (invited), "Study of density dependent asymmetric nuclear EOS by using heavy RI collisions at RIKEN-RIBF," 52nd Reimei Workshop "Experimental and Theoretical Hadron Physics: Recent Exciting Developments," Tokai, Japan, January 9–11, 2019.

T. Isobe (invited), "Experimental study of density dependent symmetry energy at RIBF-SπRIT experiment," 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, October 23–27, 2018.

P. Doornenbal (invited), "Spectroscopy of neutron-rich Ca and Ni isotopes," Nuclear Structure 2018 (NS2018), East Lansing, USA, August 6–10, 2018.

D. Suzuki (invited), "Transfer reaction experiments using deuterated isobutene gas in active targets," Workshop on Gas-filled Detectors and Systems (GDS): Rare-gas target handling and recycling systems, Institute de Physique Nucléaire d'Orsay, France, January 23–25, 2019.

S. Kubono (invited), "Possible programs at HUS pelletron in nuclear astrophysics—Approach to core-collapse supernovae—," International Workshop on research opportunity at HUS Pelletron Facility, Hanoi University of Science, Hanoi, Vietnam, April 12, 2018.

S. Kubono (invited), "Experimental challenge to the cosmological Li problem," Int. Conf. on Nuclei in the Cosmos (NIC 2018), Gran Sasso, Italy, June 25–29, 2018.

S. Kubono (invited), "Heavy element synthesis under explosive burning on neutron stars," ASRC International Workshop, Tokai, Japan, March 25–27, 2019.

H. Wang *et al*., "Nuclear reaction study for long-lived fission products in high-level radioactive waste: Cross section measurements for proton- and deuteron-induced spallation reactions," 13th International Conference on Nucleus-Nucleus Collisions (NN2018), Omiya, Saitama, Japan, December 4–8, 2018.

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M. L. Cortes *et al*., "First Spectroscopy of ^{62}Ti: Shell Evolution Towards ^{60}Ca," Nuclear Structure 2018 (NS2018), East Lansing, USA, August 5–10, 2018.

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M. Kurata-Nishimura *et al*., "SπRIT-TPC experiment with neutron rich Sn + Sn collisions in RIKEN-RIBF," 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, October 23–27, 2018.

M. Kaneko *et al*., "Study of light cluster production in intermediate energetic heavy-RI collision at RIBF," 13th International Conference on Nucleus-Nucleus Collisions NN2018, Omiya, Japan, December 4–8, 2018.

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X. Sun *et al*., "Reaction study of ^{136}Xe on proton, deuteron and carbon at 168 MeV/u," 15th Varenna Conference on Nuclear Reaction Mechanism, Varenna, Italy, June 11–15, 2018.

[Domestic Conference]

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P. Doornenbal (invited), "SUNFLOWER status report," RIBF UEC Meeting, Wako, Japan, September 5–6, 2018.

D. Suzuki (invited), "Study of rp-process at OEDO," OEDO workshop, Riken Wako Campus, Japan, June 11, 2018.

H. Wang, "Spallation reaction study for fission products in high-level radioactive waste: Towards a new invention of nuclear transmutation," the All RIKEN workshop 2018, Wako, Japan, December 14, 2018.

M. L. Cortes, "First spectroscopy of ^{62}Ti," RIBF Week 2018, Wako, Japan, September 3–7, 2018.

M. L. Cortes, "Recent developments towards a new scintillator array at RIBF using GAGG detector," RIBF Week 2018, Wako, Japan, September 3–7, 2018.

M. L. Cortes, "Fall 2018 beam time overview," RIBF Week 2018, Wako, Japan, September 3–7, 2018.

F. Browne, "Asymmetric dynamics around the magic octupole numbers $Z = 34$ and $N = 54$," RIBF Week 2018, RIKEN, Wako, Japan, September 3–7, 2018.

Posters Presentations

[International Conference etc.]

Y. Nakai, N. Watanabe, Y. Oba, “Laboratory experiment for hydrogenation of C_{60} fullerenes deposited on a solid surface under low temperature conditions,” The Olympian Symposium 2018 on “Gas and stars from milli- to mega- parsecs,” Paralia Katerini, May 31, 2018.

X. Sun *et al*., “Isotopic cross sections of proton-, deuteron- and carbon-induced reactions on ^{136}Xe,” 13th International Conference on Nucleus-Nucleus Collisions, Omiya, Japan, December 4–8, 2018.

H. Shimizu *et al*., “Isomeric RIB Production of Aluminum-26,” XV International Symposium on Nuclei in the Cosmos, Assergi, Italy, June 24–29, 2018.

[Domestic Conference]

中井陽一, 渡部直樹, “低温薄膜状 C_{60} 固体にトラップされた水素分子の振動回転励起の赤外吸収スペクトル,” 原子衝突学会第 43 回年会, 宇治, 2018 年 10 月 13 日.

Seminars/Lectures

S. Nishimura, “Introduction of RIKEN,” “Studying nuclear structure using RI beams,” “Possibility using pelletron for nuclear physics experiment,” International Training Course on the Possibilities for Studying Nuclear Physics using the Pelletron Accelerator, Hanoi, Vietnam, December 17–20, 2018.

H. Wang, “Reaction study for fission products in high-level radioactive waste for nuclear transmutation,” The 411th PKU Lecture on Nuclear Science, Peking University, Beijing, China, January 9, 2019.

Nuclear Science and Transmutation Research Division
Spin isospin Laboratory

1. Abstract

The Spin Isospin Laboratory pursues research activities putting primary focus on interplay of spin and isospin in exotic nuclei. Understanding nucleosyntheses in the universe, especially those in r-and rp-processes is another big goal of our laboratory.

Investigations on isospin dependences of nuclear equation of state, spin-isospin responses of exotic nuclei, occurrence of various correlations at low-densities, evolution of spin-orbit coupling are main subjects along the line. We are leading a mass measurement project with the Rare RI Ring project, too. Through the experimental studies, we will be able to elucidate a variety of nuclear phenomena in terms of interplay of spin and isospin, which will in turn, lead us to better understanding of our universe.

2. Major Research Subjects

(1) Direct reaction studies of neutron-matter equation of state
(2) Study of spin-isospin responses with RI-beams
(3) R-process nucleosynthesis study with heavy-ion storage ring
(4) Application of spin-polarization technique to RI-beam experiments and other fields
(5) Development of special targets for RI-beam experiments

3. Summary of Research Activity

(1) Direct reaction studies of neutron matter equation of state

Direct reactions induced by light-ions serve as powerful tools to investigate various aspects of nuclei. We are advancing experimental programs to explore equation of state of neutron matter, via light-ion induced reactions with RI-beams.

(1-1) Determination of a neutron skin thickness by proton elastic scattering

A neutron skin thickness is known to have strong relevance to asymmetry terms of nuclear equation of state, especially to a term proportional to density. The ESPRI project aims at determining density distributions in exotic nuclei precisely by proton elastic scattering at 200–300 MeV/nucleon. An experiment for ^{132}Sn that is a flagship in this project has been successfully performed.

(1-2) Asymmetry terms in nuclear incompressibility

Nuclear incompressibility represents stiffness of nuclear matter. Incompressibility of symmetric nuclear matter is determined to be 230 ± 20 MeV, but its isospin dependence still has a large uncertainty at present. A direct approach to the incompressibility of asymmetric nuclear matter is an experimental determination of energies of isoscalar giant monopole resonances (GMR) in heavy nuclei. We have developed, in close collaboration with Center for Nuclear Study (CNS) of University of Tokyo, an active gas target for deuteron inelastic scattering experiments to determine GMR energies. The active gas target has been already tested with oxygen and xenon beams at HIMAC and finally has been applied to a ^{132}Sn experiment at RIBF.

(1-3) Multi-neutron and α-cluster correlations at low densities

Occurrences of multi-neutron and α-cluster correlations are other interesting aspects of nuclear matter and define its low-density behavior. The multi-neutron and α-cluster correlations can be investigated with the large-acceptance SAMURAI spectrometer. The SAMURAI has been already applied to experiments to explore light neutron-rich nuclei close to the dripline. We plan to reinforce experimental capabilities of the SAMURAI by introducing advanced devices such as MINOS (Saclay) and NeuLAND (GSI).

(1-4) Fission barrier heights in neutron-rich heavy nuclei

The symmetry energy has a strong influence on fission barrier heights in neutron-rich nuclei. Knowledge on the fission barrier heights, which is quite poor at present, is quite important for our proper understanding on termination of the r-process. We are planning to perform, in collaboration with the TU Munich group, $(p, 2p)$-delayed fission experiments at the SAMURAI to determine the fission barrier heights in neutron-rich nuclei in Pb region.

(2) Study of spin-isospin responses with RI-beams

The study of spin-isospin responses in nuclei forms one of the important cores of nuclear physics. A variety of collective states, for example isovector giant dipole resonances, isobaric analogue states, Gamow-Teller resonances, have been extensively studied by use of electromagnetic and hadronic reactions from stable targets.

The research opportunities can be largely enhanced with light of availabilities of radioactive isotope (RI) beams and of physics of unstable nuclei. There are three possible directions to proceed. The first direction is studies of spin-isospin responses of unstable nuclei via inverse-kinematics charge exchange reactions. A neutron-detector array WINDS has been constructed, under a collaboration of CNS, Tokyo and RIKEN, for inverse kinematics (p, n) experiments at the RI Beam Factory. We have already applied WINDS to the (p, n) experiments for ^{12}Be, ^{132}Sn and plan to extend this kind of study to other exotic nuclei.

The second direction is studies with RI-beam induced charge exchange reaction. RI-beam induced reactions have unique properties which are missing in stable-beam induced reactions and can be used to reach the yet-to-be-discovered states. We have constructed the SHARAQ spectrometer and the high-resolution beam-line at the RI Beam Factory to pursue the capabilities of RI-beam induced reactions as new probes to nuclei. One of the highlights is an observation of β^{+}type isovector spin monopole resonances (IVSMR) in ^{208}Pb and ^{90}Zr via the $(t, {}^{3}\text{He})$ reaction at 300 MeV/nucleon.

The third direction is studies of neutron- and proton-rich nuclei via stable-beam induced charge exchange reactions, which is conducted under collaboration with Research Center for Nuclear Physics (RCNP), Osaka University. We have performed the double charge exchange ^{12}C(^{18}O, ^{18}Ne)^{12}Be reaction at 80 MeV/nucleon to investigate structure of a neutron-rich ^{12}Be nucleus. Peaks corresponding to ground and excited levels in ^{12}Be have been clearly observed. Another double charge exchange reaction, (^{12}C, ^{12}Be($0_2{}^{+}$)) are being used to search for double Gamow-Teller resonances.

(3) R-process nucleosynthesis study with heavy-ion storage ring

Most of the r-process nuclei become within reach of experimental studies for the first time at RI Beam Factory at RIKEN. The Rare RI Ring at RIBF is the unique facility with which we can perform mass measurements of r-process nuclei. Construction of the Rare RI Ring started in FY2012 in collaboration with Tsukuba and Saitama Universities. A major part of the ring has been completed and the commissioning run is planned in FY2014.

We are planning to start precise mass measurements of r-process nuclei soon. A series of experiments will start with nuclei in the A = 80 region and will be extended to heavier region.

(4) Application of spin-polarization technique to RI-beam experiments and other fields

A technique to produce nuclear polarization by means of electron polarization in photo-excited triplet states of aromatic molecules can open new applications. The technique is called "Tripletd-DNP." A distinguished feature of Triplet-DNP is that it works under a low magnetic field of 0.1–0.7 T and temperature higher than 100 K, which exhibits a striking contrast to standard dynamic nuclear polarization (DNP) techniques working in extreme conditions of several Tesla and sub-Kelvin.

We have constructed a polarized proton target system for use in RI-beam experiments. Recent experimental and theoretical studies have revealed that spin degrees of freedom play a vital role in exotic nuclei. Tensor force effects on the evolution of shell and possible occurrence of *p-n* pairing in the proton-rich region are good examples of manifestations of spin degrees of freedom. Experiments with the target system allow us to explore the spin effects in exotic nuclei. It should be noted that we have recently achieved a proton polarization of 40% at room temperature in a pentacene-d_{14} doped p-terphenyl crystal.

Another interesting application of Triplet-DNP is sensitivity enhancement in NMR spectroscopy of biomolecules. We started a new project to apply the Triplet-DNP technique to study protein-protein interaction via two-dimensional NMR spectroscopy, in close collaboration with biologists and chemists.

(5) Development of special targets for RI-beam experiments

For the research activities shown above, we are developing and hosting special targets for RI-beam experiments listed below:

(1) Polarized proton target (described in (4))
(2) Thin solid hydrogen target
(3) MINOS (developed at Saclay and hosted by the Spin Isospin Laboratory)

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

S. Adachi, T. Kawabata, K. Minomo, T. Kadoya, N. Yokota, H. Akimune, T. Baba, H. Fujimura, M. Fujiwara, Y. Funaki, T. Furuno, T. Hashimoto, K. Hatanaka, K. Inaba, Y. Ishii, M. Itoh, C. Iwamoto, K. Kawase, Y. Maeda, H. Matsubara, Y. Matsuda, H. Matsuno, T. Morimoto, H. Morita, M. Murata, T. Nanamura, I. Ou, S. Sakaguchi, Y. Sasamoto, R. Sawada, Y. Shimizu, K. Suda, A. Tamii, Y. Tameshige, M. Tsumura, M. Uchida, T. Uesaka, H. P. Yoshida, S. Yoshida, "Systematic analysis of inelastic α scattering off self-conjugate A = 4n nuclei," Phys. Rev. C **97**, 014601 (2018).

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T. Uesaka (invited), "Various aspects of nuclear matter studied with direct reactions," International Workshop on New Aspects of Hadron and Nuclear/Astro Physics, Tashkent, Uzbekistan, November 5–10, 2018.

T. Uesaka (invited), "30-year perspective of experimental nuclear physics at RIBF/RCNP," International Symposium on the paths of nuclear physics from 1950's towards 2020's, Tokyo, Japan, September 23, 2018.

T. Uesaka (invited), "Congelation of correlated nucleons in nuclei," 20th Northeastern Asian Symposium-2018 on Nuclear Physics in the 21st Century, Nagoya, Japan, September 19–20, 2018.
T. Uesaka (invited), "Nuclear Doube Gamow-Teller Responses—little known aspects of nuclear structure—," 6th Symposium on Neutrinos and Dark Matter in Nuclear Physics 2018, Daejeon, Korea, June 29–July 4, 2018.

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H. Sagawa (invited), "Current topics of spin-isospin response," IVth Topical Workshop on Modern Aspects of in Nuclear Structure, Bormio, Italy, February 2018.

M. Sasano, "Gamow-Teller Giant Resonance in ^{132}Sn," 13th International conference on nucleus-nucleus collisions (NN2018), Saitama, Japan, December 4–8, 2018.

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J. Zenihiro, "Direct determination of neutron skin thickness of ^{48}Ca via proton elastic scattering," 13th International conference on nucleus-nucleus collisions (NN2018), Saitama, Japan, December 4–8, 2018.

J. Zenihiro, "Direct determination of neutron skin thickness of ^{48}Ca from proton elastic scattering and the ESPRI project," Hawaii2018 -Fifth Joint Meeting of the Nuclear Physics Divisions of the APS and JPS, Hawaii, USA, October 2018.

J. Zenihiro, "New detector design for (p, p), (p, pX) experiments," SAMURAI Workshop, RIBF week 2018, Saitama, Japan, September 2018.

J. Zenihiro, "Overview of RIBF," The 17th CNS International Summer School (CNSSS18), Saitama, Japan, August 2018.

Y. Kubota, "Probing neutron-neutron correlation in ^{11}Li via the quasi-free (p, pn) reaction," Hadrons and Nuclear Physics meet ultracold atoms: a French Japanese workshop, Paris, France, January 2018.

K. Tateishi (invited), "Neutron spin filter based on nuclear polarization technique," Polarised Neutrons for Condensed-Matter Investigations (PNCMI), UK, July 2018.

J. Gao, "Study of Gamow-Teller transition on ^{14}Be with PANDORA," 13th International conference on nucleus-nucleus collisions (NN2018), Saitama, Japan, December 4–8, 2018.

M. Miwa, "Production of n-rich nuclei via 2-proton knockout with deuterium target," 13th International conference on nucleus-nucleus collisions (NN2018), Saitama, Japan, December 4–8, 2018.

[Domestic Conference]

松田洋平, 「炭素 14 偏極陽子弾性散乱測定の現状」, 日本物理学会第 73 回年次大会, 東京理科大学, 野田, 2018 年 3 月 22–25 日.

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1. Abstract

The research group has conducted nuclear-physics studies utilizing stopped/slowed-down radioactive-isotope (RI) beams mainly at the RIBF facility. These studies are based on the technique of nuclear spectroscopy such as β-ray-detected NMR (β-NMR), γ-PAD (Perturbed Angular Distribution), laser, and Mössbauer among other methods that takes advantage of intrinsic nuclear properties such as nuclear spins, electromagnetic moments, and decay modes. In particular, techniques and devices for the production of spin-controlled RI beams have been developed and combined to the spectroscopic studies, which enable high-sensitivity measurements of spin precessions/resonances through a change in the angular distribution of radiations. Anomalous nuclear structures and properties of far unstable nuclei are investigated from thus determined spin-related observables. The group also aims to apply such techniques to interdisciplinary fields such as fundamental physics and materials science by exploiting nuclear probes.

2. Major Research Subjects

(1) Nuclear spectroscopy utilizing spin-oriented fast RI beams
(2) Nuclear/Atomic laser spectroscopy & SLOWRI R&D
(3) Application of RI probes to materials science
(4) Fundamental physics: Study of symmetry

3. Summary of Research Activity

(1) Nuclear spectroscopy utilizing spin-oriented fast RI beams

Measurements of static electromagnetic nuclear moments over a substantial region of the nuclear chart have been conducted for structure studies on the nuclei far from the β-decay stability. Utilizing nuclear spin orientation phenomena of RIs created in the projectile-fragmentation reaction, ground- and excited-state electromagnetic nuclear moments been determined by means of the β-ray-detected nuclear magnetic resonance (β-NMR) and the γ-ray time differential perturbed angular distribution (γ-TDPAD) methods. In particular, a new method developed for controlling spin in a system of rare RIs, taking advantage of the mechanism of the two-step projectile fragmentation reaction combined with the momentum-dispersion matching technique, has been developed and employed making fully use of world's highest intensity rare RIBs delivered from BigRIPS for rare isotopes.

(2) Nuclear/Atomic laser spectroscopy & SLOWRI R&D

The group has been conducting system development for nuclear laser spectroscopy from the following two approaches in order to realize experiments for rare isotopes at RIBF. One is collinear laser spectroscopy for a large variety of elements using slowed-down RI beams produced via a projectile-fragmentation reaction, which can be achieved only by the universal low-energy RI-beam delivery system, SLOWRI, under installation in collaboration with the SLOWRI Team. This slowed-down RI-beam scheme enables to perform high-precision laser spectroscopy even with fast-fragmentation-based RIBs without the elemental limitation problematic in the ISOL-based RIBs.

The other approach is a new method utilizing superfluid helium (He II) as a stopping medium of energetic RI beams, in which the characteristic atomic properties of ions surrounded by superfluid helium enables us to perform unique nuclear laser spectroscopy. RI ions trapped in He II are known to exhibit a characteristic excitation spectrum significantly blue-shifted compared with the emission one. Consequently, the background derived from the excitation-laser stray light, which often causes serious problems in measurements, can be drastically reduced.

(3) Application of RI probes to materials science

The application of RI and heavy ion beams as a probe for condensed matter studies is also conducted by the group. The microscopic material dynamics and properties have been investigated through the deduced internal local fields and the spin relaxation of RI probes based on various spectroscopies utilizing RI probes such as β-NMR/NQR spectroscopy, Mössbauer spectroscopy, the γ-ray time differential perturbed angular correlation (γ-TDPAC) spectroscopy. Furthermore, studies on the control of electrical conductivity of diamond by boron and nitrogen implantation are ongoing.

Provided that highly spin-polarized RI probes are produced independently of their element properties and doped into a substance as an impurity, the constituent particle of the substance can be substituted by the same element RI probe without changing the material structure. This scheme provides a new opportunity for materials-science researches, but a key technology, production of element-independent highly spin-polarized RI beams, has not yet been achieved. In this subject, the group has conducted R&D studies to realize an ultra-slow & highly-spin-polarized RI beams, based on the technique of the atomic beam resonance.

(4) Fundamental physics: Study of symmetry

The nuclear spins of stable and unstable isotopes sometimes play important roles in fundamental physics research. New experimental methods and devices have been developed for studies of the violation of time reversal symmetry (T-violation) using spin-polarized nuclei. These experiments aim to detect the small frequency shift in the spin precession arising from new mechanisms beyond the Standard Model.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

Y. Ito, P. Schury, M. Wada, F. Arai, H. Haba, Y. Hirayama, S. Ishizawa, D. Kaji, S. Kimura, H. Koura, M. MacCormick, H. Miyatake, J. Y. Moon, K. Morimoto, K. Morita, M. Mukai, I. Murray, T. Niwase, K. Okada, A. Ozawa, M. Rosenbusch, A. Takamine, T. Tanaka, Y. X. Watanabe, H. Wollnik, and S. Yamaki, "First mass measurements of nuclides around Z = 100 with a multireflection time-of-flight mass spectrograph," Phys. Rev. Lett. **120**, 152501 (2018). *

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N. Inabe, Y. Ishibashi, Y. Kobayashi, S. Kojima, A. Kusoglu, T. Kawaguchi, T. Kawamura, I. Mukul, M. Niikura, T. Nishizaka, A. Odahara, Y. Ohtomo, T. Otsuka, D. Ralet, G. S. Simpson, T. Sumikama, H. Suzuki, H. Takeda, L. C. Tao, Y. Togano, D. Tomonaga, H. Ueno, H. Yamazaki and X. F. Yang, "Single-particle states and collective modes: results from magnetic moment measurement of ^{75m}Cu," 10th International Conference on Direct Reactions with Exotic Beams (DREB2018), Matsue, Japan, June 4–8, 2018.

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H. Nishibata, S. Kanaya, T. Shimoda, A. Odahara, S. Morimoto, A. Yagi, H. Kanaoka, M. R. Pearson, C. D. P. Levy, M. Kimura, N. Tsunoda, T. Otsuka, "Structure of neutron-rich ^{31}Mg by β-decay spectroscopy of spin-polarized ^{31}Na," Fifth Joint Meeting of the Nuclear Physics Divisions of the APS and the JPS (HAWAII2018), Waikoloa, Hawaii, USA, October 23–27 (2018).

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A. Takamine (Invited), "Prospects for laser spectroscopy project at the SLOWRI facility in RIKEN RIBF," 2018 KPS Fall Meeting, Changwon, Korea, October 24–26 (2018).

T. Sato (Invited), "Atomic EDM searches in RIKEN," The 10th China-Japan Joint Nuclear Physics Symposium (CJNP2018), Huizhou, China, November 18–23 (2018).

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Nuclear Science and Transmutation Research Division
High Energy Astrophysics Laboratory

1. Abstract

In the immediate aftermath of the Big Bang, the beginning of our universe, only hydrogen and helium existed. However, nuclear fusion in the interior of stars and the explosion of supernovae in the universe over 13.8 billion years led to the evolution of a world brimming with the many different elements we have today. By using scientific satellites or balloons to observe X-rays and gamma-rays emitted from celestial objects, we are observing the synthesis of the elements at their actual source. Our goal is to comprehensively elucidate the scenarios for the formation of the elements in the universe, together with our research on sub-atomic physics through the use of an accelerator.

2. Major Research Subjects

(1) Nucleosynthesis in stars, supernovae, and neutron star mergers
(2) Plasma and vacuum in extremely strong magnetism and gravity
(3) Research and development of innovative X-ray and gamma-ray detectors

3. Summary of Research Activity

High Energy Astrophysics Laboratory started in April 2010. The goal of our research is to reveal the mechanism of nucleosynthesis and the evolution of elements in the universe, and to observe/discover exotic physical phenomena in extremely strong magnetic and/or gravitational fields. We have observed supernova remnants, strongly magnetized neutron stars, pulsars, black holes and galaxies with X-ray astronomical satellites, balloons and ground-based telescopes.

(1) Nucleosynthesis in the universe

(1-1) ASTRO-H/Hitomi

The 6th Japanese X-ray satellite ASTRO-H/Hitomi was launched in February 2016. Hitomi carried four X-ray and gamma-ray detectors covering the 0.3–600 keV energy range. We, in collaboration with JAXA (Japan Aerospace Exploration Agency), Tokyo Metropolitan University, Kanazawa University, Saitama University, NASA/GSFC etc., contributed to the soft X-ray spectrometer (SXS), which achieves unprecedented energy resolution (<7 eV) in the 0.3–12 keV energy band with a low temperature micro calorimeter. Although we were supposed to discover many previously-unknown elemental lines in universe and measured abundance of those elements with SXS, Hitomi was unfortunately lost by an accident in March 2016. A recovery mission of Hitomi (named XRISM) was started in 2017 and is now under construction for launch in 2021.

(1-2) MAXI

From April 2018, High Energy Astrophysics Laboratory hosts MAXI (Monitor of All-sky X-ray Image) onboard International Space Station (ISS), which was attached on ISS in 2009. MAXI is a RIKEN-lead project collaborating with JAXA and other universities. Since MAXI scans X-ray all-sky in 90 minutes, many transient objects including neutron star or blackhole binaries are found. All of the data are going to public soon after they are taken, and almost all of the groups in high-energy phenomena rely on the MAXI data. In 2018, we issued 34 alerts as ATEL (Astronomer's Telegram) and 5 new blackhole candidates were found. To detect counterparts of neutron star merger events (*i.e.* gravitational wave events), we have prepared an automatic searching system and keep watching all-sky.

(1-3) Astrophysical Data Analysis

In parallel with the mission development/operations, we performed data analysis.

- We proved that the abundance ratios of the iron-peak elements in the Perseus cluster were consistent with the solar abundance. In previous studies, overabundance of Cr, Mn, and Ni are reported, but Hitomi's high spectroscopic data denied the overabundance. The inter-galactic medium of the nearby cluster has similar abundance pattern of our galaxy.
- We have detected a mysterious hump in the spectrum of the neutronstar low-mass X-ray binary, Aquila X-1. The hump can be interpreted as a recombination-edge of heavy elements (Cd) which were possibly produced by rp-process in X-ray bursts on the neutron star surface.

(2) Extremely strong magnetism and gravity

We have contributed to the NASA's world-first X-ray polarimeter mission IXPE (Imaging X-ray Polarimeter Explorer). High Energy Astrophysics Laboratory is responsible for providing the gas electron multipliers (GEMs) to the IXPE mission: the GEM is a key device of the X-ray polarimeter and produced based on our patent for space use. The IXPE satellite will be launched in 2021, and we have already provided the flight qualified GEMs to the project in FY2018.

By using the IXPE mission, we aim to proof the strong magnetism of Magnetars, which are one of the species of neutron stars which have ultra-strong magnetic field $B > 10^{11}$ T. In such ultra-strong magnetic field, higher-order diagrams, $O(eB/m^2)$, $O(eB/m^2)^2$ etc., never eliminated in the QED perturbation theory. As the results, we observe newly-emerging phenomenon such as vacuum polarization, vacuum birefringence, etc. If such exotic phenomena are detected, we sure that Magnetars have really ultra-strong magnetic field.

(3) Innovative X-ray and gamma-ray detectors

In collaboration with NASA Goddard Space Flight Center, we have developed and tested a hard X-ray polarimeter with a Time Projection Chamber technique. This TPC polarimeter is one of candidates of the future satellite XPP (X-ray polarimeter Probe mission) planned with an international consortium.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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Nuclear Science and Transmutation Research Division
Superheavy Element Research Group

1. Abstract
The elements with their atomic number $Z > 103$ are called as trans-actinide or superheavy elements. This group has been studying the physical and chemical properties of superheavy elements. They must be produced by artificially for the scientific study utilizing the accelerators in RIBF. Two teams lead the study of the superheavy elements. Superheavy Element Production Team studies various methods of efficient production of the superheavy elements and their physical and chemical properties. Superheavy Element Device Development Team develops the main experimental device, *i.e.*, the gas-filled recoil ion separator, GARIS.

The synthesis of elements having atomic numbers over 119 will be attempted with the aim of establishing nuclear synthesis technology that reaches the "island of stability" where the lifetime of atomic nuclei is expected be prolonged significantly. With the aim of constructing an ultimate nuclear model, maximum utilization will be made of key experimental devices which become fully operational in order to conduct research for the syntheses of element 119 and 120.

2. Major Research Subjects
Superheavy Element Production Team
- (1) Searching for new elements
- (2) Spectroscopic study of the nucleus of heavy elements
- (3) Chemistry of superheavy elements
- (4) Study of a reaction mechanism for fusion process

Superheavy Element Device Development Team
- (5) Maintenance of GARIS, GARIS-II and development of new gas-filled recoil ion separator GARIS-III
- (6) Maintenance and development of detector and DAQ system for GARIS, GARIS-II and GARIS-III
- (7) Maintenance and development of target system for GARIS, GARIS-II and GARIS-III

3. Summary of Research Activity
(1) Searching for new elements
To expand the periodic table of elements and the nuclear chart, we will search for new elements.

(2) Spectroscopic study of the nucleus of heavy elements
Using the high sensitivity system for detecting the heaviest element, we plan to perform a spectroscopic study of nuclei of the heavy elements.

(3) Chemistry of superheavy elements
Study of chemistry of the trans-actinide (superheavy element) has just started world-wide, making it a new frontier in the field of chemistry. Relativistic effects in chemical property are predicted by many theoretical studies. We will try to develop this new field.

(4) Study of a reaction mechanism for fusion process
Superheavy elements have been produced by complete fusion reaction of two heavy nuclei. However, the reaction mechanism of the fusion process is still not well understood theoretically. When we design an experiment to synthesize nuclei of the superheavy elements, we need to determine a beam-target combination and the most appropriate reaction energy. This is when the theory becomes important. We will try to develop a reaction theory useful in designing an experiment by collaborating with the theorists.

(5) Research Highlight
The discovery of a new element is one of the exciting topics both for nuclear physicists and nuclear chemists. The elements with their atomic number $Z > 103$ are called as trans-actinides or superheavy elements. The chemical properties of those elements have not yet been studied in detail. Since those elements do not exist in nature, they must be produced by artificially, by using nuclear reactions for the study of those elements. Because the production rate of atoms of those elements is extremely small, an efficient production and collection are key issues of the superheavy research. In our laboratory, we have been trying to produce new elements, studying the physical and chemical properties of the superheavy elements utilizing the accelerators in RIKEN.

Although the Research Group for Superheavy element has started at April 2013, the Group is a renewal of the Superheay Element Laboratory started at April 2006, based on a research group which belonged to the RIKEN accelerator research facility (RARF), and had studied the productions of the heaviest elements. The main experimental apparatus is a gas-filled recoil ion separator GARIS. The heaviest elements with their atomic numbers, 107 (Bohrium), 108 (Hassium), 109 (Meitnerium), 110 (Darmstadtium), 111 (Roentogenium), and 112 (Copernicium) were discovered as new elements at Helmholtzzentrum für Schwerionenforschung GmbH (GSI), Germany by using ^{208}Pb or ^{209}Bi based complete fusion reactions, so called "cold fusion" reactions. We have made independent confirmations of the productions of isotopes of 108th, 110th, 111th, and 112th elements by using the same reactions performed at GSI. After these work, we observed an isotope of the 113th element, ^{278}113, in July 2004, in April, 2005, and in August 2012. The isotope, ^{278}113, has both the largest atomic number, ($Z = 113$) and atomic mass number ($A = 278$) which have determined experimentally among the isotopes which have been produced by cold fusion reactions. We could show the world highest sensitivity for production and detection of the superheavy elements by these observations. Our results that related to ^{278}113 has been recognized as a discovery of new element by a Joint Working Party of the International Union of Pure and Applied Chemistry (IUPAC) and International Union of Pure and Applied Physics (IUPAP). Finally, we named the 113th element as "Nihonium."

We decided to make one more recoil separator GARIS-II, which has an acceptance twice as large as existing GARIS, in order to realize higher sensitivity. The design of GARIS-II has finished in 2008. All fabrication of the separator will be finished at the end of fiscal year 2008. It has been ready for operation after some commissioning works.

Preparatory work for the study of the chemical properties of the superheavy elements has started by using the gas-jet transport system coupled to GARIS. The experiment was quite successful. The background radioactivity of unwanted reaction products has been highly suppressed. Without using the recoil separator upstream the gas-jet transport system, large amount of unwanted radioactivity strongly prevents the unique identification of the event of our interest. This new technique makes clean and clear studies of chemistry of the heaviest elements promising.

The spectroscopic study of the heaviest elements has started by using alpha spectrometry. New isotope, ^{263}Hs (Z = 108), which has the smallest atomic mass number ever observed among the Hassium isotopes, had discovered in the study. New spectroscopic information for ^{264}Hs and its daughters have obtained also. The spectroscopic study of Rutherfordium isotope ^{261}Rf (Z = 104) has done and 1.9-s isomeric state has directly produced for the first time.

Preparatory works for the study of the new superheavy elements with atomic number 119 and 120 have started in 2013. We measured the reaction products of the ^{248}Cm(^{48}Ca, xn)$^{296-x}$Lv (Z = 116) previously studied by Frelov Laboratory of Nuclear Reaction, Russia, and GSI. We observed 5 isotopes in total which tentatively assigned to ^{293}Lv, and ^{292}Lv.

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List of Publications & Presentations

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[International Conference etc.]

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Nuclear Science and Transmutation Research Division
Superheavy Element Research Group
Superheavy Element Production Team

1. Abstract
The elements with atomic number $Z > 103$ are called as trans-actinide or superheavy elements (SHEs). Superheavy Element Production Team investigates synthesis of SHEs, nuclear properties of SHE nuclei, and chemical properties of SHEs mainly in collaboration with Superheavy Element Devise Development Team and Nuclear Chemistry Research Team of RIKEN Nishina Center.

2. Major Research Subjects
(1) Search for new superheavy elements
(2) Decay spectroscopy of the heaviest nuclei
(3) Study of reaction mechanisms for production of the heaviest nuclei
(4) Study of chemical properties of the heaviest elements

3. Summary of Research Activity
(1) Search for new superheavy elements
In November, 2016, the 7th period of the periodic table was completed with the official approval of four new elements, nihonium (Nh, atomic number $Z = 113$), moscovium (Mc, $Z = 115$), tennessine (Ts, $Z = 117$), and oganesson (Og, $Z = 118$) by IUPAC. We have started to search for new elements to expand the chart of the nuclides toward to the island of stability and the periodic table of the elements toward the 8th period of the periodic table. Since June, 2017, RIKEN heavy-ion Linear ACcelerator (RILAC) has been shut down for its upgrade until the end of 2019. During this long-term break, to continue SHE studies at RIBF, we moved GAs-filled Recoil Ion Separator II (GARIS II) from the irradiation room of RILAC to the E6 room of RIKEN Ring Cyclotron (RRC). In December 2017, the RRC + GARIS II setup became ready for SHE studies. We first conducted the commissioning of the RRC + GARIS II setup in the $^{nat}La + {}^{51}V$, $^{159}Tb + {}^{51}V$, and $^{208}Pb + {}^{51}V$ reactions. Then, we started to search for new element, element 119 in the $^{248}Cm + {}^{51}V$ reaction in January, 2018.

(2) Decay spectroscopy of the heaviest nuclei
We measured precision masses of ^{63}Cu, $^{64\text{–}66}Zn$, ^{65}Ga, $^{65\text{–}67}Ge$, ^{67}As, $^{78,81}Br$, ^{80}Rb, ^{79}Sr, $^{210\text{–}214}Ac$, $^{210\text{–}214}Ra$, ^{246}Es, ^{251}Fm, $^{249\text{–}252}Md$, and ^{254}No using a multireflection time-of-flight mass spectrograph coupled to GARIS II at RILAC mainly in collaboration with High Energy Accelerator Research Organization.

(3) Study of reaction mechanisms for production of the heaviest nuclei
SHE nuclei have been produced by complete fusion reactions of two heavy nuclei. However, the reaction mechanism of the fusion process is still not well understood both theoretically and experimentally. In collaboration with Kyushu Univ., we measured excitation functions for the quasielastic scattering of the $^{208}Pb + {}^{48}Ca$, $^{208}Pb + {}^{50}Ti$, $^{238}U + {}^{48}Ca$, $^{248}Cm + {}^{22}Ne$, $^{248}Cm + {}^{26}Mg$, $^{248}Cm + {}^{30}Si$, $^{248}Cm + {}^{34}S$, $^{248}Cm + {}^{40}Ar$, $^{248}Cm + {}^{48}Ca$, and $^{248}Cm + {}^{50}Ti$ reactions using GARIS at RILAC. The quasielastic barrier distributions were successfully extracted for these systems, and compared with coupled-channels calculations. It was found that the results can be utilized to locate the optimal energy for the future searches for undiscovered superheavy nuclei.

(4) Study of chemical properties of the heaviest elements
Chemical characterization of newly-discovered SHEs ($Z \geq 104$) is an extremely interesting and challenging subject in modern nuclear and radiochemistry. In collaboration with Nuclear Chemistry Research Team of RIKEN Nishina Center, we are developing SHE production systems as well as rapid single-atom chemistry apparatuses for chemistry studies of SHEs. We installed a gas-jet transport system to the focal plane of GARIS at RILAC. This system is a promising approach for exploring new frontiers in SHE chemistry: the background radiations from unwanted products are strongly suppressed, the intense primary heavy-ion beam is absent in the gas-jet chamber, and hence the high gas-jet extraction yield is attained. Furthermore, the beam-free conditions make it possible to investigate new chemical systems. We have been developing an ultra-rapid gas-chromatograph apparatus at the focal plane of GARIS. This apparatus consists of an RF carpet gas cell and a cryo-gas-chromatograph column with Si detector array. For the aqueous chemistry of SHEs, we have been developing a flow solvent extraction apparatus which consists of a continuous dissolution apparatus, a flow extraction apparatus, and a liquid scintillation counter.

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[Journal]

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二宮秀美, 笠松良崇, 速水翔, 永瀬将浩, 重河優大, 近藤成美, 渡邉瑛介, 羽場宏光, 横北卓也, 小森有希子, 森大輝, 王洋, ゴーシュコースタブ, 佐藤望, 篠原厚, 「102 番元素 No のアンモニア水及び水酸化ナトリウム水溶液中におけるサマリウム共沈挙動」, 日本化学会第 99 春季年会 2019, 神戸市, 2019 年 3 月.

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近藤成美, 笠松良崇, 永瀬将浩, 安田勇輝, 重河優大, 大内昴輝, 神田晃充, 二宮秀美, 渡邊瑛介, 羽場宏光, 久保木祐生, 小森有希子, 横北卓也, 矢納慎也, 佐藤望, 篠原厚, 「Rf の塩酸系での溶媒抽出挙動の有機溶媒依存性」, 2018 日本放射化学会年会・第 62 回放射化学討論会, 京都市, 2018 年 9 月.

村上郁斗, 平川貴啓, 内藤夏樹, 坂口聡志, 藤田訓裕, 郷慎太郎, 足立智, 田中聖臣, 田中泰貴, 庭瀬暁隆, 森本幸司, 羽場宏光, 加治大哉, 馬場秀忠, Pierre Brionnet, 木村創大, 酒井英行, 森田浩介, 「超重元素識別のためのデータ解析手法の開発」, 日本物理学会第 74 回年次大会, 福岡市, 2019 年 3 月.

Nuclear Science and Transmutation Research Division
Superheavy Element Research Group
Superheavy Element Device Development Team

1. Abstract

A gas-filled recoil ion separator has been used as a main experimental device for the study of superheavy elements. This team is in charge of maintaining, improving, developing and operating the separators and related devices. There are two gas-filled recoil ion separators installed at RILAC experimental hall. One is GARIS that is designed for symmetric reaction such as cold-fusion reaction, and the other is newly developed GARIS-II and GARIS-III these separators were designed for an asymmetric reaction such as hot-fusion reaction. New elements ^{278}113 were produced by ^{70}Zn + ^{209}Bi reaction using GARIS. Further the new element search $Z > 118$ are preparing by using GARIS-II and GARIS-III.

2. Major Research Subjects

(1) Maintenance of GARIS, GARIS-II and development of new gas-filled recoil ion separator GARIS-III
(2) Maintenance and development of detector and DAQ system for GARIS, GARIS-II and GARIS-III
(3) Maintenance and development of target system for GARIS, GARIS-II and GARIS-III

3. Summary of Research Activity

The GARIS-II and III are newly developed which has an acceptance twice as large as existing GARIS, in order to realize higher sensitivity. The GARIS-II was moved RILAC facility to RRC facility, and new element serach program aiming to element 119 was started using GARIS-II. New separator GARIS-III was developed and installed into the RILAC experimental hall. It will be ready for operation in fiscal year 2020 after some commissioning works. We will also offer user-support if a researcher wishes to use the devices for his/her own research program.

Members

Team Leader
Kouji MORIMOTO

Research/Technical Scientists
Masaki FUJIMAKI (concurrent: Super Technical Scientist Beam Dynamics & Diagnostics Team)
Daiya KAJI (Technical Scientist)

Postdoctoral Researchers
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Hikaru HIROSE (Niigata Univ.)
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Kenta MANABE (Kyushu Univ.)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

S. Kimura, Y. Ito, D. Kaji, P. Schury, M. Wada, H. Haba, T. Hashimoto, Y. Hirayama, M. MacCormick, H. Miyatake, J. Y. Moon, K. Morimoto, M. Mukai, I. Murray, A. Ozawa, M. Rosenbusch, H. Schatz, A. Takamine, T. Tanaka, Y. X. Watanabe, H. Wollnik, "Atomic masses of intermediate-mass neutron-deficient nuclei with relative uncertainty down to 35-ppb via multireflection time-of-flight mass spectrograph, " Int. J. Mass Spectrom. **430**, 134–142 (2018).

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Nuclear Science and Transmutation Research Division
Astro-Glaciology Research Group

1. Summary of Research Activity

Our Astro-Glaciology Research Group promotes both experimental and theoretical studies to open up the new interdisciplinary research field of astro-glaciology, which combines astrophysics, astrochemistry, climate science, and glaciology.

On the experimental side, we analyze ice cores drilled at the Dome Fuji station, in Antarctica, in collaboration with the National Institute of Polar Research (NIPR, Tokyo). These ice cores are time capsules, which preserve atmospheric information of the past. In particular, ice cores obtained around the Dome Fuji station are known to be unique because they contain much more information on conditions in the stratosphere. This means that there are significant advantages in using Dome Fuji ice cores if we wish to study the universe, since gamma-rays and high-energy protons that are emitted in certain astronomical processes affect the chemical and isotopic compositions in the stratosphere. Our principal aim is to acquire and interpret information preserved in ice cores regarding:

- Signatures of past solar cycles and volcanic eruptions;
- Relationships between climate change and solar activity;
- Traces of past supernova explosions in our galaxy, in order to understand better the rate of galactic supernova explosions.

Moreover, we are promoting the projects on:

- Development of precise analytical techniques and instrumentation of high-sensitivity and high-temporal resolution;
- The evolution of molecules in space;
- The application of our high-sensitivity method of isotopic analysis to archaeological artifacts.

On the theoretical side, we are simulating numerically:

- Changes in the chemical composition of the stratosphere induced by gamma-rays and/or high-energy particles emitted from explosive astronomical phenomena, such as galactic supernovae and solar proton events; and
- The explosive nucleosynthesis (including the r-process, the rapid neutron capture process, which creates elements heavier than iron) that arises in the environment of core-collapse supernova explosions.

It is noteworthy that the as yet not fully understood frequency of supernova explosions in our galaxy is crucial to an understanding of the r-process nucleosynthesis. These all will contribute to understanding relationships between the universe and earth, to advance the Astro-Glaciology to Astro-Terrestrial Science.

Members

Group Director
Yuko MOTIZUKI

Research/Technical Scientists
Kazuya TAKAHASHI (Senior Research Scientist)
Yoichi NAKAI (Senior Research Scientist)

Senior Visiting Scientist
Yasushige YANO

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Hideharu AKIYOSHI (Nat ‘l Inst. for Environ. Studies)
Akira HORI (Kitami Inst. of Tech.)
Hideki MADOKORO (Mitsubishi Heavy Ind., Ltd.)
Kenji TANABE (Okayama Univ. of Sci.)

Assistant
Keiko SUZUKI

Part-time Worker
Satomi NEGISHI

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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Y. Motizuki, K. Takahashi,Y. Nakai, H. Motoyama, K. Kodera, "New annually-resolved water isotope data of the past 2000 years from a Dome-Fuji shallow ice core," CLIVASH2k workshop, Cambridge, UK, September 4–5, 2018.

Y. Nakai, N. Watanabe, Y. Oba, "Laboratory experiment for hydrogenation of C_{60} fullerenes deposited on a solid surface under low temperature conditions," The Olympian Symposium 2018 on "Gas and stars from milli- to mega- parsecs," Paralia Katerini, Greece, May 31, 2018.

[Domestic Conference]

望月優子（招待講演)，「南極の氷からひもとく宇宙と地球の歴史」, 仁科記念講演会「アイソトープで探る宇宙」, 公益財団法人仁科記念財団, 西東京, 2018 年 11 月 11 日.

望月優子（招待講演)，「テラ・アストロノミー—宇宙と地球を結ぶ物理科学—」, 埼玉大学理学部物理量子力学特別講義, さいたま, 2019 年 1 月 7 日.

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高橋和也, 中井陽一, 望月優子, 井野敏行, 伊藤茂, 大久保智, 高久雄一, 山口義尊, 田中美穂, 本山秀明, 「南極氷床コアの詳細解析を見据えた硫黄同位体比分析の高感度化の試み」, 日本分析化学会第 67 回年会, 仙台, 2018 年 9 月 12–14 日.

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三宅芙沙, 堀内一穂, 望月優子, 中井陽一, 高橋和也, 増田公明, 本山秀明, 松崎浩之, 「ドームふじアイスコアの一年分解能 ^{10}Be データにみられる AD993/994 宇宙イベント」, 第 21 回 AMS シンポジウム , 東京, 2018 年 12 月 17–18 日.

三宅芙沙, 堀内一穂, 望月優子, 中井陽一, 高橋和也, 増田公明, 本山秀明, 松崎浩之, 「約単年分解能 ^{10}Be データを用いた 994 年宇宙線イベントの調査」, ドームふじアイスコアコンソーシアム年次研究集会, 立川, 2019 年 3 月 27–28 日.

菅澤佳世, 三宅芙沙, 堀内一穂, 笹公和, 望月優子, 高橋和也, 中井陽一, 本山秀明, 松崎浩之, 「ドームふじアイスコア中 ^{10}Be と ^{36}Cl の高分解能測定による BC5480 年宇宙線イベントの調査」, ドームふじアイスコアコンソーシアム年次研究集会, 立川, 2019 年 3 月 27–28 日.

Posters Presentations

[International Conference etc.]

Y. Motizuki, K. Takahashi, Y. Nakai, S. Wada, K. Horiuchi, F. Miyake, H. Motoyama, H. Akiyoshi, T. Imamura, K. Kodera, "Terra-Astronomy/multi-disciplinary studies with Antarctic Ice cores and Numerical Simulations," The Ninth International Symposium on Polar Science, Tachikawa, December 4–7, 2018.

Y. Nakai, N. Watanabe, Y. Oba, "Hydrogenation of C60 deposited on a substrate under low temperature condition," The 30th International Conference on Photonic, Electronic and Atomic Collisions, Cairns Australia, August 2017.

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K. Takahashi, Y. Nakai, Y. Motizuki, T. Ino, S. Ito, Satoru B. Ohkubo, T. Minami, Y. Takaku, Y. Yamaguchi, M. Tanaka, H. Motoyama, "Signature of the large volcanic eruption in AD1883 detected by new high-sensitivity sulfur isotopic measurement method applied to an Antarctic ice core," The Japan Society for Analytical Chemistry, Tokyo, Aug. 31, 2018, for a presentation at the 67th annual meeting of the Japan Society for Analytical Chemistry, Sendai, September 12–14, 2018.

Paper information, “High-sensitivity sulfur isotopic measurements for Antarctic ice core analyses,” Rapid Communications in Mass Spectrometry **32**, 1991–1998 (2018).

K. Takahashi, “Mass spectrometry tracks tiny amounts of sulfur in Antarctic ice cores—An advanced isotope-measuring system can reveal insights about past environments in shorter time frames,” Research Highlight, RIKEN RESEARCH, SUMMER, 2019, 11.

Nuclear Science and Transmutation Research Division
Nuclear Transmutation Data Research Group

1. Abstract

The nuclear waste problem is an inevitable subject in nuclear physics and nuclear engineering communities. Since the Chicago Pile was established in 1942, nuclear energy has become one of major sources of energy. However, nowadays the nuclear waste produced at nuclear power plants has caused social problems. Minor actinide components of the waste have been studied well as a fuel in fast breeder reactors or ADS. Long-lived fission products (LLFP) in waste, on the other hand, have not been studied extensively. A deep geological disposal has been a policy of several governments, but it is difficult to find out location of the disposal station in terms of security, sociology and politics. To solve the social problem, a scientific effort is necessary for nuclear physics community to find out efficient methods for reduction of nuclear waste radioactivity. In the world-wide situation above, our Group aims to obtain reaction data of LLFP at RIBF and other muon facilities for muon capture data. These data are necessary to design an accelerator-based system for transmutation, and also may lead to a new discovery and invention for peaceful use of nuclear power and the welfare of humanity.

2. Major Research Subjects

The Group is formed by three research teams. The first two Teams, “Fast RI Data Team” and “Slow RI Data Team,” are in charge of proton- and deuteron-induced reaction data of LLFP in inverse kinematics at RIBF. The third Team “Muon Data Team” is to obtain muon capture data of LLFP at muon facilities. All of the teams are focusing to obtain high-quality data which are essentially necessary to establish reliable reaction models. Each team has its own subjects and promotes LLFP reaction programs based on their large experiences, techniques and skills.

3. Summary of Research Activity

In 2014, all the teams polished up experimental strategies, formed collaboration and prepared experiments. Physics runs for spallation reaction were successfully organized at RIBF in 2015–2017. The muon program started at RCNP, Osaka University in spring 2016 and the data for Pd isotopes were successfully obtained in 2017–2019 via in-beam method with DC beams at RCNP, and via activation method with pulsed beams at J-PARC and ISIS-RAL/RIKEN facilities.

The reaction data obtained with both fast and energy-degraded beams at RIBF encouraged the nuclear data group of JAEA, and a new database called “JENDLE/ImPACT-2018” has been released. The new database has been generated by a newly developed reaction model “DEURACS” which treats deuteron-induced reactions. DEURACS reproduces very well cross section data, and much better than other reaction models. A simulation code “PHITS” has been re-coordianted to use the database information.

In December 2018, the Team leader, Hideaki Otsu, was invited to join Technical Meeting of IAEA, entitled “Novel Multidisciplinary Applications with Unstable Ion Beams and Complementary Techniques.” Our activity has been demonstrated and recognized internationally.

Members

Group Director

Hiroyoshi SAKURAI (concurrent: Director, RI Physics Lab.)

Assistant

Izumi YOSHIDA
Asako TAKAHASHI

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

S. Takeuchi, T. Nakamura, M. Shikata, Y. Togano, Y. Kondo, J. Tsubota, T. Ozaki, A. Saito, H. Otsu, H. Wang, H. Sakurai, Y. Watanabe, S. Kawase, D. S. Ahn, M. Aikawa, T. Ando, S. Araki, S. Chen, N. Chiga, P. Doornenbal, S. Ebata, N. Fukuda, T. Isobe, S. Kawakami, T. Kin, S. Koyama, S. Kubono, Y. Maeda, A. Makinaga, M. Matsushita, T. Matsuzaki, S. Michimasa, S. Momiyama, S. Nagamine, K. Nakano, M. Niikura, K. Ogata, T. Saito, Y. Shiga, Y. Shimizu, S. Shimoura, T. Sumikama, P. A. Söderstrom, H. Suzuki, H. Takeda, R. Taniuchi, M. Uesaka, Y. Watanabe, K. Wimmer, T. Yamamoto, and K. Yoshida, “Coulomb breakup reactions of ^{93,94}Zr in inverse kinematics,” Prog. Theor. Exp. Phys. **2019**, 013D02 (2019).

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H. Sakurai *et al*., “Nuclear reaction study for high-level radioactive waste: Cross section measurements for proton- and deuteron-induced spallation of long-lived fission products,” The 10th China-Japan Joint Nuclear Physics Symposium, Huizhou, China, November, 2018.

[Domestic Conference]

櫻井博儀, 「核変換による高レベル放射性廃棄物の大幅な低減・資源化 (6-2) ImPACT 加速器 2017 モデルの進展」, 日本原子力学会, 水戸, 2019 年 3 月 21 日.

櫻井博儀, 「加速器：核変換を実用化する革新的加速器」, ImPACT 公開成果報告会, 東京, 2019 年 3 月 9 日.

Posters Presentations

[International Conference etc.]

H. Sakurai, H. Okuno, N. Sakamoto, Y. Mori, T. Matsuzaki, M. Fukuda, R. Fujita, M. Kawashima, “Reduction and resource recycling of high-level radioactive wastes through nuclear transmutations—(5) Accelerator transmutation system and related developments for element technologies—,” Fifteenth NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, OECE/NEA, 1st, Manchester, UK, October, 2018.

[Domestic Conference]

櫻井博儀, 「システム評価」, ImPACT 公開成果報告会, 東京, 2019 年 3 月 9 日.

Awards

大津秀暁, 藤田玲子, 松崎禎市郎, 櫻井博儀, 下浦享, 水口浩司, 大井川宏之, 小澤正基, 仁井田浩二, 21 世紀発明賞, 公益社団法人発明協会, 2018 年 6 月 12 日.

Press Release

日経新聞, 核廃棄物「変換」に活路, 先端技術, 2018 年 7 月 29 日, 日刊 30 面.

読売新聞, 「核のこみ」から希少金属, 2019 年 2 月 17 日, 日刊 31 面.

Outreach Activities

櫻井博儀, 「核変換—放射性物質を高効率で短寿命・無害化する」, 第 34 回「西宮サイエンス談話会」, 甲南大学西宮キャンパス・西宮サイエンス談話会（甲南大学マネジメント創造学部）, 2018 年 7 月 28 日.

Nuclear Science and Transmutation Research Division
Nuclear Transmutation Data Research Group
Fast RI Data Team

1. Abstract

Fast RI team aims at obtaining and accumulating the cross section data for long lived fission products (LLFPs) in order to explore the possibility of using accelerator for nuclear transmutation.

LLFPs as nuclear waste have been generated continuously in nuclear power plants for wealth for human lives, while people noticed the way of disposal has not necessarily been established, especially after the Fukushima Daiichi power plant disaster. One of the ways to reduce the amount of LLFP or to recover them as recycled resources is nuclear transmutation technique.

RIBF facility has a property to generate such LLFP as a secondary beam and the beam species are identified by event by event. Utilizing the property, absolute values of the cross section of various reactions on LLFPs are measured and accumulated as database.

2. Major Research Subjects

(1) Measurement of reaction products by the interaction of LLFPs with proton, deuteron, and photon to explore candidate reactions for transmutation of LLFPs.

(2) Evaluation of the cross section data for the neutron induced reactions from the obtained data.

3. Summary of Research Activity

(1) Acting as collaboration hub on many groups which plan to take data using fast RI beam in RIBF facility.

(2) Concentrating on take data for proton and deuteron induced spallation reactions with inverse kinematics.

(3) Accumulating the cross section data and evaluating them as evaluated nuclear data.

(4) Evaluating cross section of neutron induced reaction on LLFP by collaborating with the nuclear model calculation and evaluation group.

Members

Team Leader

Hideaki OTSU (Concurrent: Team Leader, SAMURAI Team)

Technical Staff I

Nobuyuki CHIGA

Contract Researcher

He WANG

Visiting Scientists

Takashi TERANISHI (Kyushu Univ.)
Satoshi TAKEUCHI (Tokyo Tech)

Student Trainees

Keita NAKANO (Kyushu Univ.)
Kenji NISHIZUKA (Niigata Univ.)
Ayaka IKEDA (Niigata Univ.)
Junki SUWA (Kyushu Univ.)
Kazuya CHIKAATO (Niigata Univ.)
Kotaro IRIBE (Kyushu Univ.)
Hiroya YOSHIDA (Kyushu Univ.)

List of Publications & Presentations

Publications

[Proceedings]

X. Sun, H. Wang, H. Otsu, H. Sakurai *et al.*, "Reaction study of ^{136}Xe on proton, deuteron and carbon at 168A MeV," Proceedings of the 15th International Conference on Nuclear Reaction Mechanisms, CERN-Proceedings-2019-001 (CERN, Geneva, 2019), pp. 153–157.

Oral Presentations

[International Conference etc.]

H. Otsu, "Direct measurement of proton and deuteron induced reaction cross sections on long lived fission products using inverse kinematics," Technical Meeting on Novel Multidisciplinary Applications with Unstable Ion Beams and Complementary Techniques, IAEA Headquarters, Vienna, Austria, December, 2018.

H. Wang *et al.*, "Nuclear reaction study for long-lived fission products in high-level radioactive waste: Cross section measurements for proton- and deuteron-induced spallation reactions," 13th International Conference on Nucleus-Nucleus Collisions (NN2018), Omiya, Saitama, Japan, December 4–8, 2018.

H. Sakurai, H. Wang *et al.*, "Spallation reaction study for fission products in nuclear waste: Cross section measurements for ^{107}Pd, ^{137}Cs, ^{136}Xe, and ^{90}Sr on proton and deuteron at different reaction energies," the 10th China-Japan Joint Nuclear Physics Symposium, Huizhou, China, November 18–23, 2018.

H. Wang *et al.*, "Spallation reaction study for fission products in nuclear waste: Cross section measurements for ^{107}Pd, ^{137}Cs, ^{136}Xe, and ^{90}Sr on proton and deuteron at different reaction energies," Fifteenth NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Manchester Hall, Manchester, UK, September 30 October 3, 2018.

H. Wang *et al.*, "Nuclear reaction study for high-level radioactive waste: Cross section measurements for proton- and deuteron-induced spallation reactions of long-lived fission products," The 15th edition of the Varenna Conference on Nuclear Reaction Mechanisms (NRM), Varenna, Italy, June 11–15, 2018.

[Domestic Conference]

武内聡 他 6 名, ImPACT-RIBF Collaboration, 「クーロン分解反応による ^{79,80}Se および ^{93,94}Zr の光吸収断面積導出」, 日本物理学会第 73 回年次大会, 野田, 2018 年 3 月.

道正新一郎 他 8 名, ImPACT-RIBF Collaboration, 「OEDO ビームラインの開発および 2017 年度実験」, 日本原子力学会年会, 大阪, 2018 年 3 月.

堂園昌伯 他 8 名, ImPACT-RIBF Collaboration, 「低速 RI ビームを用いた ^{107}Pd, ^{93}Zr の陽子および重陽子誘起反応測定」, 日本原子力学会年会, 大阪, 2018 年 3 月.

武内聡 他 5 名, 「^{79,80}Se および, ^{93,94}Zr のクーロン分解反応断面積の統計崩壊モデルを使った解析」, 日本原子力学会年会, 大阪, 2018 年 3 月.

諏訪純貴 他 9 名, 「Y, Zr, Nb 同位体に対する 100 MeV/nucleon 陽子・重陽子入射反応の同位体生成断面積測定」, 日本原子力学会年会, 大阪, 2018 年 3 月.

千賀信幸, 「低エネルギー中重核用イオンチェンバーの設計・製作」, 平成 29 年度核融合科学研究所技術研究会, 岐阜, 2018 年 3 月.

Posters Presentations

[International Conference etc.]

X. Sun *et al.*, "Isotopic cross sections of proton-, deuteron- and carbon-induced reactions on ^{136}Xe," 13th International Conference on Nucleus-Nucleus Collisions, Omiya, Japan, December 4–8, 2018.

[Domestic Conference]

三木晴瑠, 「^{238}U の飛行核分裂反応における低速 ^{107}Pd および ^{77}Se のアイソマー比の測定」, 日本物理学会第 73 回年次大会, 野田, 2018 年 3 月.

Awards

中野敬太, 「長寿命核分裂生成物 Zr-93 の短寿命化・再資源化に向けた核反応データ測定」, 九州大学エネルギーウィーク 2018 優秀賞

Press Release

H. Otsu, T. Matsuzaki, H. Sakurai, Jointly awarded "the 21st Century Invention Prize" for their research on Radioactive waste processing method, Joint PR released with Toshiba Co, Toshiba Energy Systems & Solutions Corporation, JAEA, JST, Director General for Science and Technology and Innovation on the research, May 17, 2018.

Outreach Activities

Lecture of contents related to the 21st Century Invention Prize in the presense of Prince Hitachinomiya Masahito, Prince Hitachi House, Aoyama, Tokyo June 1, 2018.

Nuclear Science and Transmutation Research Division
Nuclear Transmutation Data Research Group
Slow RI Data Team

1. Abstract

This team is in charge of the development of low-energy RI beams of long-lived fission fragments (LLFP) from the ^{238}U by means of degrading the energy of beams produced by the BigRIPS fragment separator.

2. Major Research Subjects

Studies of the slowing down and purification of RI beams are the main subjects of the team. Developments of devices used for the slowing down of RI beams are also an important subject.

(1) Study and development of the slowed-down methods for LLFP.
(2) Development of the devices used for the slowing down.
(3) Operation of the BigRIPS separator and supply the low energy LLFP beam to the experiment in which the cross sections of LLFP are measured at the low energy.
(4) Development of the framework to seamlessly handle device, detector, DAQ, and analysis for the easy control of the complicate slowed-down RI beam production and its development.

3. Summary of Research Activity

A new OEDO beam line, designed for the slowed-down RI beams, was constructed under the collaboration with CNS, the University of Tokyo. Our group was responsible for the construction of the infrastructure such as the cooling water and the electrical equipment, and the movement and alignment of existing vacuum chambers, quadrupole magnets. The power supply for the Superconducting Triplet Quadrupoles (STQ) was made, which had a stability also under the low current condition.

Slowed-down ^{93}Zr beams with 20 or 50 MeV/nucleon were successfully developed at June 2016 for the first time. The methods to obtain the narrow energy, position, and angle distribution were developed. The methods of the energy adjustment and the particle identification at 50 MeV/nucleon were developed. The ^{93}Zr and ^{107}Pd beams with 50 MeV/nucleon were produced for the nuclear-transmutation experiments using proton or deuteron targets at October 2016. The commissioning experiment of the OEDO beam line was successfully performed at June 2017. The first transmutation experiments using OEDO beam line were performed with ^{93}Zr, ^{107}Pd, and ^{79}Se around 20 MeV/nucleon.

With our developments, the slowed-down RI beams became ready for the transmutation experiments. On the other hand, the procedure to make the slowed-down RI beams became highly specialized. In order to easily produce the slowed-down RI beam, the framework is under the development to seamlessly handle the device, detector, DAQ, and analysis.

Member

Team Leader

Toshiyuki SUMIKAMA

List of Publications & Presentations

Oral Presentations

[International Conference etc.]

T. Sumikama *et al.*, “New control method of slowed-down RI beam and new PID method of secondary-reaction fragments at RIKEN RI beam factory,” International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS XVIII), Geneva, Switzerland, September 16–21, 2018.

Nuclear Science and Transmutation Research Division
Nuclear Transmutation Data Research Group
Muon Data Team

1. Abstract
Dr. Yoshio Nishina observed muons in cosmic rays in 1937. The muon is an elementary particle similar to electron and classified to lepton group. The muon has positive or negative electric charge, and the lifetime is 2.2 μsec. The negative muon (μ^-) is 207 times heavier than the electron and behaves as a "heavy electron" in materials. The negative muon is captured by atomic orbits of nuclei to form a muonic atom and cascades down to the 1 s orbit to make muon nuclear capture. The muon is combined with a proton in the nucleus to convert to a neutron and a neutrino. The muon nuclear capture reaction on a nucleus ($^{A}_{Z}N$) with the atomic number Z and mass number A generates the isotopes of $^{A-x}_{Z-1}N$ (x = 0, 1, 2, 3, 4) by emitting some neutrons in the reaction. The phenomenon is called "muon nuclear transmutation." The reaction branching ratio of $^{A}_{Z}N(\mu^-, xn\nu)^{A-x}_{Z-1}N$ reactions (x = 0, 1, 2, 3, 4) is one of important factors toward various applications with nuclear transmutation technique. From a viewpoint of the nuclear physic, the muon nuclear capture reaction is very unique and interesting. A high-energy compound nuclear state is suddenly generated in the nuclei associated with a weak conversion process of proton to neutron and neutrino. Many experimental results have been so far reported, however, the reaction mechanism itself is not well clarified. The research team aims at obtaining the experimental data to investigate the reaction mechanism of muon nuclear capture, and also at theoretical understanding on the nuclear capture reaction.

2. Major Research Subjects
(1) Experimental clarification on the mechanism of nuclear muon capture reaction
(2) Theoretical understanding on the nuclear muon capture reaction
(3) Interdisciplinary applications with the nuclear transmutation technique

3. Summary of Research Activity
There are two experimental methods to study the muon nuclear capture reaction. The first one is "muon in-beam spectroscopy method." The neutron and γ-ray emissions from the excited states of $^{A-x}_{Z-1}N$ nuclei are prompt events and are observed by the "muon in-beam spectroscopy method" with a DC muon beam. The reaction branching ratio is directly determined by measuring the neutron multiplicity in the reaction. The DC muon beam is available at the MuSIC (Muon Science Innovative Channel) muon facility in the Research Center for Nuclear Physics (RCNP) at Osaka University. The second one is "muon activation method" with the pulsed muon beam. The produced unstable nuclei $^{A-x}_{Z-1}N$ make $\beta^{+/-}$ decays. The γ-rays associated with $\beta^{+/-}$ decays to the daughter nuclei are observed in the experiment. The build-up curve of γ-ray yield at muon beam-on and the decay curve at beam-off are measured. Since the half-lives and decay branching ratios of $\beta^{+/-}$-γ decays are known, the reaction branching ratios to the $^{A-x}_{Z-1}N$ nuclei are determined by the γ-ray yield curves. The pulsed muon beam is available at the RIKEN-RAL Muon Facility in the UK and J-PARC muon facility.

Muon nuclear capture reactions are studied on five isotope-enriched palladium targets (^{104,105,106,108,110}Pd) and five isotope-enriched zirconium targets (^{90,91,92,94,96}Zr) employing two experimental methods. By obtaining the experimental data on the Pd and Zr targets, the reaction mechanism is investigated experimentally, and the results are compared with appropriate theoretical calculations. The ^{107}Pd is classified to a long-lived fission product (LLFP) and is contained in a spent nuclear fuel. The study of muon nuclear capture on the Pd and Zr targets is aiming at exploring a possible reaction path to make the nuclear transmutation of the Pd and Zr metal extracted from the spent nuclear fuel without an isotope separation process. This research was funded by the ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

(1) Experiments with "muon in-beam spectroscopy method"
Muon nuclear capture reactions were investigated on five palladium targets (^{104,105,106,108,110}Pd) by employing the DC muon beam at MuSIC. The γ-ray and neutron in the muon nuclear capture reaction were measured with the time information relative to muon beam arrival. The measured neutron multiplicity gives the reaction branching ratio of $^{A}_{46}\mathrm{Pd}(\mu^-, xn\nu)^{A-x}_{45}\mathrm{Rh}$ reactions, where A = 104, 105, 106, 108, 110 and x = 0, 1, 2, 3, 4.

Employing a newly built neutron spectrometer, the neutron was measured to obtain the reaction branching ratios of muon capture reactions on the Pd targets. We have constructed a neutron spectrometer named "Seamine": **S**cintillator **E**nclosure **A**rray for **M**uon **I**nduced **N**eutron **E**mission. The spectrometer consists of 21 liquid scintillation counters, 2 Ge γ-ray detectors, 7 BaF_2 counters. The Pd target, muon beam counters and muon degraders are placed at the center of spectrometer. The neutron counter is a BC-501A liquid scintillation counter with 20 cm diameter and 5 cm depth and is connected to a 5" photo multiplication tube (H4144-01). The total neuron detection efficiency is estimated 5%, where the distance is 4 cm from the target to neutron counters. The Ge γ-ray detectors are placed at 10 cm form the target, and the typical detection efficiency is 0.5% for 200 keV γ-ray. The BaF_2 counters are located beneath the target to detect fast γ-rays emitted from the compound nucleus formed in the reactions. Signals from the liquid scintillation counters are processed in a CAEN V1730B waveform digitizer (16 channel, 14 bit, 500 M samplings/sec.). The neuron-γ discrimination is performed on-line during the experiment, and the detailed data analysis is conducted off-line after the experiment. The neutron energy spectrum is constructed in the digitizer. Signals from Ge detectors are also processed in the digitizer to obtain the energy and time spectrum of γ-rays associated with the reaction. Signals from the BaF_2 counters and muon beam counters are sent to the digitizer to make the fast timing signals.

We have established the muon in-beam spectroscopy method employing the "Seamine" spectrometer. The neutron data analysis is in progress to obtain the multiplicity, the energy and the TOF spectrum using start signals given by γ-rays detected in the BaF_2 counters. The γ-ray data gives the energy spectrum of prompt γ-rays and muonic X-rays originated from the ^{104,105,106,108,110}Pd targets.

(2) Experiments with "muon activation method" at the RIKEN-RAL Muon Facility

We conducted the experiments on the muon nuclear capture employing the muon activation method at the RIKEN-RAL Muon Facility in the UK. The pulsed muon beam was irradiated on the ^{104,105,106,108,110}Pd targets. The γ-rays were detected by a Ge detector located at the downstream of the Pd targets to maximize the detection efficiency. The build-up and decay curves of γ-ray intensities were measured associated with $\beta^{+/-}$ decays of produced unstable nuclei to daughter nuclei. The γ-ray-yield curves give the absolute radiation activity produced by the reaction, and the reaction branching ratios are determined for $^{A}_{46}\mathrm{Pd}(\mu^-, x\mathrm{n}\nu)^{A-x}_{45}\mathrm{Rh}$ reactions. The decay curves of γ-rays from the produced nuclei with long half-lives were measured under low γ-ray background at an experimental apparatus built in a separated room. The detailed off-line data analysis is in progress.

(3) Experiments with "muon activation method" at J-PARC muon facility

The experiments employing the muon activation method were performed at J-PARC muon facility. The five isotope-enriched Pd targets (^{104,105,106,108,110}Pd) were irradiated by the pulsed muon beam, and the build-up and decay curves of γ-ray intensities were measured.

In addition to the Pd targets, the experiments on five isotope-enriched Zr target (^{90,91,92,94,96}Zr) were conducted to obtain the reaction branching ratios of $^{A}_{40}\mathrm{Zr}(\mu^-, x\mathrm{n}\nu)^{A-x}_{39}\mathrm{Y}$ reactions, where A = 90, 91, 92, 94, 96. The obtained reaction branching ratios on the Pd and Zr targets are important to understand the reaction mechanism of muon nuclear capture. The ^{93}Zr is one of the LLFP and is contained in a spent nuclear fuel. The experiment on the Zr targets is to explore a possibility to realize the nuclear transmutation of the Zr metal extracted from the spent nuclear fuel.

In order to obtain the reaction branching ratio of $^{107}_{46}\mathrm{Pd}(\mu^-, x\mathrm{n}\nu)^{107-x}_{45}\mathrm{Rh}$ reactions, the muon activation experiment was performed employing a Pd target containing ^{107}Pd of 15.3%. The γ-ray intensities associated with $\beta^{+/-}$ decays of produced unstable nuclei were measured to obtain the build-up and decay curves. Once the branching ratios of the reactions on the ^{104,105,106,108,110}Pd targets are obtained, these contributions are extracted from the branching-ratio data obtained for the Pd target with ^{107}Pd. The reaction branching ratio of $^{107}_{46}\mathrm{Pd}(\mu^-, x\mathrm{n}\nu)^{107-x}_{45}\mathrm{Rh}$ reactions is finally determined. The detailed off-line data analysis is in progress.

(4) Comparison with theory

The muon activation method gives the reaction branching ratios. The muon in-beam spectroscopy method gives the neutron multiplicity and the neutron energy spectrum. These experimental results are important to understand the compound nuclear state and neutron emission mechanism. The reaction branching ratios obtained by the muon activation method are compared with the results of neutron multiplicity measurements. The neutron energy spectrum is considered to be reflected by the energy distribution of compound nuclear state and neutron emission mechanism. The experimental results are compared with the appropriate calculations employing the neutron emission mechanisms due to an evaporation, a cascade and a direct emission processes with assuming the energy distribution at compound nuclear state.

Members

Team Leader
Hiroyoshi SAKURAI

Contract Researcher
Teiichiro MATSUZAKI

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

D. Hatakeyama, K. Nishimura, K. Matsuda, T. Namiki, Seungwon Lee, N. Nunomura, T. Aida, T. Matsuzaki, R. Holmestad, S. Wenner, C. D. Marioara, "Effect of copper addition on the cluster formation behavior of Al-Mg-Si, Al-Zn-Mg, and Al-Mg-Ge in the natural aging," METALLURGICAL AND MATERIALS TRANSACTIONS A V49A, (2018) p. 5871.

Oral Presentations

[International Conference etc.]

T. Matsuzaki, H. Sakurai, "A new production method of ^{99}Mo by muon nuclear transmutation," International Symposium on Technetium and Rhenium, Science and Utilization, Moscow, Russia, October 2018.

[Domestic Conference]

斎藤岳志, 新倉潤, 櫻井博儀, 松崎禎市郎, 他, 「ミューオン原子 X 線を用いた Pd 同位体の核荷電半径の測定」, 日本物理学会 73 回年次大会, 東京理科大学野田キャンパス, 野田, 2018 年 3 月.

斎藤岳志, 新倉潤, 松崎禎市郎, 櫻井博儀, 他, “Study for the muon capture on palladium isotopes via neutron measurement,” 第 5 回日米物理学会 合同核物理分科会, ハワイ 米国, 2018 年 10 月.

新倉潤, 斎藤岳志, 松崎禎市郎, 櫻井博儀, 他, 「ミューオン捕獲による Pd 同位体の核変換」, 日本物理学会 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

斎藤岳志, 新倉潤, 松崎禎市郎, 櫻井博儀, 他, 「パラジウムのミューオン捕獲に伴う放出中性子の直接測定」, 日本物理学会 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

三木謙二郎, 酒井大輔, 上坂友洋, 宇津城雄大, 酒井英行, 笹野匡紀, 関口仁子, 松崎禎市郎, 「RIBF における ^{3}H(t, ^{3}He)3n 反応測定の為の三重水素標的開発」, 日本物理学会 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

新倉潤, 斎藤岳志, 松崎禎市郎, 櫻井博儀, 「ミュオン原子核捕獲反応による核変換」, 日本原子力学会春の年会, 茨城大学, 水戸, 2019 年 3 月.

Award

大津秀暁, 藤田玲子, 松崎禎市郎, 櫻井博儀, 下浦享, 水口浩司, 大井川宏之, 小澤正基, 仁井田浩二, 平成 30 年度全国発明表彰「21 世紀発明賞」, 「放射性廃棄物の処理方法の発明」, （特許第 6106892 号）, 2018 年 6 月.

Patent

松崎禎市郎, 櫻井博儀, 「ミュオン照射による放射性物質の製造方法およびその製造物質」, 特許 PCT 出願（日本, アメリカ, カナダ, ヨーロッパ）, （国際出願番号 PCT/JP2017/003226）, (2018 年 8 月).

Nuclear Science and Transmutation Research Division
High-Intensity Accelerator R&D Group

1. Abstract

The R&D group, consisting of two teams, develops elemental technology of high-power accelerators and high-power targets, aiming at future applications to nuclear transmutations of long-lived fission product into short-lived nuclides. The research subjects are superconducting rf cavities for low-velocity ions, design of high-power accelerators, high-power target systems and related technologies.

Nuclear transmutation with high-intensity accelerators is expected to reduce the high-level radioactive wastes and to recycle the precious resources such as rare-earth materials in future. This method is one of the important applications of the ion-accelerator technologies that have been developed at RIKEN for a long time. Under the framework of ImPACT Fujita Program, we have conducted R&D of elemental technology related to the high-power accelerators and high-power targets.

We gained a lot of experiences in these R&Ds. Among them, the development of a superconducting rf cavity has become the basis of the upgrade program of the RILAC facility which started in 2016.

2. Major Research Subjects

(1) R&D of elemental technology of high-power accelerators and high-power targets

3. Summary of Research Activity

(1) A high-gradient rf cavity has been constructed and tested based on the superconducting rf technology.
(2) Several candidates for the high-power target have been proposed and their prototypes have been tested.
(3) A high-current deuteron RFQ has been designed.

Member

Group Director

Osamu KAMIGAITO (concurrent: Group Director, Accelerator Group)

Nuclear Science and Transmutation Research Division
High-Intensity Accelerator R&D Group
High-Gradient Cavity R&D Team

1. Abstract

We develop new components for accelerators dedicated for low-beta-ions with very high intensity. Specifically, we are designing and constructing a cryomodule for superconducting linac efficient for acceleration of low-beta-ions. In parallel, we try to optimize an rf acceleration system by making computer simulations for acceleration of very high intensity beams.

2. Major Research Subjects

(1) Development of high-gradient cavites for low beta ions
(2) Development of power saving cryomodules

3. Summary of Research Activity

- Development of highly efficient superconducting accelerator modules

Members

Team Leader

Naruhiko SAKAMOTO (concurrent: Cyclotron Team)

Research/Technical Scientists

Kazunari YAMADA (concurrent: Senior Technical Scientist, Beam Dynamics & Diagnostics Team)
Yutaka WATANABE (concurrent: Senior Technical Scientist, RILAC team)
Kazutaka OZEKI (concurrent: Technical Scientist, Cyclotron Team)
Kenji SUDA (concurrent: Technical Scientist, Cyclotron Team)

Postdoctoral Researcher

Xingguang LIU

List of Publications & Presentations

Publications

Oral Presentations

[Domestic Conference]

N. Sakamoto, K. Yamada, K. Suda, K. Ozeki, Y. Watanabe, O. Kamigaito, H. Okuno, "Reduction and resource recycling of high-level radioactive wastes through nuclear transmutation (6-1) development of prototype superconducting-linac for intense low-beta ion beams," Annual Meeting of Atomic Energy Society Japan, Mito, March 20–22, 2019.

N. Sakamoto, K. Yamada, K. Suda, K. Ozeki, Y. Watanabe, O. Kamigaito, H. Okuno, "Advances of accelerator technology development for nuclear transmutation in the ImPACT program-2 prototype of superconducting linear accelerator for intense deuteron beam," Meeting of Atomic Energy Society Japan, Okayama, September 5–7, 2018.

Nuclear Science and Transmutation Research Division
High-Intensity Accelerator R&D Group
High-Power Target R&D Team

1. Abstract

The subjects of this team cover R&D studies with respect to target technology for the transmutation of the LLFPs. Furthermore this team works for the demonstration test of the transmutation of ^{107}Pd.

2. Major Research Subjects

(1) Liquid lithium target for production of neutron or muon
(2) Beam window without solid structure
(3) Ion implantation and TIMS for the demonstration of the transmutation of ^{107}Pd

3. Summary of Research Activity

(1) Liquid lithium target for production of neutron or muon
(H. Okuno, N. Furutachi)
(2) Beam window with solid structure
(H. Okuno)
(3) Ion plantation and TIMS of ^{107}Pd
(Y. Miyake, Y. Sahoo, M. Takahashi)

Members

Team Leader
Hiroki OKUNO (concurrent: Deputy Group Director, Accelerator Gr.)

Postdoctral Researcher
Yasuto MIYAKE

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Research Facility Development Division
Accelerator Group

1. Abstract

The Accelerator Group, consisting of seven teams, pursues various upgrade programs of the world-leading heavy-ion accelerator facility, RI Beam Factory (RIBF), to enhance the accelerator performance and operation efficiency. The programs include the R&D of superconducting ECR ion source, charge stripping systems, beam diagnostic devices, radiofrequency systems, control systems, and beam simulation studies. We are also maintaining the large infrastructure to realize effective operation of the RIBF. Moreover, we are actively promoting the applications of the facility to a variety of research fields.

Our primary mission is to supply intense, stable heavy-ion beams for the users through effective operation, maintenance, and upgrade of the RIBF accelerators and related infrastructure. The director members shown above govern the development programs that are not dealt with by a single group, such as intensity upgrade and effective operation. We also discuss the future plans of RIBF along with other laboratories belonging to the RIBF research division.

Various improvements and developments have been carried out for the RIBF accelerators in order to upgrade the beam intensities and stability. Owing to the efforts, for example, the intensity of the uranium beam has increased by 40% in the last three years, resulting in the intensity of 72 pnA (5.9 kW) at the exit of the superconducting ring cyclotron. We also started providing intense vanadium beams for the synthesis of a new element [119] at GARIS II, which was recently moved to the cyclotron facility.

In 2016, a supplemental budget was approved for the upgrade of RIBF aiming at synthesizing heavier new elements. A superconducting linac booster has been constructed at the RILAC facility with this budget under the collaboration with KEK researchers. We also constructed a new superconducting ECR ion source at RILAC, and started the test operation in 2018. The beam commissioning with the upgraded RILAC facility is scheduled in this fiscal year. The accelerating cavities of the ring cyclotron, which has been suffered from the low accelerating voltage, were also modified with this budget. It is expected that the uranium beam intensity will be increased significantly in near future for the BigRIPS experiments as well as the metallic ion beams for GARIS II experiments for the synthesis of super heavy elements.

On the other hand, we have started a new project with RCNP, Osaka university, for the promotion of application research using short-lived radioisotopes since 2017. A high-power target for production of At-211 is under development with RI Application Research Group of RNC in the framework of this project. It will be installed and tested in the upgraded RILAC facility in near future. An upgrade plan of RIBF for further increasing heavy-ion beams, especially the uranium beam, has been continuously discussed. The plan proposed recently is based on a new idea of "charge-stripper ring," which is used to improve the overall stripping efficiency of the uranium beam. This device recirculates and re-injects the uranium ions into the charge stripper until the ions become the charge state required for the succeeding acceleration, while the bunch structure is kept with its isometric orbit lengths for all the charge states. A preliminary design of the magnets is under progress after intensive optical study of the device. The final goal of this plan is to increase the uranium beam intensity by 30 times of the present value, namely up to 2000 pnA, at the exit of SRC.

2. Major Research Subjects

(1) Intensity upgrade of RIBF accelerators (Okuno)
(2) Effective and stable operation of RIBF accelerators (Fukunishi)
(3) Construction of the superconducting linac booster at the RILAC facility
(4) Promotion of the future plan

3. Summary of Research Activity

(1) The maximum intensity of the calcium beam reached 740 pnA at 345 MeV/nucleon, which corresponds to 12.3 kW. That of the krypton beam reached 486 pnA, corresponding to 13.4 kW.
(2) The maximum intensities of the uranium and xenon beams reached 72 and 102 pnA, respectively, at 345 MeV/nucleon.
(3) The overall beam availability for the RIBF experiments averaged for 5 years from 2013 to 2017 was 92%. It fell down to 79% in 2018 because of several hardware troubles. Efforts to restore the availability to more than 90% are ongoing.
(4) The large infrastructure was properly maintained based on a well-organized cooperation among the related sections.
(5) A major upgrade of the accelerator facility has been conducted aiming at synthesizing heavier new elements. It includes construction of a superconducting linac booster of RILAC, construction of a new superconducting ECR ion source, and modification of the accelerating cavities of the ring cyclotron (RRC).
(6) An intensity-upgrade plan of the RIBF has been further investigated. Design study of the charge-stripper ring has been started.

Members

Group Director

Osamu KAMIGAITO

Deputy Group Directors
Hiroki OKUNO (for intensity upgrade)
Nobuhisa FUKUNISHI (for stable and efficient operation)

Junior Research Associate
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Research Consultants
Masayuki KASE
Robert JAMESON
Tadashi FUJINAWA
Toshiyuki HATTORI

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Karen SAKUMA

Administrative Part-time Worker II
Ryoko UMEZAKI

Research Facility Development Division
Accelerator Group
Accelerator R&D Team

1. Abstract

We are developing the key hardware in upgrading the RIBF accelerator complex. Our primary focus and research is charge stripper which plays an essential role in the RIBF accelerator complex. Charge strippers remove many electrons in ions and realize efficient acceleration of heavy ions by greatly enhancing charge state. The intensity of uranium beams is limited by the lifetime of the carbon foil stripper conventionally installed in the acceleration chain. The improvement of stripper lifetimes is essential to increase beam power towards the final goal of RIBF in the future. We are developing the low-Z gas stripper. In general gas stripper is free from the lifetime related problems but gives low equilibrium charge state because of the lack of density effect. Low-Z gas stripper, however, can give as high equilibrium charge state as that in carbon foil because of the suppression of the electron capture process. Another our focus is the upgrade of the world's first superconducting ring cyclotron.

2. Major Research Subjects

(1) Development of charge strippers for high power beams (foil, low-Z gas)
(2) Upgrade of the superconducting ring cyclotron
(3) Maintenance and R&D of the electrostatic deflection/inflection channels for the beam extraction/injection

3. Summary of Research Activity

(1) Development of charge strippers for high power beams (foil, low-Z gas)

(H. Hasebe, H. Imao, H. Okuno)

We are developing the charge strippers for high intensity heavy ion beams. We are focusing on the developments on carbon or berrilium foils and gas strippers including He gas stripper.

(2) Upgrade of the superconducting ring cyclotron

(J. Ohnishi, H. Okuno)

We are focusing on the upgrade of the superconducting ring cyclotron.

(3) Maintenance and R&D of the electrostatic deflection/inflection channels for the beam extraction/injection

(J. Ohnishi, H. Okuno)

We are developing high-performance electrostatic channels for high power beam injection and extraction.

Members

Team Leader

Hiroki OKUNO (concurrent: Deputy Group Director, Accelerator Group)

Research/Technical Scientists

Hiroshi IMAO (Senior Research Scientist)
Jun-ichi OHNISHI (Senior Technical Scientist)

Technical Scientist

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Visiting Scientists

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Hironori KUBOKI (KEK)

Junior Research Associate

Naoya IKOMA (Nagaoka Univ. of Technology)

Student Trainees

Taishi SASAKI (Nagaoka Univ. of Technology)
Yoshiki SHIKUMA (Nagaoka Univ. of Technology)

List of Publications & Presentations

Publications

[Proceedings]

H. Imao, “Development of Gas stripper at RIBF,” Proceeding of IPAC2018, MOZGBE1, Vancouver, BC, Canada, 2018.

Oral Presentations

[International Conference etc.]

H. Imao, “Development of Gas stripper at RIBF,” Proceeding of IPAC2018, MOZGBE1, Vancouver, BC, Canada, 2018.

H. Okuno, “Present status of and recent developments at RIKEN RIBF,” 14th International Conference on Heavy Ion Accelerator Technology (HIAT’18), Lanzhou, China, October, 2018.

Research Facility Development Division
Accelerator Group
Ion Source Team

1. Abstract

Our aim is to operate and develop the ECR ion sources for the accelerator-complex system of the RI Beam Factory. We focus on further upgrading the performance of the RI Beam Factory through the design and fabrication of a superconducting ECR ion source for production of high-intensity heavy ions.

2. Major Research Subjects

(1) Operation and development of the ECR ion sources
(2) Development of a superconducting ECR heavy-ion source for production of high-intensity heavy ion beams

3. Summary of Research Activity

(1) Operation and development of ECR ion sources

(T. Nakagawa, M. Kidera, Y. Higurashi, T. Nagatomo, Y. Kanai, and H. Haba)

We routinely produce and supply various kinds of heavy ions such as zinc and calcium ions for the super-heavy element search experiment as well as uranium ions for RIBF experiments. We also perform R&D's to meet the requirements for stable supply of high-intensity heavy ion beams.

(2) Development of a superconducting ECR ion source for use in production of a high-intensity heavy ion beam

(T. Nakagawa, J. Ohnishi, M. Kidera, Y. Higurashi, and T. Nagatomo)

The RIBF is required to supply heavy ion beams with very high intensity so as to produce RI's and for super-heavy element search experiment. We have designed and are fabricating an ECR ion source with high magnetic field and high microwave- frequency, since the existing ECR ion sources have their limits in beam intensity. The coils of this ion source are designed to be superconducting for the production of high magnetic field. We are also designing the low-energy beam transport line of the superconducting ECR ion source.

Members

Team Leader

Takahide NAKAGAWA

Research/Technical Scientists

Takashi NAGATOMO (Technical Scientist)
Masanori KIDERA (Technical Scientist)
Yoshihide HIGURASHI (Technical Scientist)

Special temporal employee

Yasuyuki KANAI

List of Publications & Presentations

Publications

[Proceedings]

(Original Papers) *Subject to Peer Review

T. Nagatomo *et al*., "Residual gas effect in LEBT on transverse emittance of multiply charged heavy ion beams extracted from ECR ion source," IOP Conf. Proc. 2011, 080004(2018)*

Y. Higurashi *et al*., "Development of RIKEN 28 GHz SC-ECRIS for production of intense metal ion beam," Proc. of ECRIS2018, doi:10.18429/JACoW-ECRIS2018-TUA1

T. Nagatomo *et al*., "New 28-GHz superconducting electron cyclotron resonance ion source for synthesizing super-heavy elements with $Z > 118$," Proc. of ECRIS2018, doi:10.18429/JACoW-ECRIS2018-TUA3

Oral Presentations

[International Conference etc.]

T. Nakagawa, "Developments of RIKEN 28 GHz SC-ECRIS for synthesizing the super-heavy elements," 14th International Conference on Heavy Ion Accelerator Technology (HIAT2018), Lanzhou, China, October 22–26, 2018.

T. Nakagawa, "Development of RIKEN 28 GHz SC-ECRIS for production of intense metal ion beam," International Workshop on ECR Ion Sources (ECRIS2018), Catania, Italy, September 10–14, 2018.

T. Nagatomo, "New 28-GHz superconducting electron cyclotron resonance ion source for synthesizing super-heavy elements with $Z > 118$," Catania, Italy, September 10–14, 2018.

Research Facility Development Division
Accelerator Group
RILAC Team

1. Abstract

The operation and maintenance of the RIKEN Heavy-ion Linac (RILAC) have been carried out. There are two operation modes: one is the stand-alone mode operation and the other is the injection mode operation. The RILAC has been used especially as an injector for the RIKEN RI- Beam Factory accelerator complex. The RILAC is composed of the ECR ion source, the frequency-variable RFQ linac, six frequency-variable main linac cavities, and six energy booster cavities (CSM).

2. Major Research Subjects

(1) The long term high stability of the RILAC operation.
(2) Improvement of high efficiency of the RILAC operation.

3. Summary of Research Activity

The RILAC was started to supply ion beams for experiments in 1981. Thousands hours are spent in a year for delivering many kinds of heavy-ion beams to various experiments.

The RILAC has two operation modes: one is the stand-alone mode operation delivering low-energy beams directly to experiments and the other is the injection mode operation injecting beams into the RRC. In the first mode, the RILAC supplies a very important beam to the nuclear physics experiment of “the research of super heavy elements.” In the second mode, the RILAC plays a very important role as upstream end of the RIBF accelerator complex.

The maintenance of these devices is extremely important in order to keep the log-term high stability and high efficiency of the RILAC beams. Therefore, improvements are always carried out for the purpose of more stable and more efficient operation.

Members

Team Leader
Eiji IKEZAWA

Research/Technical Scientist
Yutaka WATANABE (Senior Technical Scientist)

List of Publications & Presentations

Publications

[Proceedings]

K. Kaneko, E. Ikezawa, T. Ohki, H. Yamauchi, K. Oyamada, M. Tamura, A. Yusa, Y. Watanabe, O. Kamigaito, “Present status of RILAC,” Proceedings of the 15th Annual Meeting of Particle Accelerator Society of Japan, 1304–1306 (2018).

Posters Presentations

[Domestic Conference]

K. Kaneko, E. Ikezawa, T. Ohki, H. Yamauchi, K. Oyamada, M. Tamura, A. Yusa, Y. Watanabe, O. Kamigaito, “Present status of RILAC,” The 15th Annual Meeting of Particle Accelerator Society of Japan, Nagaoka, Japan, August 7–10, 2018.

Research Facility Development Division
Accelerator Group
Cyclotron Team

1. Abstract

Together with other teams of Nishina Center accelerator division, maintaining and improving the RIBF cyclotron complex. The accelerator provides high intensity heavy ions. Our mission is to have stable operation of cyclotrons for high power beam operation. Recently stabilization of the rf system is a key issue to provide 10 kW heavy ion beam.

2. Major Research Subjects

(1) RF technology for Cyclotrons
(2) Operation of RIBF cyclotron complex
(3) Maintenance and improvement of RIBF cyclotrons
(4) Single turn operation for polarized deuteron beams
(5) Development of superconducting cavity

3. Summary of Research Activity

- Development of the rf system for a reliable operation
- Development of highly stabilized low level rf system
- Development of superconducting cavity
- Development of the intermediate-energy polarized deuteron beams.

Members

Team Leader

Naruhiko SAKAMOTO

Research/Technical Scientists

Kazutaka OZEKI (Technical Scientist)
Kenji SUDA (Technical Scientist)

List of Publications & Presentations

Publications

[Proceedings]

N. Sakamoto, K. Ozeki, O. Kamigaito, A. Miyamaoto, H. Okuno, K. Suda, Y. Watanabe, K. Yamada, H. Hara, K. Sennyu, T. Yanagisawa, E. Kako, H. Nakai, K. Umemori, "Construction status of the superconducting Linac at the RIKEN Radioactive Isotope Facility," Proceedings of the 29th Linear Accelerator Conference, Beijing, China, September16–21, 2018.

小山亮, 福澤聖児, 濱仲誠, 石川盛, 小林清志, 仲村武志, 西田稔, 西村誠, 柴田順翔, 月居憲俊, 矢冨一慎, 須田健嗣, 藤巻正樹, 福西暢尚, 後藤彰, 長谷部裕雄, 日暮祥英, 今尾浩士, 加瀬昌之, 上垣外修一, 木寺正憲, 込山美咲, 熊谷桂子, 真家武士, 長瀬誠, 長友傑, 中川孝秀, 大西純一, 奥野広樹, 大関和貴, 坂本成彦, 内山暁仁, 渡部秀, 渡邉環, 渡邉裕, 山田一成, 小高康照, 大城幸光, 「理研 AVF サイクロトロン運転の現状報告」, 第 14 回日本加速器学会年会, p.1395, 北海道大学, 札幌市, 2018 年 8 月 1–3 日.

西村誠, 福澤聖児, 濱仲誠, 石川盛, 小林清志, 小山亮, 仲村武志, 西田稔, 柴田順翔, 月居憲俊, 矢冨一慎, 須田健嗣, 藤巻正樹, 福西暢尚, 後藤彰, 長谷部裕雄, 日暮祥英, 今尾浩士, 加瀬昌之, 上垣外修一, 木寺正憲, 込山美咲, 熊谷桂子, 真家武士, 長瀬誠, 長友傑, 中川孝秀, 大西純一, 奥野広樹, 大関和貴, 坂本成彦, 内山暁仁, 渡部秀, 渡邉環, 渡邉裕, 山田一成, 山澤秀行, 「理研 RIBF における リングサイクロトロン運転の現状報告」, 第 14 回日本加速器学会年会, 北海道大学, 札幌市, 2018 年 8 月 1–3 日.

Oral Presentations

[International Conference etc.]

N. Sakamoto, K. Ozeki, O. Kamigaito, A. Miyamaoto, H. Okuno, K. Suda, Y. Watanabe, K. Yamada, H. Hara, K. Sennyu, T. Yanagisawa, E. Kako, H. Nakai, K. Umemori, "Construction Status of the Superconducting Linac at the RIKEN Radioactive Isotope Facility," 29th Linear Accelerator Conference, Beijing, China, September 16–21, 2018.

Posters Presentations

[Domestic Conference]

小山亮, 福澤聖児, 濱仲誠, 石川盛, 小林清志, 仲村武志, 西田稔, 西村誠, 柴田順翔, 月居憲俊, 矢冨一慎, 須田健嗣, 藤巻正樹, 福西暢尚, 後藤彰, 長谷部裕雄, 日暮祥英, 今尾浩士, 加瀬昌之, 上垣外修一, 木寺正憲, 込山美咲, 熊谷桂子, 真家武士, 長瀬誠, 長友傑, 中川孝秀, 大西純一, 奥野広樹, 大関和貴, 坂本成彦, 内山暁仁, 渡部秀, 渡邉環, 渡邉裕, 山田一成, 小高康照, 大城幸光, 「理研 AVF サイクロトロン運転の現状報告」, 第 14 回日本加速器学会年会, p.1395, 北海道大学, 札幌市, 2018 年 8 月 1–3 日.

西村誠, 福澤聖児, 濱仲誠, 石川盛, 小林清志, 小山亮, 仲村武志, 西田稔, 柴田順翔, 月居憲俊, 矢冨一慎, 須田健嗣, 藤巻正樹, 福西暢

尚, 後藤彰, 長谷部裕雄, 日暮祥英, 今尾浩士, 加瀬昌之, 上垣外修一, 木寺正憲, 込山美咲, 熊谷桂子, 真家武士, 長瀬誠, 長友傑, 中川孝秀, 大西純一, 奥野広樹, 大関和貴, 坂本成彦, 内山暁仁, 渡部秀, 渡邉環, 渡邉裕, 山田一成, 山澤秀行, 「理研 RIBF における リングサイクロトロン運転の現状報告」, 第 14 回日本加速器学会年会, 北海道大学, 札幌市, 2018 年 8 月 1–3 日.

Research Facility Development Division
Accelerator Group
Beam Dynamics & Diagnostics Team

1. Abstract

Aiming at stable and efficient operation of the RIBF cascaded cyclotron system, Beam Dynamics and Diagnostics Team developes power supplies, beam instrumentation, computer control and beam dynamic studies. We have successfully increased the beam availability for user experiments to more than 90%. We have also established small-beam-loss operations. The latter strongly contributes to recent high-power operations at RIBF.

2. Major Research Subjects

(1) More efficient and stable operations of the RIBF cascaded cyclotron system
(2) Maintenance and developments of the beam instrumentation
(3) Developments of computer control system for more intelligent and efficient operations
(4) Maintenance and improvements of the magnet power supplies for more stable operations
(5) Upgrade of the existing beam interlock system for high-power beams with few tens of kW

3. Summary of Research Activity

(1) High-intensity heavy-ion beams such as 72-pnA uranium, 102-pnA xenon, 486-pnA krypton, and 740-pnA calcium beams have been obtained.
(2) The world-first high-Tc SQUID beam current monitor has been developed.
(3) The bending power of the fixed-frequency Ring Cyclotron has been upgraded to 700 MeV.
(4) The world-most-intense V beams are stably supplied to super-heavy-element search experiments.
(5) The RIBF control system has been operated stably by replacing legacy hardware controllers carried over from our old facility with new ones. Several useful operation tools are also developed.
(6) The dated power supplies exciting the main coils of RIKEN Ring Cyclotron has been upgrade to a new one having a better long-term stability than the old ones.

Members

Team Leader

Nobuhisa FUKUNISHI (concurrent; Deputy Group Director, Accelerator Gr.)

Research/Technical Scientists

Masaki FUJIMAKI (Senior Technical Scientist)
Kazunari YAMADA (Senior Technical Scientist)
Keiko KUMAGAI (Senior Technical Scientist)
Akito UCHIYAMA (Technical Scientist)
Tamaki WATANABE (Senior Technical Scientist)

Expert Technician

Misaki KOMIYAMA

Part-time Worker

Makoto NAGASE

Visiting Scientists

Kenichi ISHIKAWA (Univ. of Tokyo)
Takuya MAEYAMA (Kitasato Univ.)
Shin-ichiro HAYASHI (Hiroshima Int'l Univ.)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

T. Maeyama, Y. Ishida, Y. Kudo, K. Fukasaku, K. L. Ishikawa, N. Fukunishi, “Polymer gel dosimeter with AQUAJOINT as hydrogel matrix,” Radiat. Phys. Chem. **146**, 121–125, doi:0.10216/j.radphyschem.2018.01.014 (2018).

T. Nishi, K. Itahashi, G. P. A. Berg, H. Fujioka, N. Fukuda, N. Fukunishi, H. Geissel, R. S. Hayano, S. Hirenzaki, K. Ichikawa, N. Ikeno, N. Inabe, S. Itoh, M. Iwasaki, D. Kameda, S. Kawase, T. Kubo, K. Kusaka, H. Matsubara, S. Michimasa, K. Miki, G. Mishima, H. Miya, H. Nagahiro, M. Nakamura, S. Noji, K. Okochi, S. Ota, N. Sakamoto, S. Suzuki, H. Takeda, Y. K. Tanaka, K. Todoroki, K. Tsukada, T. Uesaka, Y. N. Watanabe, H. Weick, H. Yamakami, K. Yoshida, “Spectroscopy of pionic atoms in ^{122}Sn(d, ^{3}He) reaction and angular dependence of the formation cross section,” Phys. Rev. Lett. **120**, 152502 (2018).

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[Domestic Conference]

T. Watanabe, H. Imao, O. Kamigaito, N. Sakamoto, N. Fukunishi, M. Fujimaki, K. Yamada, Y. Watanabe, R. Koyama, T. Toyama, T. Miyao, A. Miura, "Development of beam energy position monitor system for RIKEN superconducting acceleration cavity," 15th Annual Meeting of Particle Accelerator Society of Japan, pp. 49–54, Nagaoka, Japan, August 2018.

Posters Presentations

[International Conference etc.]

A. Uchiyama, T. Nagatomo, Y. Higurashi, J. Ohnishi, T. Nakagawa, M. Komiyama, N. Fukunishi, H. Yamauchi, M. Tamura, "Design of reliable control with star-topology fieldbus communication for an electron cyclotron resonance ion source at RIBF," 12th International Workshop on Personal Computers and Particle Accelerator Controls (PCaPAC2018), WEP30, Hsinchu, Taiwan, October 2018.

M. Komiyama, M. Fujimaki, N. Fukunishi, K. Kumagai, A. Uchiyama, "Recent development of the RIKEN RI Beam Factory control system," 12th International Workshop on Personal Computers and Particle Accelerator Controls (PCaPAC2018), WEP15, Hsinchu, Taiwan, October 2018.

[Domestic Conference]

T. Watanabe, H. Imao, O. Kamigaito, N. Sakamoto, N. Fukunishi, M. Fujimaki, K. Yamada, Y. Watanabe, R. Koyama, T. Toyama, T. Miyao, A. Miura, "Development of beam energy position monitor system for RIKEN superconducting acceleration cavity," 15th Annual Meeting of Particle Accelerator Society of Japan, pp. 49–54, Nagaoka, Japan, August 2018.

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Research Facility Development Division
Accelerator Group
Cryogenic Technology Team

1. Abstract

We are operating the cryogenic system for the superconducting ring cyclotron in RIBF. We are operating the helium cryogenic system in the south area of RIKEN Wako campus and delivering the liquid helium to users in RIKEN. We are trying to collect efficiently gas helium after usage of liquid helium.

2. Major Research Subjects

(1) Operation of the cryogenic system for the superconducting ring cyclotron in RIBF
(2) Operation of the helium cryogenic plant in the south area of Wako campus and delivering the liquid helium to users in Wako campus.

3. Summary of Research Activity

(1) Operation of the cryogenic system for the superconducting ring cyclotron in RIBF
(H. Okuno, T. Dantsuka, M. Nakamura, T. Maie)
(2) Operation of the helium cryogenic plant in the south area of Wako campus and delivering the liquid helium to users in Wako campus.
(T. Dantsuka, S. Tsuruma, H. Okuno).

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Research Facility Development Division
Accelerator Group
Infrastructure Management Team

1. Abstract

Our team is in charge of operation, maintenance, and monitoring of research infrastructure of the whole RIBF, such as cooling water system, air conditioner system, building equipment, and so on. It is very important to keep these infrastructures working properly for the effective and efficient operation of RIBF.

We are also involved in the planning of the RIBF beam time, which is conducted by the RIBF User Liaison Team, through the estimation of the utility costs such as the electricity and the gas used for the power generator. Another important mission of our team is to coordinate large-scale repair works carried out by the RIKEN Facility Section so that the beam time can proceed smoothly.

In the last three years, there were big construction works related to the upgrade project of the RILAC facility. We carried out the design of the SRF test facility, took part in the design work of the new building for radioisotope purification, jointly designed the ion source room, and so on. The transfer work of GARIS II and the room-temperature cavities of the RILAC booster was conducted by our team.

2. Major Research Subjects

(1) Operation, maintenance and monitoring of infrastructure of RI Beam Factory.
(2) Participation in the beam time planning through utility cost estimation.
(3) Coordination of large construction work and modification related to RI Beam Factory.

Members

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Research Facility Development Division
Instrumentation Development Group

1. Abstract

This group develops core experimental installations at the RI Beam factory. Three projects are currently going on. SLOWRI is an experimental installations under testing and a common element enabling multiple-use. This will stop high-energy RI beams in a gas-catcher system and re-accelerates up to several-tenth keV, and the high-quality cold RI beam will be delivered to the users. SCRIT is the world first facility for an electron scattering off unstable nuclei, and has been constructed independently of the RIBF main facility. The first physic result was demonstrated in 2017, and the facility is now under upgrading of the electron beam power driving the RI beam production. Rare-RI Ring is an event-by-event operated heavy-ion storage ring aiming at the precision mass measurement for extremely rare exotic nuclei. This is now open for an experimental proposal application, and has already performed PAC-approved experiments. All instrumentations were designed to maximize the research potential of the world's most intense RI beams, and the exclusive equipment available at the RI Beam Factory makes experimental challenges possible. Technologies and experiences accumulated in this group will be able to provide opportunities of new experimental challenges and the foundation for future developments of RIBF.

2. Major Research Subjects

(1) SCRIT Project
(2) SLOWRI Project
(3) Rear RI Ring Project
(4) Beam recycling development (in future plan)

3. Summary of Research Activity

We are developing beam manipulation technology in carrying out above listed project. They are the high-quality slow RI beam production (SCRIT and SLOWRI), the beam cooling and stopping (SCRIT and SLOWRI), and the beam accumulation technology (Rare RI Ring) in a storage ring. The technological knowhow accumulated in our projects will play a significant role in the next generation RIBF. Status and future plan for each project is described in subsections. The electron scattering from ^{132}Xe isotopes has been successfully measured and the nuclear charge density distribution has been obtained in SCRIT. We are almost ready for the electrons scattering experiments for unstable nuclei. Rare RI Ring has been commissioned and the performances has been evaluated. We have demonstrated a mass-measurement capability of R3 and successfully started mass-measurements for unknown-mass nuclei in the experiments approved by PAC. SLOWRI is now under test experiments to establish a slow RI beam production using two types of gas cells. PALIS has been commissioned from 2015, and basic functions such as, for instance, the RI-beam stopping in Ar gas cell and the extraction from the gas cell have beam evaluated. RF ion-guide gas cell is now under testing and it is planned to be commissioned in next year. Future plans for these projects are described in subsections.

We are going to start a new project from next year. According to the future plan of Nishina center, we are going to start to develop a beam re-cycling technique. A crculation of an RI beam in a storage ring equipped by a thin internal target is maintained until that some nuclear reaction happen at the target. The circulating beam loses a energy and the emittance grows up turn by turn because of existing internal target. In order to establish a beam re-cycling technique, the energy loss and the emittance growth have to be compensated by using a re-acceleration system and a beam-cooling or a fast feedback system. A beam re-cycling technique is supposed to greatly enhance an RI use efficiency in a nuclear physics study. As a first step for the development of these novel technique, we are going to install a testbench consisting of a relatively small size of heavy-ion storage ring that will be connect to our ISOL (ERIS) in SCRIT facility. This ring named sLSR is equipped by acceleration devices and beam-cooling devices necessary in our R&D study, and was originally constructed at the Institute for Chemical Research, Kyoto University more than ten years ago. This will be moved to RIBF in this year, and re-constructed by the SCRIT facility in following year.

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List of Publications & Presentations

Publications and presentations for each project team are listed in subsections.

Research Facility Development Division
Instrumentation Development Group
SLOWRI Team

1. Abstract

SLOWRI is a universal low-energy RI-beam facility at RIBF that provides a wide variety of short-lived nuclei as high-purity and low-emittance ion beams or stored ions in a trap, including a parasitic operation mode. The SLOWRI team develops and manages the facility and performs high-precision spectroscopy experiments. The construction of the SLOWRI facility began in FY2013 and commissioning work is ongoing. High-energy radioactive ion beams from the projectile fragment separator BigRIPS are thermalized in a large He gas catcher cell (RFC cell) or in a small Ar gas catcher cell (PALIS cell). From these gas cells, the low-energy ion beams will be delivered via mass separators and switchyards to various devices: such as an ion trap, a collinear fast beam apparatus, and a multi-reflection time of flight mass spectrograph. A multi-reflection time-of-flight mass spectrograph (MRTOF) has been also developed. Two mass measurement projects using MRTOF mass spectrographs have been started: one is for trans uranium elements at the GARIS facility and the other is for r-process nuclides at SLOWRI facility. At GARIS-II, we installed second prototype SLOWRI combined with MRTOF, which is a medium-sized cryogenic RF-carpet He gas cell. Using second prototype SLOWRI, more than 80 nuclear masses have been measured including first mass measurements of Md and Es isotopes. At SLOWRI facility, third prototype SLOWRI is under construction, which is 50-cm-long RF-carpet-type He gas cell combined with MRTOF. The third prototype will be installed at F11 of BigRIPS, downstream of ZeroDegree spectrometer, which can provide symbiotic measurements with other BigRIPS experiments.

An online commissioning experiment of parasitic low-energy production facility (PALIS) was performed and confirmed that the PALIS setup can coexist with other BigRIPS experiments. Currently, PARIS gas cell is under on- and off-line commissioning.

2. Major Research Subjects

(1) Construction of the stopped and low-energy RI-beam facility, SLOWRI.
(2) Development of a multi-reflection time-of-flight mass spectrograph for precision mass measurements of short-lived nuclei.
(3) Development of collinear laser spectroscopy apparatus.
(4) Development of a parasitic slow RI-beam production method using resonance laser ionization.
(5) Development of highly charged ion trap for fundamental physics

3. Summary of Research Activity

(1) Construction of stopped and low-energy RI-beam facility (SLOWRI)

SLOWRI consists of two gas catchers (RF carpet gas cell and PALIS gas cell), mass separators a 50-m-long beam transport line, a beam cooler-buncher, an isobar separator, and a laser system. The RF carpet gas cell will be installed at the exit of the D5 dipole magnet of BigRIPS. The gas catcher contains a large cryogenic He gas cell with a large traveling wave rf-carpet. The PALIS gas cell is installed in the vicinity of the second focal plane slit of BigRIPS. It will provide parasitic RI-beams from those ions lost in the slits during other experiments. In this gas catcher, thermalized RI ions quickly become neutral and will be re-ionized by resonant laser radiations. The beam transport line consists of four dipole magnets, two focal plane chambers, 62 electrostatic quadrupole singlets, 11 electrostatic quadrupole quartets and 7 beam profile monitors. Off- and on-line commissioning is underway.

Based on test experiments with the prototype setups, the RF-carpet gas cell contains a three stage rf-carpet structure: a gutter rf carpet (1st carpet) for the collection thermal ions in the cell into a small slit, a narrow (about 10 mm) traveling-wave rf-carpet for collection of ions from the gutter carpet and for transporting the ions towards the exit, and a small rf carpet for extraction from the gas cell. In FY2018, ion extraction test at off-line using this carpet has been successfully performed with about 60% extraction efficiency to ions gathered on 1st carpet. We will install the RF-carpet gas cell combined with MRTOF at F11 of BigRIPS at first, where the on-line commissioning and systematic mass measurements will be started from FY2019. At F11, symbiotic measurements with other BigRIPS experiments can be performed.

(2) Development of a multi-reflection TOF mass spectrograph for short-lived nuclei

The atomic mass is one of the most important quantities of a nucleus and has been studied in various methods since the early days of modern physics. From among many methods we have chosen a multi-reflection time-of-flight (MR-TOF) mass spectrometer. Slow RI beams extracted from the RF ion-guide are bunched and injected into the spectrometer with a repetition rate of ~100 Hz. A mass-resolving power of 170,000 has been obtained with a 2 ms flight time for ^{40}K and ^{40}Ca isobaric doublet. This mass-resolving power should allow us to determine ion masses with an accuracy of $\leq 10^{-7}$.

The MR-TOF mass spectrograph has been placed under the GARIS-II separator aiming at direct mass measurements of trans-uranium elements. A medium-sized cryogenic He gas cell was placed at the focal plane of GARIS-II and a bunched low-energy heavy ion beam was transported to the trap of MR-TOF. Mass measurements of more than 80 nuclides, including short-lived ($T_{1/2}$ = 10 ms) isotopes of Ra and several isotopes of the trans-uranium elements Fm, Es, No and Md were performed in collaboration with Wako Nuclear Science Center (WNSC) of KEK and Super Heavy Element Synthesis team of RIKEN. The highest precisions, achieved for Ga isotopes, reached a level of 0.03 ppm. The masses of four isotopes of Es and Md were measured for the first time, allowing for confirmation of the N = 152 shell closure in Md. Using these new mass data as anchor-points, the masses of seven isotopes of super-heavy elements up to Mt were indirectly determined. For comprehensive mass measurements of all available nuclides, multiple units of gas catchers and MR-TOF devices will be placed at GARIS-III, KISS as well as the BigRIPS + SLOWRI facilities of RIBF.

(3) Development of collinear fast beam apparatus for nuclear charge radii measurements

The root-mean-square charge radii of unstable nuclei have been determined exclusively by isotope shift measurements of the optical transitions of singly charged ions or neutral atoms by laser spectroscopy. Many isotopes of alkali, alkali-earth, and noble-gas elements in addition to several other elements have been measured by collinear laser spectroscopy since these ions all have good optical transitions and are available at conventional ISOL facilities. However, isotopes of other elements, especially refractory and short-lived ones, have not been investigated so far.

In SLOWRI, isotopes of all atomic elements will be provided as well collimated, mono-energetic ion beams. This should expand the range of nuclides available for laser spectroscopy. In the first years of the RIBF project, elements in the vicinity of Ni, such as Ni, Co, Fe, Cr, Cu, Ga, and Ge are planned to be investigated. They all have possible optical transitions in the ground states of neutral atoms with presently available laser systems. Some of them have so called recycling transitions, which enhance the detection probabilities noticeably. Furthermore, the multistep resonance ionization (RIS) method can be applied to the isotopes of Ni as well as those of some other elements. The required minimum intensity for this method can be as low as 10 atoms per second.

An off-line mass separator and a collinear fast beam apparatus with a large solid-angle fluorescence detector was built previously. A 617-nm transition of the metastable Ar^+ ion at 20 keV was measured with both collinear and anti-collinear geometry, which allowed determination of the absolute resonant frequency of the transition at rest with a relative accuracy better than 10^{-8}. A new setup is under preparation at the SLOWRI experiment area in collaboration with the Ueno nuclear spectroscopy laboratory.

(4) Development of parasitic slow RI-beam production scheme using resonance laser ionization

More than 99.9% of RI ions produced in projectile fission or fragmentation are simply dumped in the first dipole magnet and the slits. A new scheme, named PALIS, meant to rescue such precious RI using a compact gas catcher cell and resonance laser ionization, was proposed as a part of SLOWRI. The thermalized RI ions in a cell filled with Ar gas can be quickly neutralized and transported to the exit of the cell by gas flow. Irradiation of resonance lasers at the exit ionizes neutral RI atoms efficiently and selectively. The resonance ionization scheme itself can also be a useful method to perform hyperfine structure spectroscopy of RI of many elements.

An online setup has been fabricated in FY2013 and the first online commissioning took place in FY2015. It was confirmed that the PALIS gas cell is not deleterious for BigRIPS experiments, and a reasonable amount of radioactive Cu isotopes was extracted from the cell by gas flow. At off-line, using α rays from Am source, impurities inside the gas cell have been investigated. Thanks to baking the gas cell with gas flow, almost impurities have been successfully suppressed at off-line condition. Technical developments are under progress in on- and off-line commissioning.

(5) Development of highly charged ion trap for fundamental physics

Some particular transitions in highly charged ions (HCI) are sensitive to the temporal variation of the fine structure constant. High precision spectroscopy of such transitions can be a probe for the verification of fundamental physics. A cryogenic ion trap setup consisting of a micro electron beam ion trap (μEBIT) and a linear RFQ ion trap in a compact cryogenic enclosure is under development in collaboration with Quantum Metrology Laboratory. First candidate HCIs, such as Ba^{7+} or Ho^{14+} can be produced in the μEBIT and sympathetically cooled by laser cooled Be^+ ions in the linear RFQ trap, following which the "clock" transition can be measured by electron-shelving spectroscopy. The final target is $^{249}Cf^{15+}$, which is known to have the most sensitive transition to the temporal variation of the fine structure constant.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

M. Rosenbusch, Y. Ito, P. Schiry, M. Wada, D. Kaji, K. Morimoto, H. Haba, S. Kimura, H. Koura, M. MacCorimik, H. Miyatake, J. Y. Moon, K. Morita, I. Murray, T. Niwase, A. Ozawa, M. Reponen, A. Takamine, T. Tanaka, H. Wollnik, "New mass anchor points for neutron-deficient heavy nuclei from direct mass measurements of radium and actinium isotopes," Phys. Rev. C **97**, 064306 (2018). *

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K. Imamura, Y. Matsuo, W. Kobayashi, T. Egami, M. Sanjo, A. Takamine, T. Fujita, D. Tominaga, Y. Nakamura, T. Furukawa, T. Wakui, Y. Ichikawa, H. Nishibata, T. Sato, A. Gladkov, L. C. Tao, T. Kawaguchi, Y. Baba, M. Iijima, H. Gonda, Y. Takeuchi, R. Nakazato, H. Odashima, H. Ueno, "Absolute optical absorption cross-section measurement of Rb atoms injected into superfluid helium using energetic ion beams," App. Phys. Exp. **12**, 016502 (2019). *

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[International Conference etc.]

A. Takamine, "Laser spectroscopy project at the SLOWRI facility in RIKEN," 20th Northeastern Asian Symposium-2018 on Nuclear Physics in the 21st Century, Nagoya, Japan, September 18–19, 2018.

A. Takamine, "Prospects for laser spectroscopy project at the SLOWRI facility in RIKEN RIBF," 2018 Korea Physics Society Fall Meeting, Changwon, Korea, October 24–26, 2018.

N. Kimura, R. Kodama, K. Suzuki, S. Ohishi, M. Wada, K. Okada, N. Ohmae, H. Katori, N. Nakamura, "Visible spectroscopy of highly charged barium ions in a compact electron beam ion trap with a buffer gas calibration method," 19th International Conference on the Physics of Highly Charged Ions (HCI2018), Lisboa, Portugal, September, 2018.

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M. Rosenbusch, "MRTOF mass measurements at RIBF: Recent measurements of heavy isotopes and future plans for the super-heavy region," TASCA workshop, GSI (Darmstadt), Germany, September 25, 2018.

M. Rosenbusch, "Recent successes of multi-reflection devices at RIKEN's RIBF facility and some thoughts about highly accurate mass calibration using ion traps," 10th International Conference on Charged Particle Optics (CPO-10), Key West (Florida), USA, October 17–21, 2018.

M. Rosenbusch, "Follow-ups on great achievements: New MRTOF-MS projects at RIKEN-RIBF," Fifth joint meeting of the Division of Nuclear Physics of the American Physical Society (APS) with the nuclear physicists of the Physical Society of Japan (JPS)," Hawaii, USA, October 23–27, 2018.

H. Ishiyama, "SLOWRI and related topics," RIBF Seminar, Wako, Japan, July 3, 2018.

H. Ishiyama, "Present status of SLOWRI," RIBF Users Meeting 2018, Wako, Japan, September 5, 2018.

H. Ishiyama, "Present status of SLOWRI," SSRI-PNS collaboration meeting 2018, Wako, Japan, September 4, 2018.

[Domestic Conference]

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Research Facility Development Division
Instrumentation Development Group
Rare RI-ring Team

1. Abstract

The aim of Rare-RI Ring (R3) is to measure the masses of short-lived unstable nuclei far from the beta-stability line. In particular, a high-precision mass measurement for nuclei located around the r-process pass (rare-RI) is required in nucleosynthesis point of view. The R3 completed the construction at the end of 2014, and has been performed commissioning experiments several times by 2017. Through the commissioning experiments, we confirmed the high ability of R3 as a storage ring capable of handling one event, and demonstrated that it is possible to perform the time-of-flight Isochronous Mass Spectrometry (IMS) in shorter than 1 ms. We have acquired an adequate efficiency to conduct the mass measurement experiments in the end of 2017. In 2018, we have successfully conducted the first mass measurement experiment for ^{74,76}Ni, ^{122}Rh, ^{123,124}Pd, and ^{125}Ag. The analysis is in progress for giving the new experimental mass values of ^{74,76}Ni, ^{122}Rh, ^{124}Pd, and for improving the experimental mass values of ^{123}Pd, ^{125}Ag.

2. Major Research Subjects

(1) Developments of heavy-ion storage ring
(2) Precision mass measurement for rarely produced isotopes related to r-process.

3. Summary of Research Activity

In the commissioning experiments up to 2017, we confirmed the unique performances of R3 and demonstrated the time-of-flight isochronous mass measurement method. The ring structure of R3 was designed with a similar concept of a separate-sector ring cyclotron. It consists of six sectors and straight sections, and each sector consists of four rectangular bending magnets. Two magnets at both ends of each sector are additionally equipped with ten trim coils to form a precise isochronous field. We have realized in forming the precise isochronous field of 5 ppm with wide momentum range of $\Delta p/p = \pm 0.5\%$. Another performance required for R3 is to efficiently seize hold of an opportunity of the mass measurement for rare-RIs produced unpredictably. It was realized by constructing the Isotope-Selectable Self-trigger Injection (ISSI) scheme which pre-identified rare-RI itself triggers the injection kicker magnets. Key device was an ultra-fast response kicker system that has been successfully developed. Full activation of the kicker magnetic field can be completed within the flight time of the rare-RI from an originating point (F3 focal point in BigRIPS) of the trigger signal to the kicker position in R3.

Since R3 accumulates, in principle, only one event, we fabricated high-sensitive beam diagnostic devices in the ring. They should be applicable even for one event circulation. One of them is a cavity type of Schottky pick-up installed in the straight section of R3. The Schottky pick-up successfully monitored a single ^{78}Kr^{36+} ion circulation with the measurement time of less than 10 ms in the first commissioning experiment. We also confirmed that it is useful for fine tuning of the isochronous field. Another is a timing monitor, which detects secondary electrons emitted from thin carbon foil placed on the circulation orbit. The thickness of the foil is 50 μg/cm^2. This timing monitor is working well to observe first several tens turns for injected event.

We performed mass measurement in the third commissioning experiment by using unstable nuclei which masses are well-known. The masses of ^{79}As, ^{77}Ga, ^{76}Zn, and ^{75}Cu relative to ^{78}Ge were derived with the accuracy of ~10 ppm. In addition, we have improved the extraction efficiency to 2% by considering the matching condition between the emittance of injection events and the acceptance of R3. This extraction efficiency was sufficient to conduct the accepted two proposals: mass measurements of Ni isotopes and mass measurements of Sn region.

In the beginning of 2018, we examined the feasibility of these two proposals in detail. Consequently, we decided to proceed with two proposals at the same period. In the beginning of November 2018, we have conducted the first experiment using the R3 to measure the masses for ^{74,76}Ni in 4 days. After that, we also measured the masses for ^{122}Rh, ^{123,124}Pd, and ^{125}Ag in 4.5 days at the end of November 2018. These nuclei were successfully extracted from R3 with the efficiency of 1–2%. The masses of ^{74,76}Ni, ^{122}Rh, and ^{124}Pd can be determined experimentally for the first time. On the other hand, the masses of ^{123}Pd and ^{125}Ag will be improved the precision compared with previous experimental values. These analyses are still in progress. Since each proposal has a machine time of several days to measure the masses of exotic nuclei, we will plan to conduct the mass measurements of the other Ni isotopes and nuclei of Sn region in 2019.

Members

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List of Publications & Presentations

Publications

Oral Presentations

[International Conference etc.]

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洲嵜ふみ, 阿部康志, 若杉昌徳, 山口由高, 天野将道, 荒川裕樹, 馬場秀忠, Z. Ge, 細井駿, 稲田康人, 猪股玖美, 上岡大起, 北村徳隆, 小林孝彰, H. Li, Y. A. Litvinov, 増岡翔一朗, 道正新一郎, 森口哲朗, 長江大輔, S. Naimi, 西室国光, 大甕舜一朗, 大田晋輔, 小沢顕, 鈴木伸司, 上坂友洋, 若山清志, 山口貴之, 「共鳴ショットキーピックアップを用いた稀少 RI リングの等時性場調整」, 日本物理学会第 74 回年次大会, 福岡, 2019 年 3 月.

Posters Presentations

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Research Facility Development Division
Instrumentation Development Group
SCRIT Team

1. Abstract

The SCRIT Electron Scattering Facility has been constructed at RIKEN RIBF. This aims at investigation of internal nuclear structure for short-lived unstable nuclei by means of electron scattering. SCRIT (Self-Confining RI Ion Target) is a novel method to form internal targets in an electron storage ring. This is a unique method for making electron scattering experiments for unstable nuclei possible. Construction of the facility has been started in 2009. This facility consists of an electron accelerator (RTM), a SCRIT-equipped electron storage ring (SR2), an electron-beam-driven RI separator (ERIS), and a window-frame spectrometer for electron scattering (WiSES) which consists of a large window-frame dipole magnet, drift chambers and trigger scintillators. Installation of all components in the facility was completed in 2015. After the comprehensive test and tuning, the luminosity was reached to $3 \times 10^{27}/(\mathrm{cm}^2\mathrm{s})$ with the number of injected ions of 3×10^8. In 2016, we successfully completed a measurement of diffraction of scattered electrons from ^{132}Xe nuclei and determined the charge density distribution for the first time. The facility is now under setting up to move the first experiment for unstable nuclei.

2. Major Research Subjects

Development of SCRIT electron scattering technique and measurement of the nuclear charge density distributions of unstable nuclei.

3. Summary of Research Activity

SCRIT is a novel technique to form internal target in an electron storage ring. Positive ions are three dimensionally confined in the electron beam axis by transverse focusing force given by the circulating electron beam and applied electrostatic longitudinal mirror potential. The created ion cloud composed of RI ions injected from outside works as a target for electron scattering. Construction of the SCRIT electron scattering facility has been started in 2009. The electron accelerators RTM and the storage ring SR2 were successfully commissioned in 2010. Typical accumulation current in SR2 is 250–300 mA at the energy range of 100–300 MeV that is required energy range in electron scattering experiment. The SCRIT device was inserted in the straight section of SR2 and connected to an ISOL named ERIS (Electron-beam-driven RI separator for SCRIT) by 20-m long low energy ion transport line. A buncher system based on RFQ linear trap named FRAC (Fringing-RF-field-Activated dc-to-pulse converter) was inserted in the transport line to convert the continuous beam from ERIS to pulsed beam, which is acceptable for SCRIT. The detector system WiSES consisting of a high-resolution magnetic spectrometer, drift chambers and trigger scintillators, was constructed, and it has a solid angle of 100 msr, energy resolution of 10^{-3}, and the scattering angle coverage of 25–55 degrees. A wide range of momentum transfer, 80–300 MeV/c, is covered by changing the electron beam energy from 150 to 300 MeV.

We successfully measured a diffraction pattern in the angular distribution of scattered electron from ^{132}Xe isotope at the electron beam energy of 150 MeV, 200 MeV, and 300 MeV, and derived the nuclear charge distribution by assuming two-parameters Fermi model for the first time. At this time, luminosity was reached to $3 \times 10^{27}/(\mathrm{cm}^2\mathrm{s})$ at maximum and the averaged value was $1.2 \times 10^{27}/(\mathrm{cm}^2\mathrm{s})$ with the number of injected target ions of 3×10^8.

We are now under preparation for going to the experiments for unstable nuclei. There are some key issues for that. They are increasing the intensity of the RI beams from ERIS, efficient DC-to-pulse conversion at FRAC, improving the transmission efficiency from FRAC to SCRIT, and effective suppression of the background in measurement of scattered electrons. RI beam intensity will be improved by upgrading the electron beam power from 10 W to 60 W, increasing the contained amount of U in the target ion source, and some modifications in mechanical structure in the ion source. For upgrading the electron beam power, the RF system of RTM has been maintained intensively, and we will continue the development of RTM. For efficient DC-to-pulse conversion, we established the two-step bunching method, which is time compression at FRAC in combination with pre-bunching at the ion source using grid action. Furthermore, we will improve the conversion efficiency and the transmission efficiency from FRAC to the SCRIT device by cooling the trapped ions using minuscule amounts of a buffer gas. These improvements on FRAC were already confirmed in off-line test. Since one of significant contribution to the background for scattered electron is scattering from massive structural objects around the trapping region originated from halo components of the electron beam, we remodeled the SCRIT electrodes. The vacuum pump system at the SCRIT device has been upgraded to reduce the contribution of residual gases. Luminosity for radioactive Xe isotopes is expected to be more than $10^{26}/(\mathrm{cm}^2\mathrm{s})$ after these improvements. Then, we will be able to start experiments for unstable nuclei. When further upgrading in the RTM power planed to be 3 kW will be achieved, we can extend the measurements to more exotic nuclei.

In 2018, we have been developing several instruments. One is the introduction of the surface-ionization type ion source at ERIS in order to increase kinds of radioactive beam and to produce high intensity beam. Another development is the upgrading of the drift chamber located in front of the magnetic spectrometer of WiSES to improve the momentum resolution and angular acceptance. These developments help us to realize experiments for unstable nuclei.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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K. Tsukada (invited), "Electron scattering from ^{208}Pb and ^{132}Xe ions at the SCRIT facility," The 7th international conference on Trapped Charged Particles and Fundamental Physics (TCP2018), Traverse, Michigan, USA, September 30–October 5, 2018.

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高山祥汰, 須田利美, 塚田暁, 本多佑記, 玉江忠明, 笠間桂太, 青柳泰平, for the SCRIT collaboration, 「SCRIT 電子スペクトロメーター性能向上に向けた飛跡検出器の開発」, 日本物理学会, 東京理科大学, 千葉, 2018 年 3 月.

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T. Ohnishi, S. Ichikawa, M. Nakano, K. Kurita, M. Wakasugi, "Present status of electron-beam-driven RI separator for SCRIT at RIKEN RI Beam Factory," 18th International Conference on Electromagnetic Isotope separators and Related Topics (EMIS2018), Geneva, Switzerland, September 16–21, 2018.

Research Facility Development Division
Research Instruments Group

1. Abstract

The Research Instruments Group is the driving force at RI Beam Factory (RIBF) for continuous enhancement of activities and competitiveness of experimental research. Consisting of four teams, we are in charge of the operation, maintenance, and improvement of the core research instruments at RIBF, such as the BigRIPS in-flight RI separator, ZeroDegree spectrometer and SAMURAI spectrometer, and the related infrastructure and equipment. We are also in charge of the production and delivery of RI beams using the BigRIPS separator. The group also conducts related experimental research as well as R&D studies on the research instruments.

2. Major Research Subjects

Design, construction, operation, maintenance, and improvement of the core research instruments at RIBF and related R&D studies. Experimental studies on exotic nuclei.

3. Summary of Research Activity

The current research subjects are summarized as follows:

(1) Production and delivery of RI beams and related research
(2) Design, construction, operation, maintenance, and improvement of the core research instruments at RIBF and their related infrastructure and equipment
(3) R&D studies on the core research instruments and their related equipment at RIBF
(4) Experimental research on exotic nuclei using the core research instruments at RIBF

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Research Facility Development Division
Research Instruments Group
BigRIPS Team

1. Abstract

This team is in charge of design, construction, development and operation of BigRIPS in-flight separator and its related research instruments at RI beam factory (RIBF). They are employed not only for the production of RI beams but also the experimental studies using RI beams.

2. Major Research Subjects

Design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments

3. Summary of Research Activity

This team is in charge of design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer at RI beam factory (RIBF). They are employed not only for the production of RI beams but also various kinds of experimental studies using RI beams.

The research subjects may be summarized as follows:

(1) General studies on RI-beam production using in-flight scheme.
(2) Studies on ion-optics of in-flight separators, including particle identification of RI beams
(3) Simulation and optimization of RI-beam production.
(4) Development of beam-line detectors and their data acquisition system.
(5) Experimental studies on production reactions and unstable nuclei.
(6) Experimental studies of the limits of nuclear binding.
(7) Development of superconducting magnets and their helium cryogenic systems.
(8) Development of a high-power production target system.
(9) Development of a high-power beam dump system.
(10) Development of a remote maintenance and remote handling systems.
(11) Operation, maintenance and improvement of BigRIPS separator system, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer and so on.
(12) Experimental research using RI beams.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

N. Fukuda, T. Kubo, D. Kameda, N. Inabe, H. Suzuki, Y. Shimizu, H. Takeda, K. Kusaka, Y. Yanagisawa, M. Ohtake, K. Tanaka, K. Yoshida, H. Sato, H. Baba, M. Kurokawa, T. Ohnishi, N. Iwasa, A. Chiba, T. Yamada, E. Ideguchi, S. Go, R. Yokoyama, T. Fujii, H. Nishibata, K. Ieki, D. Murai, S. Momota, D. Nishimura, Y. Sato, J. Hwang, S. Kim, O. B. Tarasov, D. J. Morrissey, G. Simpson, "Identification of new neutron-rich isotopes in the rare-earth region produced by 345 MeV/nucleon ^{238}U," J. Phys. Soc. Jpn. **87**, 014202 (2018).*

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Research Facility Development Division
Research Instruments Group
SAMURAI Team

1. Abstract

In collaboration with research groups in and outside RIKEN, the team designs, develops and constructs the SAMURAI spectrometer and relevant equipment that are and will be used for reaction experiments using RI beams at RI Beam Factory. The SAMURAI spectrometer consists of a large superconducting dipole magnet and a variety of detectors to measure charged particles and neutrons. After the commissioning experiment in March 2012, the team prepared and conducted, in collaboration with researchers in individual experimental groups, the first series of experiments with SAMURAI in May 2012. Then, several numbers of experiments were well performed until now utilizing the property of SAMURAI. The team also provides basis for research activities by, for example, organizing collaboration workshops by researchers who are interested in studies or plan to perform experiments with the SAMURAI spectrometer.

2. Major Research Subjects

Design, operation, maintenance and improvement of the SAMURAI spectrometer and its related research instruments. Support and management for SAMURAI-based research programs. Generate future plans for next generation instruments for nuclear reaction studies.

3. Summary of Research Activity

The current research subjects are summarized as follows:

(1) Operation, maintenance and improvement of a large superconducting dipole magnet that is the main component of the SAMURAI spectrometer.
(2) Design, development and construction of various detectors that are used for nuclear reaction experiments using the SAMURAI spectrometer.
(3) Preparation for planning experiments using SAMURAI spectrometer.
(4) Maintenance and improvement of the SAMURAI beam line.
(5) Formation of a collaboration platform called SAMURAI collaboration.
(6) Preparation for next generation spectrometer for nuclear reaction studies.

Members

Team Leader
Hideaki OTSU

List of Publications & Presentations

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安田昌弘, 「逆転の島境界核のスペクトロスコピー」, 東京工業大学理学院物理学系.

松本真由子, 「中性子過剰核 ^{32}Ne の非束縛準位の探索」, 東京工業大学理学院物理学系.

Bachelor Thesis

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Research Facility Development Division
Research Instruments Group
Computing and Network Team

1. Abstract

This team is in charge of development, management and operation of the computing and network environment, mail and information servers and data acquisition system and management of the information security of the RIKEN Nishina Center.

2. Major Research Subjects

(1) Development, management and operation of the general computing servers
(2) Development, management and operation of the mail and information servers
(3) Development, management and operation of the data acquisition system
(4) Development, management and operation of the network environment
(5) Management of the information security

3. Summary of Research Activity

This team is in charge of development, management and operation of the computing and network environment, mail and information servers and data acquisition system and management of the information security. The details are described elsewhere in this progress report.

(1) Development, management and operation of the general computing servers

We are operating Linux/Unix NIS/NFS cluster system for the data analysis of the experiments and general computing. This cluster system consists of eight computing servers with 64 CPU cores and totally 200 TB RAID of highly-reliable Fibre-channel interconnection. Approximately 700 user accounts are registered on this cluster system. We are adopting the latest version of the Scientific Linux (X86_64) as the primary operating system, which is widely used in the accelerator research facilities, nuclear physics and high-energy physics communities in the world.

(2) Development, management and operation of the mail and information servers

We are operating RIBF.RIKEN.JP server as a mail/NFS/NIS server. This server is a core server of RIBF Linux cluster system. Postfix has been used for mail transport software and dovecot has been used for imap and pop services. These software packages enable secure and reliable mail delivery. Sophos Email Security and Control (PMX) installed on the mail front-end servers which tags spam mails and isolates virus-infected mails. The probability to identify the spam is approximately 95–99%. We are operating several information servers such as Web servers, Integrated Digital Conference (INDICO) server, Wiki servers, Groupware servers, Wowza streaming servers. We have been operating approximately 70 units of wireless LAN access points in RNC. Almost the entire radiation-controlled area of the East Area of RIKEN Wako campus is covered by wireless LAN for the convenience of experiments and daily work.

(3) Development, management and operation of the data acquisition system

We have developed the standard data-acquisition system named as RIBFDAQ. This system can process up to 40 MB/s data. By using crate-parallel readout from front-end systems such as CAMAC and VME, the dead time could be minimized. To synchronize the independent DAQ systems, the time stamping system has been developed. The resolution and depth of the time stamp are 10 ns and 48 bits, respectively. This time stamping system is very useful for beta decay experiments such as EURICA, BRIKEN and VANDLE projects. One of the important tasks is the DAQ coupling, because detector systems with dedicated DAQ systems are transported to RIBF from foreign facilities. In case of SAMURAI Silicon (NSCL/TUM/WUSTL), the readout system is integrated into RIBFDAQ. The projects of MUST2 (GANIL), MINOS (CEA Saclay), NeuLAND (GSI) and TRB3 (TUM) cases, data from their DAQ systems are transferred to RIBFDAQ and merged online. For SPIRIT (RIKEN/GANIL/CEA Saclay/NSCL), RIBFDAQ is controlled from the NARVAL-GET system that is a large-scale signal processing system for the time projection chamber. EURICA (GSI), BRIKEN (GSI/Univ. Liverpool/IFIC), VANDLE (UTK) and OTPC (U. Warsaw) projects, we adopt the time stamping system to apply individual trigger for each detector system. In this case, data are merged in offline. In addition, we are developing intelligent circuits based on FPGA. General Trigger Operator (GTO) is an intelligent triggering NIM module. Functions of "common trigger management," "gate and delay generator," "scaler" are successfully implemented. The trigger system in BigRIPS DAQ has been successfully upgraded by 5 GTO modules. To improve the data readout speed of VME system, we are developing FPGA-based small VME controller named as Mountable-Controller (MOCO). This controller can be attached to each ADC/TDC VME module. Usually, in the VME system, one master controller readout data from all modules in the VME shelf. On the other hand, data readout is carried out in parallel by multiple MOCO boards even ADC/TDC modules are in the same VME shelf. To establish robust MOCO-based VME system, we have developed MOCO with Parallelized VME (MPV) system which is a kind of the parallel readout extension of the VME bus. This MPV system merges data from multiple MOCOs and send it to the DAQ server.

(4) Development, management and operation of the network environment

We have been managing the network environment collaborating with Information Systems Division in RIKEN. All the Ethernet ports of the information wall sockets are capable of the Gigabit Ethernet connection (10/100/1000 BT). In addition, a 10 Gbps network port has been introduced to the RIBF Experimental area in for the high-speed data transfer of RIBF experiment to HOKUSAI. Approximately 70 units of wireless LAN access points have been installed to cover the almost entire area of Nishina Center.

(5) Management of the information security

It is essential to take proper information security measures for information assets. We are managing the information security of Nishina Center collaborating with Information Systems Division in RIKEN.

Members

Team Leader

Hidetada BABA

Research/Technical Scientist

Yasushi WATANABE (concurrent; Senior Research Scientist, Radiation Lab.)

Junior Research Associates

Fumiya GOTO (Nagoya Univ.)

Special Temporary Employee

Takashi ICHIHARA (concurrent; Special Temporary Employee, RI Physics Lab.)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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Oral Presentations

[International Conference etc.]

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Posters Presentations

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Research Facility Development Division
Research Instruments Group
Detector Team

1. Abstract
This team is in charge of development, fabrication, and operation of various detectors used for nuclear physics experiments at RIBF. Our current main mission is maintenance and improvement of detectors which are used at BigRIPS separator and its succeeding beam lines for beam diagnosis and particle identification of RI beams. We are also engaged in R&D of new detectors that can be used for higher-intensity RI beams. In addition, we are doing the R&D which uses the pelletron accelerator together with other groups.

2. Major Research Subjects
Development, fabrication, and operation of various detectors for nuclear physics experiments, including beam-line detectors which are used for the production and delivery of RI beams (beam diagnosis and particle identification). R&D which uses the pelletron accelerator.

3. Summary of Research Activity
The current research subjects are summarized as follows:
(1) Maintenance and improvement of the beam-line detectors which are used at BigRIPS separator and its succeeding beam lines.
(2) Development of new beam-line detectors with radiation hardness and tolerance for higher counting rates
(3) Management of the pelletron accelerator and R&D which uses the pelletron

Members

Team Leader
Hiromi SATO

Research/Technical Scientist
Tokihiro IKEDA (Senior Research Scientist)

Special Temporary Employee
Manabu HAMAGAKI

Visiting Scientist
Takeshi KOIKE (Tohoku University)

Student Trainees
Shunya KAWAMURA (Toho University)
Masaya SAKAI (University of Tokyo)
Kento TAKEMOTO (University of Tokyo)
Mayuka IKEKAME (Toho University)
Yuka HIKIMA (Toho Universicy)
Mitsumasa MORI (Toho University)

List of Publications & Presentations

Publications

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Posters Presentations

[International Conference etc.]

K. Yokokawa, K. Takahashi, J. Matsumoto, H. Shiromaru, T. Ikeda, T. M. Kojima, "Current-dependent ion beam guiding by straight macro capillaries," 10th International Symposium on Swift Heavy Ions in Matter & 28th International Conference on Atomic Collisions in Solids (SHIM-ICACS 2018), (Université Caen Normandie), Caen, France, July 2018.

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Accelerator Applications Research Division
Beam Mutagenesis Group

1. Abstract

This group promotes various applications of ion beams from RI Beam Factory (RIBF). Ion Beam Breeding Team studies various biological effects of fast heavy ions and develops new technology to breed plants and microbes by heavy-ion irradiations. RI Applications Team studies production and application of radioisotopes for various research fields, development of trace element analysis and its application, and development of chemical materials for ECR ion sources of RIBF accelerators.

2. Major Research Subjects

Research and development in biology, chemistry and materials science utilizing heavy-ion beams from RI Beam Factory.

3. Summary of Research Activity

(1) Biological effects of fast heavy ions
(2) Molecular nature of DNA alterations induced by heavy-ion irradiation
(3) Research and development of heavy-ion breeding
(4) RI application researches
(5) Research and development of RI production technology at RIBF
(6) Developments of trace elements analyses
(7) Development of chemical materials for ECR ion sources of RIBF accelerators

Members

Group Director
Tomoko ABE

List of Publications & Presentations

Publications and presentations for each research team are listed in subsections.

Accelerator Applications Research Division
Beam Mutagenesis Group
Ion Beam Breeding Team

1. Abstract

Ion beam breeding team studies various biological effects of fast heavy ions. It also develops new technique to breed plants and microbes by heavy-ion irradiations. Fast heavy ions can produce dense and localized ionizations in matters along their tracks, in contrast to photons (X rays and gamma rays) which produce randomly distributed isolated ionizations. These localized and dense ionization can cause double-strand breaks of DNA which are not easily repaired and result in mutation more effectively than single-strand breaks. A unique feature of our experimental facility at the RIKEN Ring Cyclotron (RRC) is that we can irradiate living tissues in atmosphere since the delivered heavy-ion beams have energies high enough to penetrate deep in matter. This team utilizes a dedicated beam line (E5B) of the RRC to irradiate microbes, plants and animals with beams ranging from carbon to iron. Its research subjects cover physiological study of DNA repair, genome analyses of mutation, and development of mutation breeding of plants by heavy-ion irradiation. Some new cultivars have already been brought to the market.

2. Major Research Subjects

(1) Study on the biological effects by heavy-ion irradiation
(2) Study on the molecular nature of DNA alterations induced by heavy-ion irradiation
(3) Innovative applications of heavy-ion beams

3. Summary of Research Activity

We study biological effects of fast heavy ions from the RRC using 135 *A* MeV C, N, Ne ions, 95 *A* MeV Ar ions, 90 *A* MeV Fe ions and from the IRC using 160 *A* MeV Ar ions. We also develop breeding technology of microbes and plants. Main subjects are:

(1) Study on the biological effects by heavy-ion irradiation

Heavy-ion beam deposits a concentrated amount of dose at just before stop with severely changing the linear energy transfer (LET). The peak of LET is achieved at the stopping point and known at the Bragg peak (BP). It is well known to be good for cancer therapy to adjust the BP to target malignant cells. On the other hand, a uniform dose distribution is a key to the systematic study for heavy-ion mutagenesis, and thus to the improvement of the mutation efficiency. Therefore plants and microbes are treated using ions with stable LET. We investigated the effect of LET ranging from 23 to 640 keV/μm, on mutation induction using dry seeds of the model plants *Arabidopsis thaliana*. The most effective LET (LETmax) was 30 keV/μm. LETmax irradiations showed the same mutation rate as that by chemical mutagens, which typically cause high mutation rate. The LETmax of imbibed rice (*Oryza sativa* L.) seeds, dry rice seeds and dry wheat (*Triticum monococcum*) seeds were shown to be 50–63 keV/μm, 23–30 keV/μm and 50 keV/μm, respectively. In the case of microbe (*Mesorhizobium lothi*), the results showed a higher incidence of deletion mutations for Fe ions at 640 keV/μm than for C ions at 23–40 keV/μm. Thus, the LET is an important factor to be considered in heavy-ion mutagenesis.

(2) Study on the molecular nature of DNA alterations induced by heavy-ion irradiation

Detailed analyses on the molecular nature of DNA alterations have been reported as an LET-dependent effect for induced mutation. The most mutations were deletions ranging from a few to several tens of base pairs (bp) in the *Arabidpsis thaliana* mutants induced by irradiation with C ions at 30 keV/μm and rice mutants induced by irradiation with C ions at 50 keV/μm or Ne ions at 63 keV/μm. LETmax is effective for breeding because of its very high mutation frequency. Since most mutations are small deletions, these are sufficient to disrupt a single gene. Thus, irradiation can efficiently generate knockout mutants of a target gene, and can be applied to reverse genetics. On the other hand, irradiation with Ar ions at 290 keV/μm showed a mutation spectrum different from that at LETmax: the proportion of small deletions (<1 kbp) was low, while that of large deletions ranging from several to several tens of kbp, and rearrangements was high. Many genes in the genome (>10%) are composed of tandem duplicated genes that share functions. For knockout of the tandem duplicated genes, large deletions are required, and the appropriate deletion size is estimated to be around 5–10 kbp and 10–20 kbp based on the gene density in *Arabidpsis* and rice, respectively. No method is currently available to efficiently generate deletion mutants of this size. As such, higher LET irradiation is promising as a new mutagen suitable for the functional analysis of tandem duplicated genes.

(3) Innovative application of heavy-ion beams

We have formed a consortium for ion-beam breeding. It consisted of 24 groups in 1999, in 2018, it consisted of 180 groups from Japan and 17 from overseas. Breeding was performed previously using mainly flowers and ornamental plants. We have recently put a new sweet-smelling onion cultivar with tearless and non-pungent, 'Smile Balls' on the market. Beneficial variants have been grown for various plant species, such as high yield rice, semi-dwarf early rice, semi-dwarf buckwheat, semi-dwarf barley, hypoallergenic peanut, spineless oranges, non-flowering Eucalyptus and lipids-hyperaccumulating unicellular alga. The target of heavy-ion breeding is extended from flowers to crops so that it will contribute to solve the global problems of food and environment. We collaborate with the National Research and Development Agency, Japan Fisheries Research and Education Agency and Nagasaki University. The monogonont rotifer (*Brachionus* spp.) is a complex species and an essential food source for finfish aquaculture. The *B. plicatilis* is divided into three major clades (small, medium and large (L)) based on body length. Although the body size ranges from 100 to 300 μm in length, a mutation breeding of rotifers with larger size is expected for the purpose of productivity improvement in the aquaculture industry. Therefore, we conducted a large-scale screening to isolate gigantic rotifers by heavy-ion-beam irradiation to L-type rotifers. Then we have established 23 mutant lines that have an average length of over 350 μm (a maximum length reached 404 μm) through over ten thousand of individual mutagenized lines. These data will be useful to choose the suitable lines that satisfies the request of the aquaculture industry.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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Q. N. Vuong, 風間裕介, 石井公太郎, 大部澄江, 國武久登, 阿部知子, 平野智也, 「シロイヌナズナ大輪変異体リソースを用いた花器官サイズ制御機構の解析」, 日本植物学会第 82 回大会, 広島, 2018 年 9 月.

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Accelerator Applications Research Division
Beam Mutagenesis Group
Plant Genome Evolution Research Team

1. Abstract
The plant genome evolution research team studies the effect of heavy-ion induced chromosomal rearrangements on plant phenotypes. Chromosome rearrangements including translocation, inversion, and deletion are thought to play an important role in evolution and have a great potential to provide large phenotypic changes. However, this potential has not been fully investigated because of the lack of an effective method to induce rearrangements. We recently found that chromosomal rearrangements are frequently induced after heavy-ion irradiations with high valence numbers such as Fe ions or Ar ions. This frequency is 30 times higher than that of the previous techniques and allows characterization of the effect of chromosomal rearrangements. By analyzing changes of gene expressions and chromatin statuses in mutants having chromosomal rearrangements, we study the effect of the chromosome rearrangements on plant phenotypes of the mutants. In addition, we investigate the developmental process of a plant sex chromosome, which is a representative example of the naturally occurring chromosomal rearrangements involved in adaptation and evolution.

2. Major Research Subjects
(1) Study on the effect of chromosomal rearrangements on plant genomes and phenotypes
(2) Identification of the plant sex-determining genes and their evolutionary study

3. Summary of Research Activity
(1) Study on the effect of chromosomal rearrangements on plant genomes and phenotypes
In order to investigate the effect of chromosome rearrangements on plant phenotypes, we analysed the *Arabidopsis* mutant Ar55-as1, which were originally induced by Ar-beam irradiation at a dose of 50 Gy with an LET of 290 keV/μm. This mutant has no homozygous mutation in any genes but has chromosomal rearrangements in the genome. This mutant shows a clear morphological mutant phenotype in which the petiole is shorter than wild-type plants. As a result of the investigation of the trait of each individual and the presence or absence of chromosome rearrangements in the M3 generation of the mutant, we found that the inversion of chromosome 2 is responsible for the phenotype. In addition, this inversion was found to be a dominant mutation. From this finding, we showed that a chromosome rearrangement can dominantly affect the plant phenotype. We are currently investigating the effect of this inversion on gene expression.

We also attempted to induce a chromosome rearrangement at a target position by using genome editing technology, because this technique will be necessary when the functional analysis of chromosomal rearrangements will be performed in the future. There has been no report in which a large chromosomal rearrangement was induced in *A. thaliana* by the genome editing. However, we expected that if it is a proven chromosomal region where chromosome rearrangement has occurred by heavy-ion irradiation, it can be induced even when using genome editing. As a result, 760-kb inversion or deletion was successfully induced by genome editing.

(2) Identification of the plant sex-determining genes and their evolutionary study
A dioecious plant, *Silene latifolia*, has heteromorphic sex chromosomes (X and Y). We previously identified sex changing mutants of *S. latifolia* by heavy-ion mutagenesis. The sex-changing mutants include hermaphroditic mutants and asexual mutants. The formers have both stamens and gynoecium, while the latter have no reproductive organs. By using the deletion status of these mutant lines, we previously developed *S. latifolia* Y chromosome map, which identified the location of both GSF and SPF on the same chromosome arm. By whole-genome analysis and RNA seq analysis, we are now narrowing down the GSF and SPF regions.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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Y. Kazama, K. Ishii, T. Hirano, M. Yamada, S. Ohbu, T. Abe, "Highly efficient induction of chromosomal rearrangement by heavy-ion irradiation in the model plant *Arabidopsis thaliana*," EMBO|EMBL Symposium: Principles of Chromosome Structure and Function, Heidelberg, Germany, September 2018.

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Q. N. Vuong, 風間裕介, 石井公太郎, 大部澄江, 國武久登, 阿部知子, 平野智也, 「シロイヌナズナ大輪変異体リソースにおける花器官サイズ制御機構の解析」, 日本植物学会第 82 回大会, 広島, 2018 年 9 月.

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藤田尚子, 風間裕介, 山岸紀子, 安藤咲, 辻寛之, 吉川信幸, 小松健, 「ウイルスベクターを利用したヒロハノマンテマの遺伝子機能解析系の確立」, 日本植物学会第 82 回大会, 広島, 2018 年 9 月.

Accelerator Applications Research Division
RI Application Research Group

1. Abstract

RI Application Research Group promotes industrial applications of radioisotopes (RI) and ion beams at RIKEN RI Beam Factory (RIBF). Nuclear Chemistry Research Team develops production technologies of useful RIs for application studies in nuclear and radiochemistry. The team also develops technologies of mass spectrometry for trace-element and isotope analyses and apply them to the research fields such as cosmochemistry, environmental science, archaeology and so on. Industrial Application Research Team promotes industrial applications of the accelerator facility and its related technologies.

2. Major Research Subjects

(1) Research and development of RI production technologies at RIBF
(2) RI application researches
(3) Development of trace element analyses using accelerator techniques and its application to geoscience and archaeological research fields
(4) Development of chemical materials for ECR ion sources of the RIBF accelerators
(5) Development of technologies on industrial utilization and novel industrial applications of RIBF
(6) Support of industrial utilization of the heavy-ion beams at RIBF
(7) Support of some materials science experiments
(8) Fee-based distribution of RIs produced at RIBF

3. Summary of Research Activity

See the subsections of Nuclear Chemistry Research Team and Industrial Application Research Team.

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List of Publications & Presentations

See the subsections of Nuclear Chemistry Research Team and Industrial Application Research Team.

Accelerator Applications Research Division
RI Application Research Group
Nuclear Chemistry Research Team

1. Abstract

The Nuclear Chemistry Research Team develops production technologies of radioisotopes (RIs) at RIKEN RI Beam Factory (RIBF) for application studies in the fields of physics, chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences. We use the RIs mainly for nuclear and radiochemical studies such as RI production and superheavy element chemistry. The purified RIs such as ^{65}Zn, ^{67}Cu, ^{85}Sr, ^{88}Y, and ^{109}Cd are delivered to universities and institutes through Japan Radioisotope Association. We also develop new technologies of mass spectrometry for the trace-element analyses using accelerator technology and apply them to the research fields such as cosmochemistry, environmental science, archaeology and so on. We perform various isotopic analyses on the elements such as S, Pd, and Pb using ICP-MS, TIMS, IRMS, and so on. We also develop chemical materials for ECR ion sources of the heavy-ion accelerators at RIBF.

2. Major Research Subjects

(1) Research and development of RI production technologies at RIBF
(2) RI application researches
(3) Development of trace element analyses using accelerator techniques and its application to geoscience and archaeological research fields
(4) Development of chemical materials for ECR ion sources of the heavy-ion accelerators at RIBF

3. Summary of Research Activity

(1) Research and development of RI production technologies at RIBF and RI application researches

Due to its high sensitivity, the radioactive tracer technique has been successfully applied for investigations of the behavior of elements in the fields of chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences. We have been developing production technologies of useful radiotracers at RIBF and conducting their application studies in collaboration with many researchers in various fields. With 14-MeV proton, 24-MeV deuteron, and 50-MeV alpha beams from the AVF cyclotron, we presently produce about 50 radiotracers from ^{7}Be to ^{211}At. Among them, ^{65}Zn, ^{67}Cu, ^{85}Sr, ^{88}Y, and ^{109}Cd are delivered to Japan Radioisotope Association for fee-based distribution to the general public in Japan. Our RIs are also distributed to researchers under the Supply Platform of Short-lived Radioisotopes for Fundamental Research, supported by MEXT KAKENHI. On the other hand, radionuclides of a large number of elements are simultaneously produced from metallic targets such as ^{nat}Ti, ^{nat}Ag, ^{nat}Hf, and ^{197}Au irradiated with a 135-MeV/nucleon ^{14}N beam from the RIKEN Ring Cyclotron. These multitracers are also supplied to universities and institutes as collaborative researches.

In 2018, we developed production technologies of radioisotopes such as ^{24}Na, ^{42,43}K, ^{44m}Sc, ^{74}As, ^{124}Sb, ^{111}Ag, ^{206}Bi, and ^{211}At which were strongly demanded but lack supply sources in Japan. We also investigated the excitation functions for the ^{nat}Zn(d,x), ^{89}Y(d,x), ^{93}Nb(d,x), ^{nat}Pd(d,x), ^{159}Tb(d,x), ^{nat}Er(d,x), ^{nat}Ni(α,x), ^{169}Tm(α,x), and ^{nat}W(α,x) reactions to quantitatively produce useful RIs. We used radiotracers of ^{206}Bi and ^{211}At for application studies in chemistry, ^{24}Na, ^{42,43}K, ^{44m}Sc, ^{67}Cu, and ^{211}At in nuclear medicine. We also produced ^{65}Zn and ^{88}Y for our scientific researches on a regular schedule and supplied the surpluses through Japan Radioisotope Association to the general public. In 2018, we accepted 3 orders of ^{65}Zn with a total activity of 9.7 MBq and 2 orders of ^{88}Y with 2 MBq. We also distributed ^{44m}Sc (10 MBq $\times$ 1), ^{88}Zr (1 MBq $\times$ 1 and 2 MBq $\times$ 3), ^{95}Nb (2 MBq $\times$ 3), ^{121m}Te (2 MBq $\times$ 2), ^{124}Sb (2 MBq $\times$ 1), ^{175}Hf (1 MBq $\times$ 1 and 2 MBq $\times$ 1), ^{179}Ta (1 MBq $\times$ 2), and ^{211}At (5 MBq $\times$ 3, 10 MBq $\times$ 2, 40 MBq $\times$ 1, 50 MBq $\times$ 1, 70 MBq $\times$ 1, 80 MBq $\times$ 5, and 100 MBq $\times$ 4) under the Supply Platform of Short-lived Radioisotopes for Fundamental Research.

(2) Superheavy element chemistry

Chemical characterization of newly-discovered superheavy elements (SHEs, atomic numbers $Z \geq 104$) is an extremely interesting and challenging subject in modern nuclear and radiochemistry. We are developing SHE production systems as well as rapid single-atom chemistry apparatuses at RIBF. Using heavy-ion beams from RILAC and AVF, ^{261}Rf (Z = 104), ^{262}Db (Z = 105), ^{265}Sg (Z = 106), and ^{266}Bh (Z = 107) are produced in the ^{248}Cm(^{18}O$,5n$)^{261}Rf, ^{248}Cm(^{19}F$,5n$)^{262}Db, ^{248}Cm(^{22}Ne$,5n$)^{265}Sg, and ^{248}Cm(^{23}Na$,5n$)^{266}Bh reactions, respectively, and their chemical properties are investigated.

We installed a gas-jet transport system to the focal plane of the gas-filled recoil ion separator GARIS at RILAC. This system is a promising approach for exploring new frontiers in SHE chemistry: the background radiations from unwanted products are strongly suppressed, the intense primary heavy-ion beam is absent in the gas-jet chamber, and hence the high gas-jet extraction yield is attained. Furthermore, the beam-free condition makes it possible to investigate new chemical systems. To realize aqueous chemistry studies of Sg and Bh, we have been developing a continuous and rapid solvent extraction apparatus which consists of a continuous dissolution apparatus Membrane DeGasser (MDG), a Flow Solvent Extractor (FSE), and a liquid scintillation detector for α/SF-spectrometry. On the other hand, we have a gas-jet coupled target system and a safety system for a radioactive ^{248}Cm target on the beam line of AVF. In 2018, the distribution coefficients of ^{261}Rf on the anion-exchange resin in the H_2SO_4 system were measured with the AutoMated Batch-type solid-liquid Extraction apparatus for Repetitive experiments of transactinides (AMBER). The co-precipitation behavior of ^{255}No with Sm hydroxide was also investigated with the computer-controlled suction filtration apparatus for the preparation of precipitated samples of heavy elements (CHIN). In 2018, we also produced radiotracers of ^{88}Zr, ^{95}Nb, ^{95m}Tc, ^{175}Hf, ^{177,179}Ta, and

^{183}Re at AVF and conducted model experiments for aqueous chemistry studies on Rf, Db, and Bh.

(3) Development of trace element analyses using accelerator techniques and its application to geoscience and archaeological research fields

We have been developing the ECR Ion Source Mass Spectrometer (ECRIS-MS) for trace element analyses. In 2018, we renovated the detection system of ECRIS-MS and evaluated its sensitivity and mass resolution power. We equipped a laser-ablation system with an ion source and a pre-concentration system to achieve high-resolution analyses for noble gases such as Kr and Xe.

Using the conventional ICP-MS, TIMS, IRMS, and so on, we analyzed sediments such as a ferro-manganese nodule in the Pacific Ocean to elucidate its growth history concerning the environmental changes in the ocean. We also studied Pb and S isotope ratios on cinnabar and asphalt samples from ancient ruins in Japan to elucidate the distribution of goods in the archaic society and to reveal the establishment of the Yamato dynasty in the period from Jomon to Tumulus. In 2018, we improved the sensitivity in the S isotopic analyses using “trapping and focusing” techniques and analyzed pigments of the Roman ruins. We improved the sampling method for the pigments using a S-free adhesive tape. We applied this method to analyze the red-color substances on the artifacts from Kyoden remains from Izumo to show that they were originated from Hokkaido. We also measured Pd isotopic ratios to investigate the ^{107}Pd transmutation.

(4) Development of chemical materials for ECR ion sources of the heavy-ion accelerators at RIBF

In 2018, we prepared metallic ^{238}U rods and $^{238}UO_2$ on a regular schedule for ^{238}U-ion accelerations with the 28-GHz ECR of RILAC II.

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List of Publications & Presentations

Publications

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Accelerator Applications Research Division
RI Application Research Group
Industrial Application Research Team

1. Abstract

Industrial application research team handles non-academic activities at RIBF corresponding mainly to industries.

2. Major Research Subjects

(1) Support of industrial utilization of the RIBF accelerator beam.
(2) Development of technologies related to the industrial utilization and novel industrial applications.
(3) Fee-based distribution of radioisotopes produced at RIKEN AVF Cyclotron.
(4) Development of real-time wear diagnostics of industrial material using RI beams.

3. Summary of Research Activity

(1) Support of Industrial Utilization of RIBF

RNC promote facility-sharing program "Promotion of applications of high-energy heavy ions and RI beams." In this program, RNC opens the old part of the RIBF facility, which includes the AVF cyclotron, RILAC, RIKEN Ring Cyclotron and experimental instruments, to non-academic proposals from users including private companies. The proposals are reviewed by a program advisory committee, industrial PAC (IN-PAC). The proposals which have been approved by the IN-PAC are allocated with beam times and the users pay RIKEN the beam time fee. The intellectual properties obtained by the use of RIBF belong to the users. In order to encourage the use of RIBF by those who are not familiar with utilization of ion beams, the first two beam times of each proposal can be assigned to trial uses which are free of beam time fee.

In June 2018, the eighth IN-PAC met and approved one fee-based proposal from a new private company. In January 2019, IN-PAC reviewed by e-mail one fee-based continuing proposal from a private company and approved it. In July 2018, a fee-based beamtime was performed with a Kr-84 (70 MeV/nucleon) and an Ar-40 (95 MeV/nucleon) beam at the E5A beamline. In December 2018, a fee-based beamtime was performed with a Kr-86 (66 MeV/nucleon) beam at the E3A beamline. The clients used the beam to simulate single-event effects of space-use semiconductors by heavy-ion components of cosmic rays.

(2) Development of technologies related to the industrial utilization and novel industrial applications

We develop technologies to assess and improve the quality of the beam used for the semiconductor irradiations. Before each beam time, we measure the properties of the beam; the dependence of the beam energy on the degrader thickness, the beam LET-distribution at a certain depth of an irradiated sample calculated with the energy-loss code (SRIM), and the relation between the beam flux and the reading of a transmission-type detectors. Since the beam is extracted to the atmosphere and passes through materials, it can be contaminated with secondary nuclides produced by nuclear reactions in the materials. We study the beam impurity using radiochemical measurements and compared the results with simulations by the PHITS code. In 2018, the results were reported at the IEEE international conference and were shared with the clients.

(3) Fee-based distribution of radioisotopes produced at RIKEN AVF Cyclotron

We have been handling fee-based distribution of radioisotopes since 2007. The radionuclides are Zn-65 ($T_{1/2}$ = 244 days), Cd-109 (463 days), Y-88 (107 days) and Sr-85 (65 days) which are produced at the AVF cyclotron by the nuclear chemistry research team. According to a material transfer agreement (MTA) drawn between Japan Radioisotope Association (JRIA) and RIKEN, JRIA mediates the transaction of the RIs and distributes them to users. Details can be found on the online ordering system J-RAM home page of JRIA.

In 2018, we started distribution of new RI Cu-67 (62 hours). We delivered one shipment of Cu-67 with an activity of 5 MBq, 3 shipments of Zn-65 with a total activity of 9 MBq and 3 shipments of Y-88 with an activity of 3 MBq. The final recipients of the RIs are universities, research institutes and medical research centers.

(4) Development of real-time wear diagnostics of industrial material using RI beams

We are developing a method to determine the spatial distribution of gamma-ray emitting RIs on periodically-moving objects, named "GIRO" (Gamma-ray Inspection of Rotating Object), that is based on the same principle as the medical PET imaging but is simpler and less expensive. Two pairs of detectors were employed to obtain 3D image data. We also performed single-photon emission computer tomography (SPECT) mode measurement. GIRO can obtain SPECT-mode data together with PET-mode data. This method can be used for real-time inspection of a closed system in a running machine. In 2018, we are developing a portable size GIRO system in order to bring and demonstrate it for private companies.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

A. Yoshida, 「21.5.1 RI ビ-ムによるリアルタイム摩耗試験」, 日本加速器学会著 加速器ハンドブック 21 章暮らしに役立つ加速器技術 21.5 化学工業・工業技術, 丸善出版 2018 年 4 月, ISBN 978-4-621-08901-9.

T. Kambara, A. Yoshida, "Facility for Heavy-Ion Irradiation of Semiconductors at RIKEN RI-Beam Factory," 2018 IEEE Radiation Effects Data Workshop (REDW) Workshop Record, pg.94, DOI: 10.1109/NSREC.2018.8584278.

Oral Presentations

[International Conference etc.]

A. Yoshida, "Wear diagnostics using low-energy RIBs and their γ-ray imaging," Technical Meeting on Novel Multidisciplinary Applications with Unstable Ion Beams and Complementary Techniques, International Atomic Energy Agency (IAEA), Wien Austria, December 10–14, 2018.

Posters Presentations

[International Conference etc.]

T. Kambara, A. Yoshida, "Facility for heavy-ion irradiation of semiconductors at RIKEN RI-Beam Factory," 2018 IEEE Radiation Effects Data Workshop (REDW) Workshop, July 19, 2018.

Patents

A. Yoshida, T. Kambara, R. Uemoto, A. Nagano, H. Uno, N. Takahashi, "Wear diagnostics method and instrument," 2015-1490 patent applied.

T. Kambara, A. Yoshida, H. Takeichi, "Gamma-ray measurement method and instrument," 2014-034417, patent registered.

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1. Abstract

Atomic nuclei are made of protons and neutrons bound by the exchange of pion and other mesons. Also, protons and neutrons are made of quarks bound by the exchange of gluons. These strong interactions are governed by the non-Abelian gauge theory called the quantum chromodynamics (QCD). On the basis of theoretical and numerical analyses of QCD, we study the interactions between the nucleons, properties of the dense quark matter realized at the center of neutron stars, and properties of the hot quark-gluon plasma realized in the early Universe. Strong correlations common in QCD and cold atoms are also studied theoretically to unravel the universal features of the strongly interacting many-body systems. Developing perturbative and non-perturbative techniques in quantum field theory and string theory are of great importance not only to solve gauge theories such as QED and QCD, but also to find the theories beyond the standard model of elementary particles. Various theoretical approaches along this line have been attempted.

2. Major Research Subjects

(1) Perturbative and non-perturbative methods in quantum field theories
(2) Theory of spontaneous symmetry breaking
(3) Lattice gauge theory
(4) QCD under extreme conditions
(5) Nuclear and atomic many-body problems

3. Summary of Research Activity

(1) Perturbative and non-perturbative methods in quantum field theories

(1-1) 10^{th} order QED calculation and the lepton anomalous magnetic moments

First preliminary value of the tenth-order QED contribution to the electron anomalous magnetic moment $a_e = (g-2)/2$ was reported by us in 2012. Since then, we have been improving and establishing its accuracy: We reevaluated the most difficult and large set of the Feynman diagrams by using advanced techniques of numerical calculation especially suitable to RIKEN's supercomputer. As a result, we have obtained precise values for the eighth- and tenth-order terms. Assuming the validity of the standard model, it leads to the world-best value of the fine-structure constant $\alpha^{-1}(a_e) = 137.035\,999\,1570(29)(27)(18)(331)$, where uncertainties are from the eighth-order term, tenth-order term, hadronic and electroweak terms, and the experimental measurement of a_e. This is the most precise value of α available at present in the world and provides a stringent constraint on possible theories beyond the standard model.

(1-2) Picard-Lefschetz theory and the sign problem

Understanding strongly-correlated quantum field theories and many-body systems has been one of the ultimate goals in contemporary physics. Exact diagonalization of a Hamiltonian provides us with complete information on the system; however, it usually requires the huge computational cost and is limited to small systems. For large systems, numerical simulation on discretized space-time lattice with quantum Monte Carlo method is a powerful ab initio tool based on the importance sampling. In many quantum systems of great interest, however, it suffers from the so-called sign problem; large cancellation occurs between positive and negative quantities to obtain physical signals, so that the computational time grows exponentially with the system size. So far, many attempts have been proposed overcome the sign problem, which include the two promising candidates, the complex Langevin method and the Lefschetz-thimble method. In particular, the Lefschetz-thimble approach is a generalization of the steepest descent method for multiple oscillatory integrals. In the past few years, we have studied extensively the mathematical basis of the Lefschetz-thimble method as well as its practical applications to quantum systems such as the real-time path integral for quantum tunneling, zero-dimensional bosonic and fermionic models, the one-site Hubbard model, and Polyakov-loop effective models for QCD. We have shown that the interference among multiple Lefschetz thimbles is important to reproduce the general non-analytic behavior of the observables as a function of the external parameter. Such an interference is a key to understand the sign problem of finite-density QCD.

(1-3) Functional renormalization group

- BEC-BCS crossover in cold fermionic atoms

We have developed a fermionic functional renormalization group (FRG) and applied this method to describe the superfluid phase transition of the two-component fermionic system with an attractive contact interaction. The connection between the fermionic FRG approach and the conventional Bardeen-Cooper-Schrieffer (BCS) theory with Gorkov and Melik-Barkhudarov (GMB) correction was clarified in the weak coupling region by using the renormalization group flow of the fermionic four-point vertex with particle-particle and particle-hole scatterings. To go beyond the BCS + GMB theory, coupled FRG flow equations of the fermion self-energy and the four-point vertex are studied under an Ansatz concerning their frequency/momentum dependence. We found that the fermion self-energy turns out to be substantial even in the weak coupling regime, and the frequency dependence of the four-point vertex is essential to obtain the correct asymptotic-ultraviolet behavior of the flow for the self-energy. The superfluid transition temperature and the associated chemical potential were evaluated in the region of negative scattering lengths.

- Tricritical point of the superconducting transition

The order of the phase transition in the Abelian Higgs model with complex scalar fields became of interest because of the analyses of the spontaneous symmetry breaking due to radiative corrections in 3 + 1 dimensions, and of a superconductor near the critical point with the dimensionally reduced Ginzburg-Landau theory. Indeed, the fluctuations of the gauge field were of great importance and may even turn the second-order transition to first-order at least for strongly type-I superconductors. We analyzed the order of the superconducting phase transition via the functional renormalization group approach: We derived for the first time fully analytic expressions for the β functions of the charge and the self-coupling in the Abelian Higgs model with N-component scalar field in $d = 3$ dimensions. The result supports the existence of two charged fixed-points: an infrared (IR) stable fixed point describing a second-order phase transition and a tricritical fixed point controlling the region of the parameter space that is attracted by the former one. It was found that the region separating first and second-order transitions can be uniquely characterized by the critical Ginzburg-Landau parameter, $\kappa_c \approx 0.62/\sqrt{2}$ for $N = 1$.

- Chiral dynamics under strong magnetic field

The magnetic field is not only interesting as a theoretical probe to the dynamics of QCD, but also important in cosmology and astrophysics: A class of neutron stars called magnetars has a strong surface magnetic field of order 10^{10} T while the primordial magnetic field in early Universe is estimated to be even as large as $\sim 10^{19}$ T. In non-central heavy-ion collisions at RHIC and LHC, a magnetic field of the strength $\sim 10^{15}$ T perpendicular to the reaction plane could be produced and can have impact on the thermodynamics and transport properties of the quark-gluon plasma. We investigated the quark-meson model in a magnetic field using the functional renormalization group equation beyond the local-potential approximation. We considered anisotropic wave function renormalization for mesons in the effective action, which allows us to investigate how the magnetic field distorts the propagation of neutral mesons. We found that the transverse velocity of mesons decreases with the magnetic field at all temperatures. Also, the constituent quark mass is found to increase with magnetic field, resulting in the crossover temperature that increases monotonically with the magnetic field.

(1-4) Emergent spacetime

In quantum field theories, symmetry plays an essential and exceptional role. Focusing on some proper symmetry and delving into its meaning have been proven to be one of the most fruitful strategies. A recent example is the SO(2, 4) symmetry in AdS/CFT correspondence which leads to unexpected connection between gravity and gauge theory defined in different dimensions. We offer another example of quantum field theory where symmetry plays a central role and reveals interesting phenomena: Our focal point is the global conformal symmetry in two dimensional conformal field theory (2d CFT), which is homomorphic to SL(2, R). We have shown that 2d CFT admits a novel quantization which we call dipolar quantization. Usually the study of the quantum field theory starts by defining the spacetime where the field is situated. On the other hand, in our case, we first obtain quantum system and then the nature of spacetime emerges. This is in accordance with the general ideas of emergent spacetime such as those discussed in matrix models.

(2) Theory of spontaneous symmetry breaking

(2-1) Dispersion relations of Nambu-Goldstone modes at finite temperature and density

We clarified the dispersion relations of Nambu-Goldstone (NG) modes associated with spontaneous breaking of internal symmetries at finite temperature and/or density. We showed that the dispersion relations of type-A and type-B NG modes are linear and quadratic in momentum, whose imaginary parts are quadratic and quartic, respectively. In both cases, the real parts of the dispersion relations are larger than the imaginary parts when the momentum is small, so that the NG modes can propagate for long distances. We derived the gap formula for NG modes in the presence of explicit symmetry breaking. We also discussed the gapped partners of type-B NG modes, when type-A and type-B NG modes coexist.

(2-2) Effective field theory for spacetime symmetry breaking

We studied the effective field theory for spacetime symmetry breaking from the local symmetry point of view. By gauging spacetime symmetries, the identification of Nambu-Goldstone (NG) fields and the construction of the effective action were performed based on the breaking pattern of diffeomorphism, local Lorentz, and isotropic Weyl symmetries as well as the internal symmetries including possible central extensions in nonrelativistic systems. Such a local picture provides a correct identification of the physical NG fields, while the standard coset construction based on global symmetry breaking does not. We also revisited the coset construction for spacetime symmetry breaking: Based on the relation between the Maurer-Cartan one-form and connections for spacetime symmetries, we classified the physical meanings of the inverse Higgs constraints by the coordinate dimension of broken symmetries. Inverse Higgs constraints for spacetime symmetries with a higher dimension remove the redundant NG fields, whereas those for dimensionless symmetries can be further classified by the local symmetry breaking pattern.

(2-3) Nambu-Goldstone modes in dissipative systems

Spontaneous symmetry breaking (SSB) in Hamiltonian systems is a universal and widely observed phenomena in nature, *e.g.*, the electroweak and chiral symmetry breakings, superconductors, ferromagnets, solid crystals, and so on. It is also known that the SSB occurs even in dissipative systems such as reaction diffusion system and active matters. The translational symmetry in the reaction diffusion system is spontaneously broken by a spatial pattern formation such as the Turing pattern in biology. The rotational symmetry is spontaneously broken in the active hydrodynamics which describes collective motion of biological organisms. We found that there exist two types of NG modes in dissipative systems corresponding to type-A and type-B NG modes in Hamiltonian systems. By taking the O(N) scalar model obeying a Fokker-Planck equation as an example, we have shown that the type-A NG modes in the dissipative system are diffusive modes, while they are propagating modes in Hamiltonian systems. We pointed out that this difference is caused by the existence of two types of Noether charges, $Q^{\alpha}{}_R$ and $Q^{\alpha}{}_A$: $Q^{\alpha}{}_R$ are symmetry generators of Hamiltonian systems, which are not generally conserved in dissipative systems. $Q^{\alpha}{}_A$ are symmetry generators of dissipative systems described by the Fokker-Planck equation and are conserved. We found that the NG modes are propagating modes if $Q^{\alpha}{}_R$ are conserved, while those are diffusive modes if they are not conserved.

(3) Lattice gauge theory

(3-1) Hadron interactions from lattice QCD

One of the most important goals in nuclear physics is to determine baryon-baryon interactions directly from QCD. To achieve this goal, the HAL QCD Collaboration has been developing a novel lattice QCD formulation (HAL QCD method) and performing first-principles numerical simulations. We have calculated the spin-orbit forces for the first time from QCD by the HAL QCD method, and have observed the attraction in the $^3P_2$ channel related to the P-wave neutron superfluidity in neutron star cores. Our calculation of the N-Ω interaction shows that this system is bound in the $^5S_2$ channel. We have shown that the Ω-Ω interaction in the spin-singlet channel is in the unitary region where the scattering length becomes large. Three-nucleon forces have been calculated for several heavy quark masses. Our lattice calculations was extended to the heavy quark systems, *e.g.* the exotic tetraquark, T_{cc} and T_{cs}. Properties of the light and medium-heavy nuclei (^{4}He, ^{16}O, ^{40}Ca) have been calculated by combining the nuclear many-body techniques and the nuclear forces obtained from lattice QCD. Also, we have theoretically and numerically shown that the Luscher's method traditionally used in studying the hadron-hadron interactions does not lead to physical results for baryon-baryon interactions unless the lattice volume is unrealistically large, so that the HAL QCD method is the only reliable approach to link QCD to nuclear physics.

As a part of the High Performance Computing Infrastructure (HPCI) Project 5, we have completed the generation of $(2+1)$-flavor full QCD configurations with a large box, $V = (8\ \mathrm{fm})^3$, and with nearly physical pion mass, 145 MeV, on the 10 Pflops super computer "K." We are currently in the process of calculations of baryon-baryon interactions using these configurations.

(3-2) Momenta and Angular Momenta of Quarks and Gluons inside the Nucleon

Determining the quark and gluon contributions to the spin of the nucleon is one of the most challenging problems in QCD both experimentally and theoretically. Since the quark spin is found to be small (~ 25% of the total proton spin) from the global analysis of deep inelastic scattering data, it is expected that the rest should come from the gluon spin and the orbital angular momenta of quarks and gluons. We made state-of-the-art calculations (with both connected and disconnected insertions) of the momenta and the angular momenta of quarks and gluons inside the proton. The u and d quark momentum/angular momentum fraction extrapolated to the physical point is found to be 0.64(5)/0.70(5), while the strange quark momentum/angular momentum fraction is 0.024(6)/0.023(7), and that of the gluon is 0.33(6)/0.28(8). This implies that the quark spin carries a fraction of 0.25(12) of the proton spin. Also, we found that the quark orbital angular momentum, which turned out to be dominated by the disconnected insertions, constitutes 0.47(13) of the proton spin.

(4) QCD under extreme conditions

(4-1) Production and Elliptic Flow of Dileptons and Photons in the semi-Quark Gluon Plasma

A notable property of peripheral heavy-ion collisions at RHIC and LHC is the elliptic flow which is a measure of the transfer of initial spatial anisotropy to momentum anisotropy. Both the PHENIX experiment at RHIC and the ALICE experiment at LHC have announced a puzzling observation; a large elliptic flow for photons, comparable to that of hadrons. We considered the thermal production of dileptons and photons at temperatures above the QCD critical temperature (T_c) on the basis of semi-QGP, a theoretical model for describing the quark-gluon plasma (QGP) near T_c. With realistic hydrodynamic simulations, we have shown that the strong suppression of photons in semi-QGP due to the inhibition of colored excitations tends to bias the elliptical flow of photons to that generated in the hadronic phase. This increases the total elliptic flow for thermal photons significantly towards the experimental data.

(4-2) Deriving relativistic hydrodynamics from quantum field theory

Hydrodynamics describes the spacetime evolution of conserved quantities, such the energy, the momentum, and the particle number. It does not depend on microscopic details of the system, so that it can be applied to many branches of physics from condensed matter to high-energy physics. One of the illuminating examples is the recent success of relativistic hydrodynamics in describing the evolution of QGP created in heavy-ion collisions. Inspired by the phenomenological success of relativistic hydrodynamics in describing QGP, theoretical derivations of the relativistic hydrodynamics have been attempted on the basis of the kinetic theory, the fluid/gravity correspondence, the non-equilibrium thermodynamics, and the projection operator method. In our study, a most microscopic and non-perturbative derivation of the relativistic hydrodynamics from quantum field theory was given on basis of the density operator with local Gibbs distribution at initial time. Performing the path-integral formulation of the local Gibbs distribution, we derived the generating functional for the non-dissipative hydrodynamics microscopically. Moreover, we formulated a procedure to evaluate dissipative corrections.

(4-3) Hadron-quark crossover in cold and hot neutron stars

We studied bulk properties of cold and hot neutron stars (NS) on the basis of the hadron-quark crossover picture where a smooth transition from the hadronic phase to the quark phase takes place at finite baryon density. By using a phenomenological equation of state (EOS) "CRover" which interpolates the two phases at around 3 times the nuclear matter density (ρ_0), it is found that the cold NSs with the gravitational mass larger than two solar mass can be sustained. This is in sharp contrast to the case of the first-order hadron-quark transition. The radii of the cold NSs with the CRover EOS are in the narrow range (12.5 ± 0.5) km which is insensitive to the NS masses. Due to the stiffening of the EOS induced by the hadron-quark crossover, the central density of the NSs is at most $4\rho_0$ and the hyperon-mixing barely occurs inside the NS core. This constitutes a solution of the long-standing hyperon puzzle first pointed out by Takatsuka *et al*. The effect of color superconductivity (CSC) on the NS structures was also examined with the hadron-quark crossover picture. For the typical strength of the diquark attraction, a slight softening of the EOS due to two-flavor CSC takes place and the maximum mass is reduced by about 0.2 solar mass. The CRover EOS is generalized to the supernova matter at finite temperature to describe the hot NSs at birth. The hadron-quark crossover was found to decrease the central temperature of the hot NSs under isentropic condition. The gravitational energy release and the spin-up rate during the contraction from the hot NS to the cold NS were also estimated.

(5) Nuclear and atomic many-body problems

(5-1) Giant dipole resonance in hot nuclei

Over the last several decades, extensive experimental and theoretical works have been done on the giant dipole resonance (GDR) in excited nuclei covering a wide range of temperature (T), angular momentum (J) and nuclear mass. A reasonable stability of the GDR centroid energy and an increase of the GDR width with T (in the range ∼1–3 MeV) and J are the two well-established results. Some experiments have indicated the saturation of the GDR width at high T: The gradual disappearance of the GDR vibration at much higher T has been observed. Experiments on the Jacobi transition and the GDR built on superdeformed shapes at high rotational frequencies have been reported in a few cases. We have demonstrated that thermal pairing included in the phonon damping model (PDM) is responsible for the nearly constant width of GDR at low temperature $T < 1$ MeV. We have also shown that the enhancement observed in the recent experimentally extracted nuclear level densities in ^{104}Pd at low excitation energy and various angular momenta is the first experimental evidence of the pairing reentrance in finite (hot rotating) nuclei. The results of calculations within the PDM were found in excellent agreement with the latest experimental data of GDR in the compound nucleus ^{88}Mo.

(5-2) Hidden pseudospin symmetries and their origins in atomic nuclei

The quasi-degeneracy between single-particle orbitals, (n, l, $j = l+1/2$) and ($n-1$, $l+2$, $j = l+3/2$), indicates a hidden symmetry in atomic nuclei, the so-called pseudospin symmetry (PSS). Since the introduction of the concept of PSS in atomic nuclei, there have been comprehensive efforts to understand its origin. Both splittings of spin doublets and pseudospin doublets play critical roles in the evolution of magic numbers in exotic nuclei discovered by modern spectroscopic studies with radioactive ion beam facilities. Since the PSS was recognized as a relativistic symmetry in 1990s, many special features, including the spin symmetry (SS) for anti-nucleon, and other new concepts have been introduced. We have published a comprehensive review article (Liang *et al*., Phys. Rept. 2015) on the PSS and SS in various systems, including extensions of the PSS study from stable to exotic nuclei, from non-confining to confining potentials, from local to non-local potentials, from central to tensor potentials, from bound to resonant states, from nucleon to anti-nucleon spectra, from nucleon to hyperon spectra, and from spherical to deformed nuclei. We also summarized open issues in this field, including the perturbative nature, the supersymmetric representation with similarity renormalization group, and the puzzle of intruder states.

(5-3) Efimov Physics in cold atoms

For ultra-cold atoms and atomic nuclei, the pairwise interaction can be resonant. Then, universal few-body phenomena such as the Efimov effect may take place. We carried out an exploratory study suggesting that the Efimov effect can induce stable many-body ground states whose building blocks are universal clusters. We identified a range of parameters in a mass and density imbalanced two-species fermionic mixture for which the ground state is a gas of Efimov-related universal trimers. An explicit calculation of the trimer-trimer interaction reveals that the trimer phase is an SU(3) Fermi liquid stable against recombination losses. We proposed to experimentally observe this phase in a fermionic mixture of ^{6}Li-^{53}Cr atoms. We have also written a comprehensive review article on theoretical and experimental advances in Efimov physics.

(5-4) Supersymmetric Bose-Fermi mixtures

Some special Bose-Fermi mixtures of cold atoms and molecules in optical lattices could be prepared in such a way as they exhibit approximate supersymmetry under the interchange of bosons and fermions. Since supersymmetry is broken at finite temperature and/or density, an analog of the Nambu-Goldstone excitation, dubbed the "Goldstino," should appear. We evaluated the spectral properties of the Goldstino in a Bose-Fermi mixture of cold atoms and molecules. We derived model independent results from sum rules obeyed by the spectral function. Also, by carrying out specific calculations with random phase approximation, analytic formula for the dispersion relation of Goldstino at small momentum was obtained.

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1. Abstract

We proposed accurate calculation method called 'Gaussian Expansion Method using infinitesimally shifted Gaussian lobe basis function.' When one proceeds to four-body systems, calculation of the Hamiltonian matrix elements becomes much laborious. In order to make the four-body calculation tractable even for complicated interactions, the infinitesimally-shifted Gaussian lobe basis function has been proposed. The GEM with the technique of infinitesimally-shifted Gaussians has been applied to various three-, four- and five-body calculations in hypernuclei, the four-nucleon systems, and cold-atom systems. As results, we succeeded in extracting new understandings in various fields.

2. Major Research Subjects

(1) Hypernuclear structure from the view point of few-body problem
(2) Structure of exotic hadron system
(3) quantum atomic system and ultra cold atomic system
(4) Equation of state for neutron star

3. Summary of Research Activity

(1) To investigate the effect of $T = 3/2$ three-body force, we have studied super heavy hydrogen system, ^{5}H as a five-body system. In this calculation, we employ several realistic forces and calculate resonant state. As a result, without $T = 3/2$ three-body force, we reproduce the experimental data.
(2) Motivated by observed data of pentaquark system by LHCb, we studied this system as a five-boy system within the framework of non-relativistic constituent quark model. It was difficult to describe the experimental data. It would be indicated that the observed state should be meson-baryon resonant state which we are not able to calculate with the present framework.
(3) We calculate $^{9}_{\Lambda}$Be within the framework of $\alpha\alpha\Lambda$ three-body model. We obtain many resonant states above $^{5}_{\Lambda}$He + α threshold. Furthermore, we categorized ^{8}Be analog, genuine hypernuclear analog, and ^{9}Be analog which are consistent with past calculation by Motoba *et al*.

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List of Publications & Presentations

Publications

[Book]

K. U. Can, "*Electromagnetic Form Factors of Charmed Baryons in Lattice QCD, Springer Theses Series*," (Springer, Singapore, 2018).

[Journal]

(Original Papers) *Subject to Peer Review

E. Hiyama, K. Nakazawa, "Structre of $S = -2$ hypernuclei and hyperon-hyperon interaction," Annual Review of Nuclear and Particle Science and Particle Science **68** (2018).

Y. Shimizu, Y. Yamaguchi, M. Harada, "Heavy quark spin multiplet structure of $\bar{P}^{(*)}\Sigma_Q^{(*)}$ molecular states," Phy. Rev. D **98**, 014021 (2018).

E. Hiyama, M. Kamimura, "Study of various few-body systems using Gaussian expansion method (GEM)," Frontiers of Physics **13**, (2018).

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U. Yakhshiev, H. C. Kim, E. Hiyama, "Instanton effects on charmonium states," Phy. Rev. D **98**, 114036 (2018).

H. Bahtiyar, K. U. Can, G. Erkol, M. Oka, T. T. Takahashi, "Radiative transitions of doubly charmed baryons in lattice QCD," Phy. Rev. D **98**, 114505 (2018).

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Y. Yamaguchi, "Spin degeneracy of Hadronic molecules in the heavy quark region," J. Phys. Conf. Ser. **981**, 012015 (2018).

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[International Conference etc.]

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E. Hiyama, "Recent progress of few-body problems in Physics," International Conference on Simplicity, Symmetry and Beauty of Atomic Nuclei, Shanghai, China, September 2018.

E. Hiyama, "Recent progress of hypernuclear physics," 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, October 2018.

E. Hiyama, "Structure of light hypernuclei," International workshop on Universal Physics In Many-Body Quantum Systems—From Atoms to Quarks—, Tokai, Ibaraki, December 2018.

E. Hiyama, "Future Prospect In hypernuclear physics using HIAF," International workshop on "HIAF High-Energy Beam Line Physics and Nuclear Astrophysics," Beijing, China, December 2018.

E. Hiyama, "Structure of light s-shell Ξ hypernuclei," 57th International Winter meeting on Nuclear physics, Bormio, Italy, January 2019.

E. Hiyama, "Five-body structure of pentaquark," Korea-Japan Joint Workshop on the Present and Future in Hadron Physics at J-PARC, Busan, Korea March, 2019.

H. Togashi, E. Hiyama, M. Takano, “Hyperon equation of state for core-collapse simulations based on the variational many-body theory,” HYP2018, Norfolk, USA, June 2018.

H. Togashi, K. Nakazato, Y. Takehara, S. Yamamuro, H. Suzuki, M. Takano, “Supernova equation of state and symmetry energy at sub-nuclear densities,” 8th International Symposium on Nuclear Symmetry Energy (NuSYM2018), Busan, Korea, September 2018. (招待講演)

H. Togashi, “Systematic study of nuclear equations of state in core-collapse supernovae,” Deciphering Multi-dimensional Nature of Core-collapse Supernovae via Gravitational-wave and Neutrino Signatures (SNeGWν2018), Toyama, Japan, October 2018.

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Y. Yamaguchi, “$\pi J/\psi$-$D\bar{D}^*$ potential described by the quark exchange diagram,” The XXIVth International Baldin Seminar on High Energy Physics Problems, Dubna, Russia, September 2018.

Y. Yamaguchi, “Short range $\pi J/\psi$-$D\bar{D}^*$ potential by the constituent quark model,” Workshop on Dense Matter from Chiral Effective Theories 2018, Nagoya, Japan, October 2018.

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Y. Yamaguchi, “Short range $\pi J/\psi$-$D\bar{D}^*$ potential,” International workshop on Hadron structure and interaction in dense matter, Tokai, Ibaraki, November 2018.

Y. Yamaguchi, “Short-range meson-meson interaction in the hidden-charm sector,” International workshop: Clusters in quantum systems: from atoms to nuclei and hadrons, Sendai, Japan, January, 2019.

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E. Hiyama, “Gaussian Expansion Method and itsapplication to nuclear physics,” RIKEN-YCU Joint Workshop, Wako, Japan, April 2018.

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富樫甫, 肥山詠美子, 鷹野正利, 「バリオン間相互作用に基づく核物質の状態方程式と天体物理への応用」, 研究会「重力波観測時代の r プロセスと不安定核」, 和光市, 2018 年 6 月.

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Awards

富樫甫, 平成 30 年度理化学研究所桜舞賞研究奨励賞, 2019 年 3 月.

富樫甫, 2018 年度基礎科学・国際特別研究員研究成果発表会ポスター賞（物理学 I 分野）, 2019 年 1 月.

Subnuclear System Research Division
Radiation Laboratory

1. Abstract

Nucleons, such as protons and neutrons, are a bound state of constituent quarks glued together with gluons. The detail structure of nucleons, however, is not well understood yet. Especially the mechanism to build up the spin of proton, which is 1/2, is a major problem in physics of the strong force. The research goal of Radiation Laboratory is to solve this fundamental question using the world first polarized-proton collider, realized at RHIC in Brookhaven National Laboratory (BNL) in USA. RHIC stands for Relativistic Heavy Ion Collider, aiming also to create Quark Gluon Plasma, the state of Universe just after the Big Bang, and study its property. RIKEN-BNL Research Center (RBRC) directed by S. Aronson carries our core team at BNL for those exciting researches using the PHENIX detector. We have observed that the proton spin carried by gluons is finite and indeed sizable. We also identified W bosons in the electron/positron decay channel and in the muon decay channel, with which we are about to conclude how much anti-quarks carry the proton spin. Other than the activities at RHIC we are preparing and starting new experiments at J-PARC and Fermilab to study the nature of hadron. We are also performing technical developments such as novel ion sources, fine-pitch silicon pixel detectors and high-performance trigger electronics.

2. Major Research Subjects

(1) Spin physics with relativistic polarized-proton collisions at RHIC
(2) Study of nuclear matter at high temperature and/or at high density
(3) Technical developments on radiation detectors and accelerators

3. Summary of Research Activity

(1) Experimental study of spin structure of proton using RHIC polarized proton collider

[See also RIKEN-BNL Research Center Experimental Group for the activities at BNL]

The previously published central neutral pion double spin asymmetries at the highest collision energies at RHIC of 510 GeV have been augmented with the release of charged pion double spin asymmetries in 2017 by PHENIX and are currently being prepared for publication. The ordering of the three pion asymmetries allows a direct determination of the sign of the gluon polarization which has been found to be nonzero. With the valence quark spin contribution already reasonably well known, the contributions from sea quarks and orbital angular momenta remain to be understood. PHENIX has collected data to access the sea quark polarizations via leptonic decays of W bosons. In 2018, the world's only forward and backward W boson single spin asymmetries have been published, thus completing the publication of all W related measurements of PHENIX.

While orbital angular momentum cannot be directly accessed at RHIC, several transverse spin phenomena have been observed which relate to orbital angular momentum and the three-dimensional structure of the nucleon. These phenomena by themselves have become a major field of research as the dynamics of the strong interaction. During the 2015 RHIC operation, collisions of transversely polarized protons with Au and Al nuclei were provided for the first time. Two rather surprising results have been discovered here. First, the single transverse spin asymmetries for J/ψ particles which are found to be consistent with zero to even higher precisions, show distinctly nonzero asymmetries in proton-Au collisions at the lowest transverse momenta both if detected at slightly forward or backward regions with respect to the polarized beam. The mechanism for such a behavior is not known and the publication of these results in 2018 has stimulated substantial theoretical discussions to understand these findings. Also charged hadron single spin asymmetries have been observed in all three colliding systems. While a previously known nonzero forward asymmetry for positive hadrons was confirmed, a substantial reduction of these asymmetries for p + Al and p + Au collisions was observed. Such a reduction was predicted by several theoretical models describing the non-linear effects of high gluon densities in nuclei suggested by the so-called color-glass-condensate. While the kinematic region does not reach into the range where the color-glass-condensate is expected, this reduction in asymmetries has been met with interest by the theory community. The results have been submitted to publication for positive hadrons and a more detailed publication is prepared including the negative hadrons.

In June of 2017, we installed an electro-magnetic calorimeter in the most forward area of the STAR experiment and took polarized proton collision data for neutral particle production (neutron, photon, neutral pion). The cross-section measurement will give us new inputs to develop high-energy particle-collision models which are essential to understand air-shower from ultra-high energy cosmic rays. The asymmetry measurement will enable us to understand the hadron collision mechanism based on QCD. An unexpectedly large neutral pion asymmetry has been found using this data that may connect to the large pion asymmetries at smaller rapidities and higher transverse momenta. The preliminary results are currently being prepared for publication. Some of us are participating in the Fermilab SeaQuest experiment as a pilot measurement of muon pairs from Drell-Yan process using a 120-GeV unpolarized proton at Fermilab. After finishing unpolarized measurements in 2017 to study the quark spin-orbit effect, a new measurement with a polarized proton target will start in 2019 to study the sea-quark orbit effect of the polarized proton in the target.

For many jet related measurements fragmentation functions are necessary to gain spin and or flavor sensitivity. Those are currently extracted by some of us using the Belle data. In addition to using the fragmentation results with RHIC measurements, they will also provide the basis for most of the key measurements to be performed at the electron-ion collider. In 2018, transverse momentum dependent cross sections of pions, kaons and protons were extracted as a function of fractional energy and event topology. These measurements relate to essentially all transverse spin or momentum dependent measurements at RHIC, semi-inclusive DIS and the EIC.

(2) Experimental study of quark-gluon plasma using RHIC heavy ion collider

[See also RIKEN-BNL Research Center Experimental Group for the activities at BNL]

We have completed several key measurements in the study of quark-gluon plasma at RHIC. As the top of them, we lead the analysis of the first thermal photon measurement in heavy ion collisions. The measurement indicates that the initial temperature reached in the central Au + Au collision at 200 GeV is about 350 MeV, far above the expected transition temperature $T_c \sim 170$ MeV, from hadronic phase to quark-gluon plasma. This work was rewarded by Nishina Memorial Prize given to Y. Akiba in 2011. We also measured direct photons in d + Au and direct photon flow strength v_2 and v_3 in Au + Au.

We lead measurement of heavy quark (charm and bottom) using VTX, a 4-layer silicon vertex tracker which we jointly constructed with US DOE. The detector was installed in PHENIX in 2011. PHENIX recorded approximately 10 times more data of Au + Au collisions in the 2014 run than the 2011 run. PHENIX recorded high statistics $p + p$ and p + A data in 2015, and the doubled the Au + Au in 2016. PHENIX concluded its data taking in the 2016 run.

The results of the 2011 run was published in Physical Review C (Phy. Rev. C **93**, 034904 (2016)). This is the first publication from VTX. The result showed that the electrons from bottom quark decay is suppressed for $p_T > 4$ GeV/c, but the suppression factor is smaller than that of charm decay electrons for $3 < p_T < 4$ GeV/c. This is the first observation of bottom electron suppression in heavy ion collisions, and the first result that shows the bottom and charm suppression is different. The results of b → e and c → e measurement in the 2015 $p + p$ run has been published in Phys. Rev. D **99**, 092003 (2019). The centrality dependence of the suppression b → e and c → e from the 2014 Au+Au data will be published soon. Preliminary results of the flow of b → e and c → e was presented in Quark Matter 2018 conference.

In Wako we are operating a cluster computer system (CCJ) specialized to analyze huge data sets taken with the PHENIX detector. It consists of 28 nodes (18 old nodes and 10 new nodes) each of which has two CPUs and 10 sets of local disks for data repository (old node: quad-core CPU, 1 TB disk, new node: six-core CPU, 2 TB disk). There are 264 CPU cores and 380 TB disks in total. This configuration ensures the fastest disk I/O when each job is assigned to the node where the required data sets are stored. It is also important that this scheme doesn't require an expensive RAID system and network. Through this development we have established a fast and cost-effective solution in analyzing massive data.

The data of 0.9 Pbyte obtained by the PHENIX experiment is stored in a hierarchical storage system which is a part of HOKUSAI GreatWave supercomputer system operated by the Advanced Center for Computing and Communication (ACCC). In addition, we operate a dedicated server for the RHICf group and two servers for the J-PARC E16 group, to keep their dedicated compilation and library environments, and some data.

(3) Study of properties of mesons and exotic hadrons with domestic accelerators

Preparation of the experiment E16 at J-PARC Hadron experimental facility is underway with several Grant-in-Aids. This experiment aims to perform a systematic study of the spectral modification of low-mass vector mesons in nuclei to explore the physics of chiral symmetry breaking and restoration in dense nuclear matter, namely, the mechanism proposed by Nambu to generate most of hadron masses.

The Gas Electron Multiplier (GEM) technology is adopted for the two key detectors, GEM Tracker (GTR) and Hadron-blind Cherenkov detector (HBD). To improve electron-identification performance, lead-glass calorimeters (LG) are used in combination with HBD. We are in the production phase. The parts for six modules of GTR, four modules of HBD and six modules of LG are delivered, and their assembly processes have started. Read-out electronics and trigger logic modules were also fabricated and delivered. Development of firmware on the trigger logic modules is on-going. We have been a member of the CERN-RD51 collaboration to acquire the read-out technology for GEM. The current MoU for RD51will be extended for the period of 2019–2023.

Due to the budgetary limitation, we aim to install a part of detectors at the beginning of the experiment, eight modules of GTR/HBD/LG out of 26 modules in the full installation. J-PARC PAC gave us a stage-2 approval on July 2017, to the commissioning run (Run 0), which will be performed when the beam line is completed. Although there is a significant delay from the originally planned date of March 2016, the construction of the beam line by KEK will be completed in the first half of 2020 to perform this experiment with the stage-2 approval. We are preparing the spectrometer toward the Run 0.

(4) Detector development for PHENIX experiment

The PHENIX experiment proposes substantial detector upgrades to go along the expected accelerator improvements, including the future electron-ion collider "eRHIC." The present PHENIX detector is repurposed to the sPHENIX (super PHENIX) detector which reuses the Babar solenoid magnet at SLAC and is covered by the hadronic calorimeter which was not available in the previous RHIC experiments. The sPHENIX project is now funded by DOE, and RIKEN will participate in the construction of the inner silicon tracker (INTT). The R&D of the INTT has been in progress since 2015 and the 2nd generation prototype successfully demonstrated a designed performance through the beam test executed at Fermilab in March 2018. The pre-production model including a full readout chain will be completed after the examination in the 2nd round beam test at Fermilab in June 2019 followed by the final technical review in Summer, 2019.

We have been developing a plan to build a forward spectrometer to be added to the sPHENIX detector. With this addition, the fsPHENIX detector will have both hadronic and electromagnetic calorimetry as well as tracking in the forward rapidity region. This upgrade makes it possible to study forward jets and hadrons in jets which are of vital importance for the cold QCD program in polarized $p + p$ and p + A collisions at RHIC. The fsPHENIX detector can be further upgraded to the ePHENIX detector to be used for electron-ion collisions at eRHIC. We are preparing test bench to perform R&D for the forward hadron calorimeter.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

R. Arnaldi *et al.* (NA60 Collaboration), "Nuclear dependence of light neutral meson production in *p*-A collisions at 400 GeV with NA60," Eur. Phys. J. C **79**, no.5, 443 (2019).

C. Aidala *et al.* (PHENIX Collaboration), "Measurement of charm and bottom production from semileptonic hadron decays in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV," Phy. Rev. D **99**, no.9, 092003 (2019).

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Y. Itow *et al.*, "Recent results from the LHCf and RHICf experiments," EPJ Web Conf. **208**, 05004 (2019).

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I. Nakagawa, "Medium-energy nuclear physics at RHIC with sPHENIX and an sPHENIX forward upgrade," XXVI International Workshop on Deep Inelastic Scattering and related Subjects, 17th, Kobe, Japan, April 2018.

Y. Goto, "Asymmetry measurement of very forward neutral particle production in the RHICf experiment," Diffraction and Low-x 2018, 29th, Reggio Calabria, Italy (Invited), August 2018.

Y. Goto (RHICf collaboration), "Very forward neutral particle measurement in the RHICf experiment," 5th Joint Meeting of the APS Division of Nuclear Physics and the Physics Society of Japan, Hawaii, USA, October 26, 2018.

Y. Goto, "Nucleon structure study at RHIC and EIC," YKIS2018b Symposium on Recent Developments in Quark-Hadron Sciences, 12th, Kyoto, Japan (Invited), June 2018.

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[Domestic Conference]

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Subnuclear System Research Division
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1. Abstract

Particles like muons, pions, and kaons have finite life times, so they do not exist in natural nuclei or matters. By implanting these particles into nuclei/matters, exotic phenomena in various objects can be studied from new point of view.

For example, kaon is the second lightest meson, which has strange quark as a constituent quark. It is expected that if one embeds mesons into nuclei, the sizes of the nuclei become smaller and one can form a high-density object beyond the normal nuclear density. Study of this object could lead to better understanding of the origin of the mass of the matter, and may reveal the quark degree of freedom beyond the quark-confinement. The other example is the weak interaction in nuclear matter. It can only be studied by the weak decay of hypernuclei, which have Lambda particle in the nuclei.

Muon provides even wider scope of studies, covering condensed matter physics as well as nuclear and atomic physics, and we are trying to extend the application field further into chemical and biological studies. For instance, stopping positively charged muon in a material, we obtain information on the magnetic properties or the local field at the muon trapped site (μSR). Injecting negatively charged muon to hydrogen gas, muonic hydrogen atom μp) is formed. We are planning to measure μp hyperfine splitting energy to measure proton magnetic radius, which is complementary quantity to the proton charge radius and its puzzle. We are also interested in precision measurement of muon property itself, such as muon anomalous magnetic moment ($g-2$).

In our research, we introduce different kind of impurities into nuclei/matters, and study new states of matter, new phenomena, or the object properties.

2. Major Research Subjects

(1) Study of meson property and interaction in nuclei
(2) Origin of matter mass/quark degree of freedom in nuclei
(3) Condensed matter and material studies with muon
(4) Nuclear and particle physics studies via muonic hydrogen
(5) Development of ultra cold muon beam, and its application from material science to particle physics

3. Summary of Research Activity

(1) Hadron physics at J-PARC, RIKEN-RIBF, GSI and SPring-8

Kaon and pion will shed a new insight to the nuclear physics. The recent discovery of deeply bound pionic atom enables us to investigate the properties of mesons in nuclear matter. At RIKEN-RIBF, we are preparing precise experimental study of the pionic atom. Very lately, we succeeded to discover kaonic nuclear bound state, "K^-pp," at J-PARC. The yield dependence on momentum-transfer shows that observed system is unexpectedly small. We extended our study on Λ (1405) that could be K^-p bound state. By these experiments, we are studying the $\overline{K}N$ interaction, and clarify the nature of kaon in nuclei. At Spring-8 and at GSI, we are planning to study omega and eta' nuclei. By these experiments, we aim to be a world-leading scientific research group using these light meta-stable particles.

(1-1) Deeply bound kaonic nuclei

J-PARC E15 experiment had been performed to explore the simplest kaonic nuclear bound state, "K^-pp." Because of the strong attraction between $\overline{K}N$, the $\overline{K}$ in nuclei may attract surrounding nucleons, resulting in forming a deeply bound and extremely dense object. Measurement of the kaon properties at such a high density medium will provide precious information on the origin of hadron masses, if the standard scenario of the hadron-mass-generation mechanism, in which the hadron masses are depends on matter density and energy, is correct. Namely, one may study the chiral symmetry breaking of the universe and its partial restoration in nuclear medium.

The E15 experiment was planned to identify the nature of the "K^-pp" bound state by the in-flight ^{3}He(K^-, n) reaction, which allows us to investigate such state both in the formation via the missing-mass spectroscopy using the emitted neutron, and in its decay via the invariant-mass spectroscopy by detecting decay particles from "K^-pp." For the experiment, we constructed a dedicated spectrometer system at the secondary beam-line, K1.8BR, in the hadron hall of J-PARC.

With the Λpn final states obtained in the first stage experiment, we observed a kinematic anomaly in the Λp invariant mass near the mass threshold of M(K^-pp) (total mass of kaon and two protons) at the lower momentum transfer q region. We conducted a successive experiment to examine the nature of the observed kinematical anomaly in the Λpn final state, and we confirmed the existence of the bound state below the mass threshold of $M(K^-pp)$ at as deep as the binding energy of 50 MeV. The momentum transfer q naturally prefers lower momentum for the bound state formation, but the observed event concentration extended as large as ~650 MeV/c. The simplest interpretation based on the PWIA calculation indicates that the observed object could be as small as ~0.5 fm. This observation means that ***a meson ($\overline{q}q$) forms a quantum state where baryons (qqq) exist as nuclear medium***, *i.e.*, a highly excited novel form of nucleus with a kaon, in which ***the mesonic degree-of-freedom still holds***. This is totally new form of nuclear system, which never been observed before.

(1-2) Precision X-ray measurement of kaonic atom

To study the $\overline{K}N$ interaction at zero energy from the atomic state level shift and width of kaon, we have performed an X-ray spectroscopy of atomic $3d \to 2p$ transition of negatively charged K-mesons captured by helium atoms. However, our first experiment is insufficient in energy resolution to see the K^--nucleus potential. Aiming to provide a breakthrough from atomic level observation, we introduce a novel X-ray detector, namely superconducting transition-edge-sensor (TES) microcalorimeter offering unprecedented high energy resolution, being more than one order of magnitude better than that achieved in the past experiments using conventional semiconductor detectors. The experiment J-PARC E62 aims to determine 2*p*-level strong interaction shifts of kaonic ^{3}He and ^{4}He atoms by measuring the atomic $3d \rightarrow 2p$ transition X-rays using TES detector with 240 pixels having about 23 mm^2 effective area and the average energy resolution of 7 eV (FWHM) at 6 keV. We carried out the experiment at J-PARC in June 2018 and successfully observed distinct X-ray peaks from both atoms. The data analysis is now ongoing.

Another important X-ray measurement of kaonic atom would be $2p \rightarrow 1s$ transition of kaonic deuteron (K^{-}-d). We have measured same transition of kaonic hydrogen (K^{-}-p), but the width and shift from electro-magnetic (EM) value reflect only isospin average of the $K^{bar}N$ interaction. We can resolve isospin dependence of the strong interaction by the measurements both for K^{-}-p and K^{-}-d. The experiment J-PARC E57 aims at pioneering measurement of the X-rays from K^{-}-d atoms. Prior to full (stage-2) approval of the E57 proposal, we performed a pilot run with hydrogen target in March 2019.

(1-3) Deeply bound pionic atoms and η' mesonic nuclei

We have been working on precision spectroscopy of pionic atoms systematically, which leads to understanding of the non-trivial structure of the vacuum and the origin of hadron masses. The precision data set stringent constraints on the chiral condensate at nuclear medium. We are presently preparing for the precision systematic measurements at RIBF. A pilot experiment performed in 2010 showed a unprecedented results of pionic atom formation spectra with finite reaction angles. The measurement of pionic ^{121}Sn performed in 2014 showed a very good performance of the system. We have been analyzing the data to achieve information on the pion-nucleus interaction based on the pionic atom spectroscopy.

We are also working on spectroscopy of η' mesonic nuclei in GSI/FAIR. Theoretically, peculiarly large mass of η' is attributed to UA(1) symmetry and chiral symmetry breaking. As a result, large binding energy is expected for η' meson bound states in nuclei (η'-mesonic nuclei). From the measurement, we can access information about gluon dynamics in the vacuum via the binding energy and decay width of η'-nuclear bound state.

(2) Muon science at RIKEN-RAL branch

The research area ranges over particle physics, condensed matter studies, chemistry and life science. Our core activities are based on the RIKEN-RAL Muon Facility located at the Rutherford-Appleton Laboratory (UK), which provides intense pulsed-muon beams. We have variety of important research activities such as particle/nuclear physics studies with muon's spin and condensed matter physics by muon spin rotation/relaxation/resonance (μSR).

(2-1) Condensed matter/materials studies with μSR

To improve our two μSR spectrometers, ARGUS (Port-2) and CHRNUS (Port-4), we adjusted the threshold level of the muon-detector system for the zero-field condition. At this condition, we optimized the efficiency of the detector system and the counting rate was improved nearly 50% without any deformation of the time spectrum.

Among our scientific activities on μSR studies from year 2016 to 2019, following studies are most important subjects of material sciences at the RIKEN-RAL muon facility:

(1) Novel superconducting state having the steeper nodal gaps in the quasi two-dimensional organic superconductor λ-$[BETS]_2GaCl_4$
(2) Tiny magnetic moments and spin structures of Ir^{4+} in hole-doped pyrochlore iridates $Y_{1.95-y}Cu_{0.05}Ca_yIr_2O_7$ and $Eu_{2-x}Ca_xIr_2O_7$
(3) Magnetism and spin structure in superoxide CsO_2, RbO_2 and NaO_2
(4) Magnetic properties of the nano-cluster gold in the border of macro- and micro-scale
(5) Novel magnetic properties of nano-size La-based high-T_c superconducting cuprates
(6) Effects of the spatial distributions of magnetic moments and muon positions estimated from density functional theory (DFT) and dipole-field calculations

(2-2) Nuclear and particle physics studies via ultra-cold muon beam and muonic atoms

If we can improve muon beam emittance, timing and energy dispersion (so-called "ultra-cold muon"), then the capability of μSR studies will be drastically improved. The ultra-cold muon beam can stop in a thin foil, multi-layered materials and artificial lattices, so one can apply the μSR techniques to surface and interface science. The development of ultra-cold muon beam is also very important as the source of pencil-like small emittance muon beam for muon $g-2$ measurement.

We had been working on the R&D of the "ultra-cold muon" generation based on the following technique, namely, positive muon beam with thermal energy has been produced by laser ionization of muoniums in vacuum (bound system of μ^{+} and electron) emitted from the hot tungsten surface by stopping "surface muon beam" at Port-3. However, the muon yield and obtained emittance was far from satisfactory, and remained to be far from any kind of realistic application.

Therefore, in this mid-term, we are developing two key components, high efficiency muonium generator at room temperature and high intensity ionization laser. The study of muonium generator has been done in collaboration with TRIUMF. In 2013, we demonstrated at least 10 times increase of the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. Further study was done in 2017 with more than 20 aerogel target having different surface conditions. We are analyzing the data to identify which condition most contributed to increasing the muonium emission efficiency. We also developed a high power Lyman-α laser in collaboration with laser group at RIKEN. In this laser development, we succeeded to synthesize novel laser crystal Nd:YGAG, which has an ideal wavelength property for laser amplification to generate Lyman-α by four-wave mixing in Kr gas cell. We already achieved 10 times increase of Lyman-α generation than before. While we plan to increase the intensity by one more order, we are suffering from optical inhomogeneity in making a larger size crystal so far. We are developing several schemes to solve this problem.

Concerning the muonic atom, we are planning a new precise measurement of proton radius. A large discrepancy was found recently in the proton charge radius between the new precise value from muonic hydrogen atom at PSI and those from normal hydrogen spectroscopy and e-p scattering. We propose a precise measurement of Zemach radius (with charge and magnetic distributions combined) using the laser spectroscopy of hyperfine splitting energy in the muonic hydrogen atom. Preparation of the hydrogen target, mid-infrared laser and muon spin polarization detectors is in progress. As a key parameter for designing the experiment, we need the quench rate of the muonic proton polarization due to collision with surrounding protons, for which only theoretical estimations are available. We successfully measured the quench rate of muonic deuterium polarization in deuterium gas, which confirmed the long lifetime consistent with the calculation. Measurement for muonic proton is planned in FY2019.

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List of Publications & Presentations

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S. Okada, "Kaonic atom X-ray spectroscopy with transition edge sensors," The 2018 Applied Superconductivity Conference (ASC2018), Seattle, USA, October 28–November 2, 2018.

T. Yamaga, "Results of $\overline{K}NN$ search via the (K^-, n) reaction at J-PARC," The 8th International Conference on Quarks and Nuclear Physics (QNP2018), Tsukuba, Japan, November 13–17, 2018.

S. Kawasaki, "The E31 spectroscopic experiment of $\Lambda(1405)$ via in-flight $d(K^-, n)$ reaction at J-PARC K1.8BR," The 8th International Conference on Quarks and Nuclear Physics (QNP2018), Tsukuba, Japan, November 13–17, 2018.

F. Sakuma, "$\overline{K}$-nuclear bound state at J-PARC," 13th International Conference on Nucleus-Nucleus Collisions (NN2018), Omiya, Saitama, Japan, December 4–8, 2018.

T. Hashimoto, "Kaonic atom experiments at J-PARC," The 8th International Conference on Quarks and Nuclear Physics (QNP2018), Tsukuba, Japan, November 13–17, 2018.

T. Yamaga, "Results of experimental search for $\overline{K}NN$ bound state at J-PARC," Reimei Workshop on Experimental and Theoretical Hadron Physics: Recent Exciting Developments, Tokai, Japan, January 9–11, 2019.

H. Asano, "$\Lambda(1405)$ from $d(K^-, n)$ reaction," Reimei Workshop on Experimental and Theoretical Hadron Physics: Recent Exciting Developments, Tokai, Japan, January 9–11, 2019.

S. Okada, "Kaonic atom x-ray spectroscopy at J-PARC," Reimei Workshop on Experimental and Theoretical Hadron Physics: Recent Exciting Developments, Tokai, Japan, January 9–11, 2019.

K. Ishida, "Proton radius measurement with muonic atoms," International Workshop on the Structure of the Proton, Sagae, Yamagata, February 2019.

S. Kanda, "Development of instruments for the proton radius measurement at RIKEN," International Workshop on the Structure of the Proton, Sagae, Yamagata, February 2019.

K. Itahashi, "Spectroscopy of pionic atoms and deduction of chiral symmetry in nuclear matter," NN2018, Omiya, Saitama, December 2018.

K. Itahashi, "Spectroscopy of meson-nucleus bound states," HIAF Workshop, Beijing, November 2018.

[Domestic Conference]

石田勝彦,「ミュオン原子による陽子半径決定」, 大阪大学理学部物理セミナー, 豊中, 2018 年 8 月.

佐久間史典,「New results on the "K^-pp" bound state from J-PARC 原子核中におけるハドロンの性質とカイラル対称性の役割」, 東北大学電子光理学研究センター, 仙台, 2018 年 9 月.

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神田聡太郎, "Residual polarization and hyperfine transition rate in muonic hydrogen," 新学術領域研究「宇宙観測検出器と量子ビームの出会い. 新たな応用への架け橋」, キックオフシンポジウム, 東北, 2018 年 12 月.

神田聡太郎, "Laser spectroscopy of the hyperfine splitting in muonic hydrogen," 第 9 回 Muon 科学と加速器研究研究会, 大阪, 2019 年 1 月.

石田勝彦,「理研 RAL ミュオン施設」, 第 9 回「Muon 科学と加速器研究」, RCNP, 吹田, 2019 年 1 月.

石田勝彦,「ミュオン水素原子による由志半径測定」, ELPH 研究会 C021「電子散乱による原子核研究—陽子半径, 不安定核の電荷密度分布を中心に—」, 東北大学電子光理学研究センター, 仙台, 2019 年 3 月.

浅野秀光,「J-PARC E31 実験における $\Lambda(1405)$ 生成の運動量移行依存性」, 日本物理学会第 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

O. Zhadyra, "The physics experiment E31 to search for the $\Lambda(1405)$ via the $d(K^-, n)\pi\Sigma$ reaction at J-PARC K1.8BR," 日本物理学会第 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

浅野秀光,「J-PARC E31PARC E31 実験における $\Lambda(1405)$ 生成の運動量移行性」, 日本物理学会第 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

川﨑新吾,「$d(K^-, n)\pi^0\Sigma^0$ 反応による $\Lambda(1405)$ の研究」, 日本物理学会第 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

神田聡太郎,「ミューオン水素原子のレーザー分光に向けたスピン回転実験」, 日本物理学会第 74 回年次大会, 九州大学, 福岡, 2019 年 3 月.

Subnuclear System Research Division
RIKEN BNL Research Center

1. Abstract

The RIKEN BNL Research Center was established in April 1997 at Brookhaven National Laboratory with Professor T. D. Lee of Columbia University as its initial Director. It is funded by the Rikagaku Kenkyusho (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD and RHIC physics through the nurturing of a new generation of young physicists. Professor Lee was succeeded by BNL Distinguished Scientist, N. P. Samios, who served until 2013. Dr. S. H. Aronson led the Center from 2013. After strong and significant leadership for 4 years, S. Aronson stepped down from Director in March 31st 2017. Hideto En'yo succeeds from JFY 2017. Support for RBRC was initially for five years and has been renewed four times, and presently extends to 2023. The Center is located in the BNL Physics Department. The RBRC Theory Group activities are closely and intimately related to those of the Nuclear Theory, High Energy Theory, and Lattice Gauge Theory Groups at BNL. The RBRC Experimental Group works closely with Radiation Laboratory at RIKEN, Wako, the RHIC Spin Group at BNL, the RHIC Spin Physics community, and the PHENIX collaboration. BNL provides office space, management, and administrative support. In addition, the Computational Science Initiative (CSI) and Information Technology Division (ITD) at BNL provide support for computing, particularly the operation and technical support for the RBRC 400 Teraflop QCDCQ (QCD Chiral Quark) lattice gauge theory computer. D. Kharzeev (Stony Brook/BNL) is leader of the Theory Group. Y. Akiba (RIKEN) is Experimental Group leader. T. Izubuchi (BNL) is Computing Group leader.

2. Major Research Subjects

Major research subjects of the theory group are
(1) Heavy Ion Collision
(2) Perturbative QCD
(3) Phenomenological QCD

Major research subjects of the computing group are
(1) Search for new law of physics through tests for Standard Model of particle and nuclear physics
(2) Dynamics of QCD and related theories
(3) Theoretical and algorithmic development for lattice field theories, QCD machine design

Major research subject of the experimental group are
(1) Experimental Studies of the Spin Structure of the Nucleon
(2) Study of Quark-Gluon Plasma at RHIC
(3) sPHENIX detector construction

3. Summary of Research Activity

Summary of Research Activities of the three groups of the Center are given in the sections of each group.

Members

Director

Hideto EN'YO (concurrent: Director, Nishina Center for Accelerator-Based Science)

Administrative Staff

Kazushige FUKUSHIMA (Administration Manager, Nishina Center and iTHEMS Promotion Office)
Pamela ESPOSITO (Administrative Assistant)
Maureen MCNEIL-SHEA (Administrative Assistant)
Hiroshi ITO (Deputy Administration Manager, Nishina Center and iTHEMS Promotion Office)

Subnuclear System Research Division
RIKEN BNL Research Center
Theory Group

1. Abstract

The efforts of the RBRC theory group are concentrated on the major topics of interest in High Energy Nuclear Physics and strongly interacting Chiral Matter. This includes: understanding of the Quark-Gluon Plasma; the nature of dense quark matter; the initial state in high energy collisions, the Color Glass Condensate; its evolution through a Glasma; spin physics, as is relevant for polarized hadronic collisions; physics relevant to electron-hadron collisions and the Electron-Ion Collider; quantum transport and the Chiral Magnetic Effect.

Theory Group hosted many joint tenure track positions with universities in U.S. and Japan.

2. Major Research Subjects

(1) Heavy Ion Collisions
(2) Perturbative Quantum Chromo-Dynamics (QCD)
(3) Phenomenological QCD
(4) Chiral Matter

3. Summary of Research Activity

(1) Phase diagram of QCD

The heavy ion program at Relativistic Heavy Ion Collider (RHIC) at BNL is focused on the study of the properties of QCD matter at high energy densities and high temperatures. The RBRC Theory group performs research that supports and guides the experimental program at RHIC. In the past year, RBRC researchers had identified the possibility for the higher-order phase transitions in QCD (H. Nishimura, R. Pisarski, V. Skokov) by using the novel approach based on the matrix models.

The first-principle studies of QCD phase diagram at finite baryon density using the lattice Monte Carlo approach are very difficult because of the so-called "sign problem." The work by H. Nishimura and Y. Tanizaki, in collaboration with J. Verbaarschot of Stony Brook Nuclear Theory group, has proposed a new kind of the gradient flow method that can be used to alleviate this problem.

An important feature of strongly interacting matter at finite baryon density is the liquid-gas phase transition. The paper by H. Nishimura (in collaboration with M. Ogilvie and K. Pangeni) develops a field-theoretic approach to the liquid-gas phase transition based on an effective 3D field theory.

Quantum anomalies play an important role in QCD phase transitions. Y. Tanizaki, Y. Kikuchi (who will join the RBRC Theory group in 2018) and collaborators utilized the method of "anomaly matching" to obtain important constraints on the dynamics of deconfinement and chiral restoration phase transitions in QCD. They also used this method to study the vacuum structure of QCD at finite theta-angle.

(2) QCD Matter at High Energy Density and at small *x*

The RHIC experimental heavy ion program is designed to study the properties of matter at energy densities much greater than that of atomic nuclei. This includes the initial state of nucleus-nucleus collisions, the Color Glass Condensate, the intermediate state to which it evolves, the Glasma, and lastly the thermal state to which it evolves, the Quark-Gluon Plasma. Theorists at the RBRC have made important contributions to all of these subjects.

During the past year, V. Skokov (in collaboration with A. Kovner, and others) investigated the role of entanglement in gluon fields at small Bjorken x in generating the azimuthal anisotropy of hadrons produced in AA and pA collisions at RHIC. It has been found that the correlations inside the small x distributions effectively generate odd azimuthal harmonics in hadron distributions, with a long-range separation in rapidity. In collaboration with A. Kovner and M. Lublinsky, V. Skokov also investigated the possible effect of quark-gluon correlations at small x on the studies of the Chiral Magnetic Effect in pA collisions at RHIC. D. Kharzeev, in collaboration with W. Li and Z. Tu, investigated the role of fluctuating proton size on the CME studies in pA collisions, and found that these fluctuations induce a significant correlation between the direction of magnetic field and the reaction plane, enabling the observation of CME.

The Isobar run at RHIC (made possible due to the RIKEN scientists working on Zr source) completed in 2018 will establish or rule out the existence of the Chiral Magnetic Effect (originally proposed by RBRC theorists) in the quark-gluon plasma. During the past year, D. Kharzeev and H.-U. Yee, in collaboration with Y. Hirono, M. Mace and others have developed the Chiral Magneto-Hydrodynamics (CMHD) approach to the Chiral Magnetic Effect (CME) in quark-gluon plasma. The first numerical results of CMHD have become available due to the collaboration of RBRC with the ECHO-QGP group. H.-U. Yee and collaborators investigated dynamical instabilities in CMHD. D. Kharzeev and H.-U. Yee, in collaboration with M. Stephanov, solved a long-standing puzzle of the apparent discrepancy between the field theory and the kinetic theory on the magnitude of the CME current at finite frequency. D. Kharzeev, with Y. Hirono and A. Sadofyev, proposed a new "chiral propulsion effect" for the chiral solitons on vortices in chiral media.

The activity of RBRC members described above bridges the gap between fundamental theory and phenomenology of heavy ion collisions. This includes the lattice QCD studies, the analytical work on the dynamics of phase transitions, the development of hydrodynamical and kinetic theory approaches incorporating quantum anomalies, and phenomenology. Much of the current work in the field is based on the ideas originally developed by the RBRC theorists.

(3) Chiral Matter

Much of the work done at the RBRC Theory group has broad implications beyond the domain of Nuclear and High Energy physics. One example is the Chiral Magnetic Effect, originally proposed to occur in quark-gluon plasma, but discovered recently in condensed matter systems, so-called Dirac and Weyl semimetals (the original experimental observation of CME was made at BNL in $ZrTe_5$ in a paper co-authored by D. Kharzeev). It has become clear that RBRC can make a very substantial impact also on condensed matter physics, where the methods developed at RBRC can be applied to a new set of problems. Vice versa, some of the new theoretical developments in condensed matter physics can be utilized for the study of QCD matter. Because of this, the RBRC developed a new initiative on Chiral Matter focusing on the studies of quantum behavior in strongly interacting matter containing chiral fermions—this includes the quark-gluon plasma, electroweak plasma, Dirac and Weyl semimetals, and topological insulators.

In the past year, the RBRC members within this new initiative obtained a number of new results. Some of them, with a direct relevance for the quark-gluon plasma, have been already described above; other results are of direct relevance for condensed matter physics. D. Kharzeev, Y. Tanizaki and Y. Kikuchi (a postdoc who has joined RBRC in 2018), in collaboration with R. Meyer, found that asymmetric Weyl semimetals support a giant photocurrent as a result of chiral anomaly. D. Kharzeev, Y. Kikuchi and R. Meyer also proposed a new kind of dynamical CME in asymmetric Weyl semimetals that does not require an external source of chirality, and proposed an experiment to test their prediction. D. Kharzeev with his Stony Brook student S. Kaushik have identified a new type of quantum oscillations in the CME conductivity at finite doping, and with another student E. Philip have established the existence of the chiral magnetic photocurrent.

The Chiral Matter initiative has already broadened the impact of RBRC beyond the traditional domain of high-energy nuclear physics, and has extended the RBRC research into a new and extremely active area.

Members

Group Leader

Dmitri KHARZEEV

Special Postdoctoral Researchers

Yuya TANIZAKI
Hiromichi NISHIMURA

RBRC Researchers

Yuta KIKUCHI (Postdoctoral Researcher)
Jordy DE VRIES (RHIC Physics Fellow)
Chun SHEN (RHIC Physics Fellow)
Vladimir SKOKOV (RHIC Physics Fellow)

Subnuclear System Research Division
RIKEN BNL Research Center
Experimental Group

1. Abstract

RIKEN BNL Research Center (RBRC) Experimental Group studies the strong interactions (QCD) using RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized $p + p$ collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment at RHIC.

We study the spin structure of the proton using the polarized proton-proton collisions at RHIC. This program has been promoted by RIKEN's leadership. The first focus of the research is to measure the gluon spin contribution to the proton spin. Recent results from PHENIX π^0 measurement and STAR jet measurement has shown that gluons in the proton carry about 30% of the proton spin. This is a major milestone of RHIC spin program. The second goal of the spin program is to measure the polarization of anti-quarks in the proton using $W \to e$ and $W \to \mu$ decays. The results of $W \to e$ measurement was published in 2016. The final results of $W \to \mu$ was published in 2018.

The aim of Heavy ion physics at RHIC is to re-create Quark Gluon Plasma (QGP), the state of Universe just after the Big Bang. Two important discoveries, jet quenching effect and strong elliptic flows, have established that new state of dense matter is indeed produced in heavy ion collisions at RHIC. We are now studying the property of the matter. Recently, we have measured direct photons in Au + Au collisions for $1 < p_{\mathrm{T}} < 3$ GeV/c, where thermal radiation from hot QGP is expected to dominate. The comparison between the data and theory calculations indicates that the initial temperature of 300 MeV to 600 MeV is achieved. These values are well above the transition temperature to QGP, which is calculated to be approximately 160 MeV by lattice QCD calculations.

We had major roles in detector upgrades of PHENIX experiment, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. Both of the upgrade is now complete. The VTX is the main device to measure heavy quark (charm and bottom) production and the muon trigger is essential for $W \to \mu$ measurement. The results from the first run with VTX detector in 2011 was published. The results show that electrons from bottom quark decay is strongly suppressed at high p_{T}, but the suppression is weaker than that of charm decay electron for $3 < p_{\mathrm{T}} < 4$ GeV/c. We have recorded 10 times as much Au + Au collisions data in each of the 2014 run and 2016 run. The large dataset will produce definitive results on heavy quark production at RHIC.

PHENIX completed its data taking in 2016. We are now working on R&D of intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that will be installed in the PHENIX IR.

2. Major Research Subjects

(1) Experimental Studies of the Spin Structure of the Nucleon
(2) Study of Quark-Gluon Plasma at RHIC
(3) PHENIX detector upgrades

3. Summary of Research Activity

We study the strong interactions (QCD) using the RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized $p + p$ collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment. From 2015, Y. Akiba (Experimental Group Leader) is the Spokesperson of PHENIX experiment.

(1) Experimental study of spin structure of proton using RHIC polarized proton collider

How is the spin of proton formed with 3 quarks and gluons? This is a very fundamental question in Quantum Chromodynamics (QCD), the theory of the strong nuclear forces. The RHIC Spin Project has been established as an international collaboration between RIKEN and Brookhaven National Laboratory (BNL) to solve this problem by colliding two polarized protons for the first time in history. This project also has extended the physics capabilities of RHIC.

The first goal of the Spin Physics program at RHIC is to determine the gluon contribution to proton spin. It is known that the spin of quark accounts for only 25% of proton spin. The remaining 75% should be carried either by the spin of gluons or the orbital angular momentum of quarks and gluons. One of the main goals of the RHIC spin program has been to determine the gluon spin contribution. Before the start of RHIC, there was little experimental constraint on the gluon polarization, ΔG.

PHENIX measures the double helicity asymmetry (A_{LL}) of π^0 production to determine the gluon polarization. Our most recent publication of π^0 A_{LL} measurement at 510 GeV shows non-zero value of A_{LL}, indicating that gluons in the proton is polarized. Global analysis shows that approximately 30% of proton spin is carried by gluons.

RHIC achieved polarized $p + p$ collisions at 500 GeV in 2009. The collision energy increased to 510 GeV in 2012 and 2013. The main goal of these high energy $p + p$ run is to measure anti-quark polarization via single spin asymmetry A_L of the W production. We upgraded the muon trigger system to measure $W \to \mu$ decays in the forward direction. With the measurement of $W \to e$ and $W \to \mu$, we can cover a wide kinematic range in anti-quark polarization measurement. The 2013 run is the main spin run at 510 GeV. PHENIX has recorded more than 150/pb of data in the run. The final results of the $\mathrm{A_L}$ measurement in $W \to e$ channel in combined data of 2011 to 2013 was published in 2016. The paper on the final results of $W \to \mu$ was published in 2018. These high statistics results give strong constraints on the polarization of anti-quarks in the proton.

RHIC has the first polarized proton nucleus collision run in 2015. In this run, we discovered a surprisingly large nuclear dependence of single spin asymmetry of very forward neutron. The paper of this discovery was published in Physical Review Letters.

(2) Experimental study of Quark-Gluon Plasma using RHIC heavy-ion collider

The goal of high energy heavy ion physics at RHIC is study of QCD in extreme conditions *i.e.* at very high temperature and at very high energy density. Experimental results from RHIC have established that dense partonic matter is formed in Au + Au collisions at RHIC. The matter is very dense and opaque, and it has almost no viscosity and behaves like a perfect fluid. These conclusions are

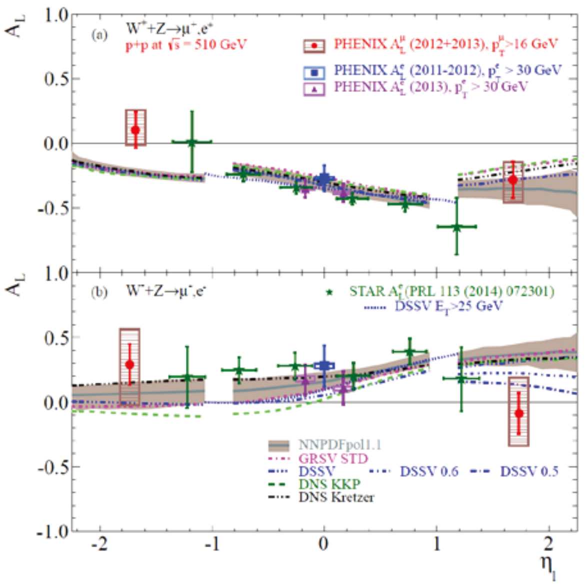

Fig. 1. Single spin asymmetry A_L of electrons from W and Z decays. The A_L is sensitive to the polarization of anti-quarks in the proton. The curves and the shaded region show theoretical calculations based on various polarized parton distribution (PDF) sets. The mid-rapidity points were published in Phys. Rev. D **93**, 051103(R) (2016). The forward/backward points were published in Phys. Rev. D **98**, 032007 (2018).

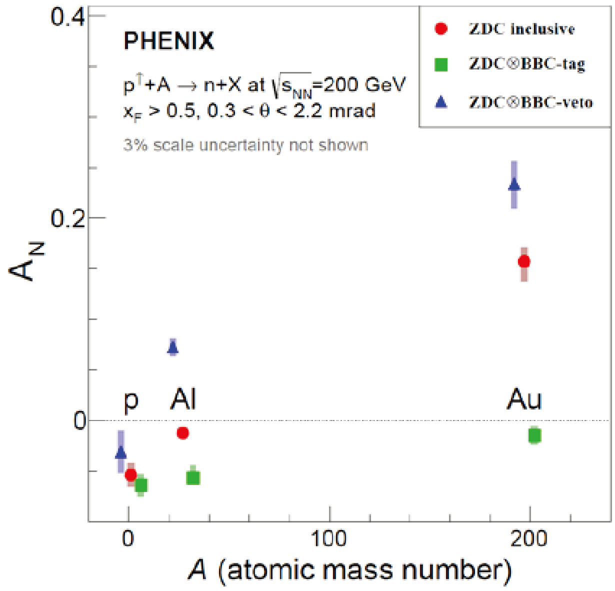

Fig. 2. Single spin asymmetry A_N of very forward neutron in $p + p$, p + Al, and p + Au collision. Published in Phys. Rev. Lett. **120**, 022001 (2018).

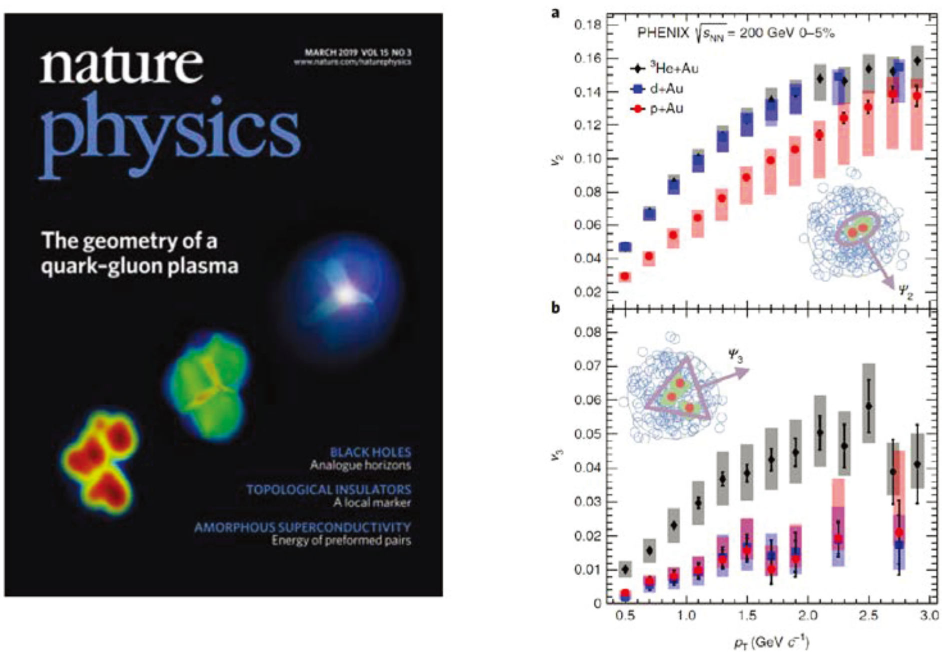

Fig. 3. Left: Cover of Nature Physics March 2019 issue featuring the PEHNIX article reporting strong evidence of small QGP droplent formation. Right: Data of elliptic and triangular flow measured in p + Au, d + Au and ^{3}He + Au collisions.

primarily based on the following two discoveries:

- Strong suppression of high transverse momentum hadrons in central Au + Au collisions (jet quenching)
- Strong elliptic flow

These results are summarized in PHENIX White paper, which has approximately 2700 citations to date.

The focus of the research in heavy ion physics at RHIC is now to investigate the properties of the matter. RBRC have played the leading roles in some of the most important results from PHENIX in the study of the matter properties. These include (1) measurements of heavy quark production from the single electrons from heavy flavor decay (2) measurements of J/ψ production (3) measurements of di-electron continuum and (4) measurements of direct photons.

Our most important result is the measurement of direct photons for $1 < p_T < 5$ GeV/c in $p + p$ and Au + Au through their internal conversion to e^+e^- pairs. If the dense partonic matter formed at RHIC is thermalized, it should emit thermal photons. Observation of thermal photon is direct evidence of early thermalization, and we can determine the initial temperature of the matter. It is predicted that thermal photons from QGP phase is the dominant source of direct photons for $1 < p_T < 3$ GeV/c at the RHIC energy. We measured the direct photon in this p_T region from measurements of quasi-real virtual photons that decays into low-mass e^+e^- pairs. Strong enhancement of direct photon yield in Au + Au over the scaled $p + p$ data has been observed. Several hydrodynamical models can reproduce the central Au + A data within a factor of two. These models assume formation of a hot system with initial temperature of T_{init} = 300 MeV to 600 MeV. This is the first measurement of initial temperature of quark gluon plasma formed at RHIC. These results are recently published in Physical Review Letters. Y. Akiba is the leading person of the analysis and the main author of the paper. **He received 2011 Nishina memorial Prize mainly based on this work.**

PHENIX experiment measured the flow in small collision systems (p + Au, d+Au, and ^{3}He + Au), and observed strong flow in all of these systems. Theoretical models that assume formation of small QGP droplets best describe the data. These results are published in Nature Physics in 2019.

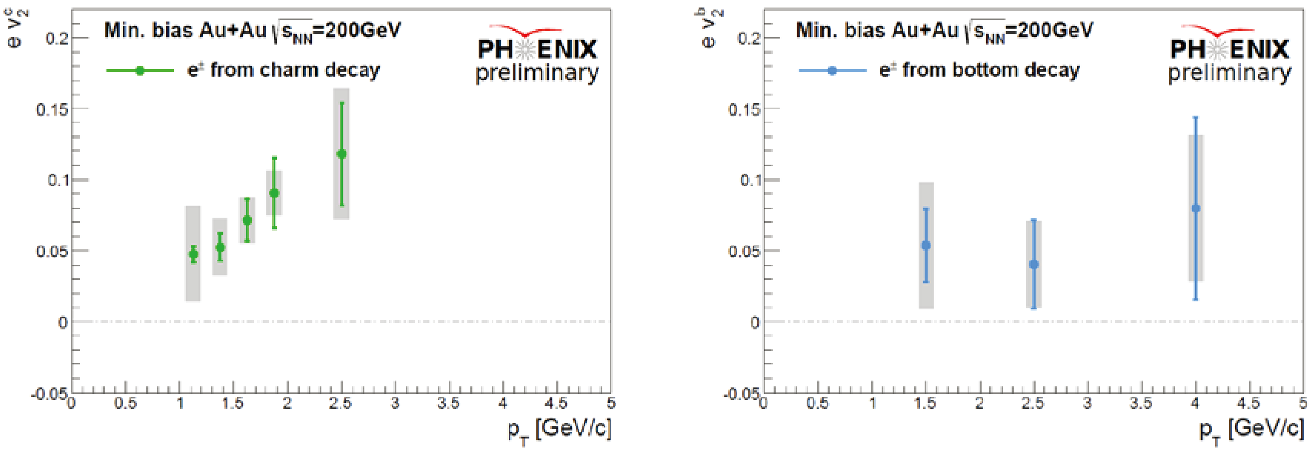

Fig. 4. Preliminary results of the elliptic flow strength v_2 of single electrons from charm and bottom decays.

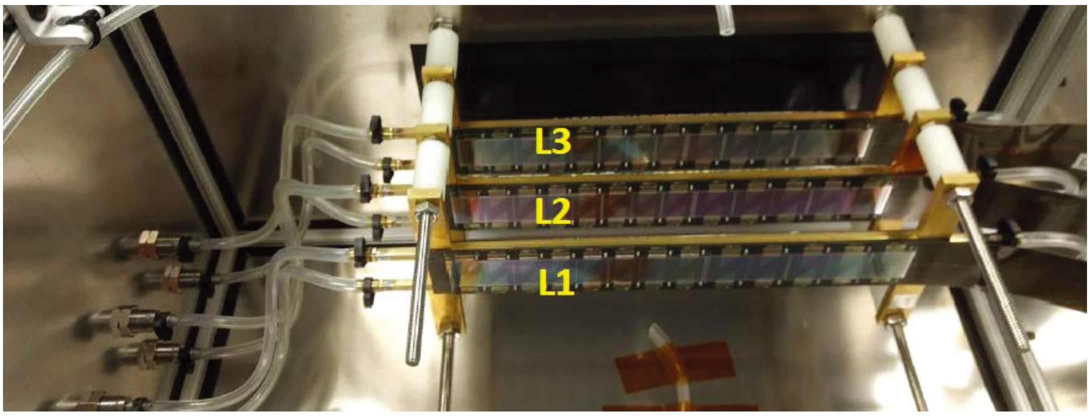

Fig. 5. Three ladder telescope made from INTT silicon tracker prototype. The prototype detector was tested in a beam test at FNAL in February 2018.

(3) Detector upgrade

The group had major roles in several PHENIX detector upgrades, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. VTX is a high precision charged particle tracker made of 4 layers of silicon detectors. It is jointly funded by RIKEN and the US DOE. The inner two layers are silicon pixel detectors and the outer two layers are silicon strip detectors. Y. Akiba is the project manager and A. Deshpande is the strip system manager. The VTX detector was completed in November 2010 and subsequently installed in PHENIX. The detector started taking data in the 2011 run. With the new detector, we measure heavy quark (charm and bottom) production in $p + p$, A + A collisions to study the properties of quark-gluon plasma. The final result of the 2011 run was published. The result show that single electrons from bottom quark decay is suppressed, but not as strong as that from charm decay in low p_{T} region ($3 < p_{\mathrm{T}} < 4$ GeV/c). This is the first measurement of suppression of bottom decay electrons at RHIC and the first observation that bottom suppression is smaller than charm. We have recorded 10 times as much Au + Au collisions data in each of the 2014 run and 2016 run. The large dataset will produce definitive results on heavy quark production at RHIC. A preliminary results on the elliptic flow strength v_2 of $b \to e$ and $c \to e$ has been presented in Quark Matter 2018 conference.

PHENIX completed its data taking in 2016. We are now working on R&D of intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that will be installed in the PHENIX IR. A three ladder telescope of INTT prototype modules was tested in a beam test at FNAL. The prototype detector worked very well during the test.

Members

Group Leader

Yasuyuki AKIBA (Deputy Chief Scientist)

RBRC Researchers

Jan BERNAUER (RHIC Physics Fellow)
Itaru NAKAGAWA (RIKEN Spin Program Researcher, concurrent: Radiation Lab.)
Takashi HACHIYA (RIKEN BNL Fellow, Nara Women's University)
Takashi ICHIHARA (RIKEN Spin Program Researcher, concurrent: RI Physics Lab.)
Yorito YAMAGUCHI
Takahito TODOROKI
Atsushi TAKETANI (RIKEN Spin Program Researcher, concurrent: Neutron Beam Technology Team, Advanced Photonics Technology Development Group, RAP)
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Satoshi YOKKAICHI (RIKEN Spin Program Researcher, concurrent: Radiation Lab.)
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Takao SAKAGUCHI (BNL)
Rachid NOUICER (BNL)
Takashi SAKO (University of Tokyo)
Masahiro OKAMURA (BNL)
Hiroaki MENJO (Nagoya University)
Gaku MITSUKA (KEK)

List of Publications & Presentations

Publications

Oral Presentations

[International Conference etc.]

T. Hachiya, "Nuclear modification factor and flow of charm and bottom quarks in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX Experiment," Quark Matter 2018 (QM2018), Venice, Italy, May 13–19, 2018.

T. Hachiya, "Heavy Flavor Physics at RHIC," :Fifth Joint Meeting of the Nuclear Physics Divisions of the APS and the JPS (HAWAII2018), Waikoloa, HI, USA, October 23–27, 2018.

T. Hachiya, "Recent experimental studies on high-energy heavy ion collisions," 13th International Conference on Nucleus-Nucleus Collisions (NN2018), Omiya, Japan, December 4–8, 2018.

Subnuclear System Research Division
RIKEN BNL Research Center
Computing Group

1. Abstract

The computing group founded in 2011 as a part of the RIKEN BNL Research Center established at Brookhaven National Laboratory in New York, USA, and dedicated to conduct researches and developments for large-scale physics computations important for particle and nuclear physics. The group was forked from the RBRC Theory Group.

The main mission of the group is to provide important numerical information that is indispensable for theoretical interpretation of experimental data from the first principle theories of particle and nuclear physics. Their primary area of research is lattice quantum chromodynamics (QCD), which describes the sub-atomic structures of hadrons, which allow us the ab-initio investigation for strongly interacting quantum field theories beyond perturbative analysis.

The RBRC group and its collaborators have emphasized the necessity and importance of precision calculations, which will precisely check the current understandings of nature, and will have a potential to find a physics beyond the current standard model of fundamental physics. We have therefore adopted techniques that aim to control and reduce any systematic errors. This approach has yielded many reliable results.

The areas of the major activities are R&D for high performance computers, developments for computing algorithms, and researches of particle, nuclear, and lattice theories. Since the inception of RBRC, many breakthroughs and pioneering works has carried out in computational forefronts. These are the use of the domain-wall fermions, which preserve chiral symmetry, a key symmetry for understanding nature of particle nuclear physics, the three generations of QCD devoted supercomputers, pioneering works for QCD calculation for Cabibbo-Kobayashi-Maskawa theory, QCD + QED simulation for isospin breaking, novel algorithm for error reduction in general lattice calculation. Now the chiral quark simulation is performed at the physical up, down quark mass, the precision for many basic quantities reached to accuracy of sub-percent, and the group is aiming for further important and challenging calculations, such as the full and complete calculation of CP violating K $\to \pi\pi$ decay and ε'/ε, or hadronic contributions to muon's anomalous magnetic moment $g-2$. Another focus area is the nucleon's shape, structures, and the motion of quarks and gluon inside nucleon called parton distribution, which provide theoretical guidance to physics for future Electron Ion Collider (EIC), Hyper Kamiokande, DUNE, or the origin of the current matter rich universe (rather than anti-matter). Some of members carry out interesting research on strong gauge dynamics other than QCD to get hints for the true nature of the Higgs particle or the Dark Matter, or even quantum gravity.

2. Major Research Subjects

(1) Search for new law of physics through tests for Standard Model of particle and nuclear physics, especially in the framework of the Cabibbo-Kobayashi-Maskawa (CKM), hadronic contributions to the muon's anomalous magnetic moment $(g-2)$ for FNAL and J-PARC's experiments, as well as B physics at Belle II and LHCb.

(2) Nuclear Physics and dynamics of QCD or related theories, including study for the structures of nucleons related to physics for Electron Ion Collider (EIC or eRHIC), Hyper Kamiokande, T2K, DUNE.

(3) Theoretical and algorithmic development for lattice field theories, QCD machine (co-)design and code optimization.

3. Summary of Research Activity

In 2011, QCD with Chiral Quarks (QCDCQ), a third-generation lattice QCD computer that is a pre-commercial version of IBM's Blue Gene/Q, was installed as an in-house computing resource at the RBRC. The computer was developed by collaboration among RBRC, Columbia University, the University of Edinburgh, and IBM. Two racks of QCDCQ having a peak computing power of 2×200 TFLOPS are in operation at the RBRC. In addition to the RBRC machine, one rack of QCDCQ is owned by BNL for wider use for scientific computing. In 2013, 1/2 rack of Blue Gene/Q is also installed by US-wide lattice QCD collaboration, USQCD. The group has also used the IBM Blue Gene supercomputers located at Argonne National Laboratory and BNL (NY Blue), and Hokusai and RICC, the super computers at RIKEN (Japan), Fermi National Accelerator Laboratory, the Jefferson Lab, and others. From 2016, the group started to use the institutional cluster both GPU and Intel Knight Landing (KNL) clusters installed at BNL and University of Tokyo extensively.

Such computing power enables the group to perform precise calculations using up, down, and strange quark flavors with proper handling of the important symmetry, called chiral symmetry, that quarks have. The group and its collaborators carried out the first calculation for the direct breaking of CP (Charge Parity) symmetry in the hadronic K meson decay (K $\to \pi\pi$) amplitudes, ε'/ε, which provide a new information to CKM paradigm and its beyond. They also provide the hadronic contribution in muon's anomalous magnetic moment $(g-2)_\mu$. These calculation for ε'/ε, hadronic light-by-light of $(g-2)$, are long waited calculation in theoretical physics delivered for the first time by the group. The K $\to \pi\pi$ result in terms of ε'/ε currently has a large error, and deviates from experimental results by 2.1 σ. To collect more information to decide whether this deviation is from the unknown new physics or not, the group continues to improve the calculation in various way to reduce their error. Hadronic light-by-light contribution to $(g-2)_\mu$ is improved by more than two order of magnitudes compared to our previous results. As of 2019 summer, their calculation is among the most precise determination for the $g-2$ hadronic vacuum polarization (HVP), and only one calculation in the world for the hadronic light-by-light (HLbL) contribution at physical point. These $(g-2)_\mu$ calculations provide the first principle theoretical prediction for on-going new experiment at FNAL and also for the planned experiment at J-PARC. Other projects including flavor physics in the framework of the

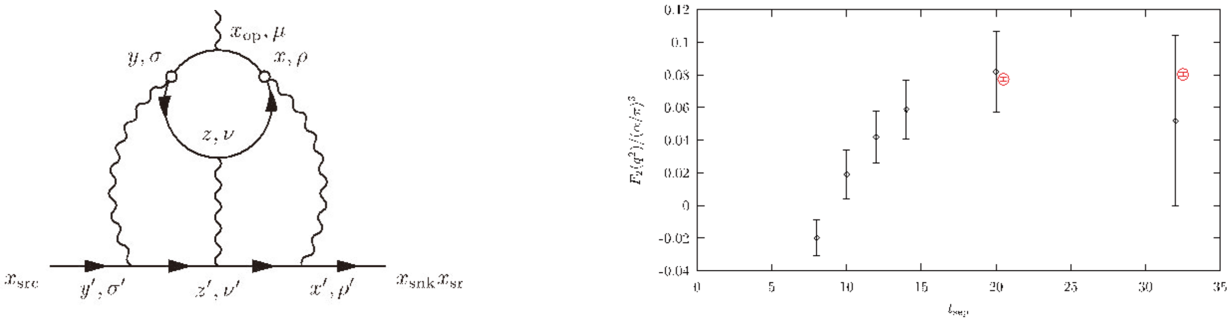

Fig. 1. Muon $g-2$ Hadronic Light-by-Ligh contribution. HLbL diagram (left). New sampling method (red) reduce the statistical noise from the previous method (black) by more than a factor of 10 at the same cost.

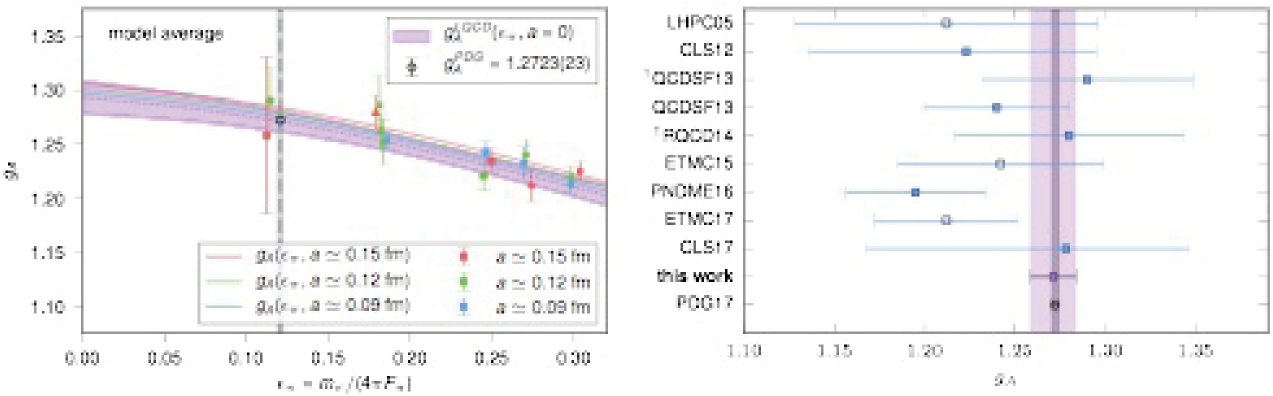

Fig. 2. Physical-point extrapolation for gA (left), Summary of LQCD calculations (right) from Nature **558**, 91–94 (2018).

CKM theory for kaons and B mesons that include the new calculation of b-baryon decay, $\Lambda_b \rightarrow p$; the electromagnetic properties of hadrons; the proton's and neutron's form factors and structure function including electric dipole moments; proton decay; nucleon form factors, which are related to the proton spin problem or neutrino-nucleon interaction; Neutron-antineutron oscillations; inclusive hadronic decay of τ leptons; nonperturbative studies for beyond standard model such composite Higgs or dark matter models from strong strongly interacting gauge theories; a few-body nuclear physics and their electromagnetic properties; QCD thermodynamics in finite temperature/density systems such as those produced in heavy-ion collisions at the Relativistic Heavy Ion Collider; Quantum Information, Quantum Computing; and applications of machine learning in field theories.

The lifetime of the neutron is determined by its axial charge, gA, which also governs pion exchange between nucleons. Member of RBRC (Rinaldi) and collaborators (including C. C. Chang of iTHEMS) carried out 1%-level accurate LQCD calculation of gA for the first time by employing several innovative methods (such as unconventional extraction of the QCD matrix element using Feynman-Hellmann theorem, different sea- and valence quark actions, or the computational use of Graphic Processor Units). The paper was published in the Nature journal, was covered by many press releases, and also led to the Gordon Bell Prize finalist.

The RBRC group and its collaborators have emphasized the necessity and importance of precision calculations, which will provide stringent checks for the current understandings of nature, and will have a potential to find physics beyond the current standard model of fundamental physics. We have therefore adopted techniques that aim to control and reduce any systematic errors. This approach has yielded many reliable results, many of basic quantities are now computed within sub-percent accuracies.

The group also delivers several algorithmic breakthroughs, which speed up generic lattice gauge theory computation. These novel technique divides the whole calculation into frequent approximated calculations, and infrequent expensive and accurate calculation using lattice symmetries called All Mode Averaging (AMA), or a compression for memory needs by exploiting the local-coherence of QCD dynamics. Together with another formalism, zMobius fermion, which approximate chiral lattice quark action efficiently, the typical calculation is now improved by a couple of orders of magnitudes, and more than an order of magnitude less memory needs compared to the traditional methods. RBRC group and its collaborators also provide very efficient and generic code optimized to the state-of-arts CPU or GPU, and also improve how to efficiently generate QCD ensemble.

Table 1. Summery of current physics program and their impacts.

Theme	Significant Outcomes	Expected Impacts & Extensions
(a) DWF QCD ensemble generation and measurements of basic quantities	Hadron spectrum, f_π, f_K, K_{l3}, B_K, and accurate ChPT Low Energy Constants (LECs)	Basis of physical observables
(b) Operator Renormalization	Precise matrix elements, bag parameters quark masses, and coupling constants	Reduced systematic error in *e.g.* $K \to \pi\pi$ amplitudes
(c) Computational Algorithms, Software, and Machines	Fast and Cost-Effective Computing All Mode Averaging (AMA) PhySyHCAl	Unprecedented precision and new physical quantities
(d) K physics	$K_{l3}, \Delta I = 1/2, 3/2, K \to \pi\pi$ amplitudes, ε'/ε $K_L - K_S$ Mass Difference, $\varepsilon_K^{\mathrm{LD}}$	New tests of the SM
(e) B physics	Matrix elements for (semi-)leptonic decays and $B^0 - \overline{B^0}$ oscillations	CKM matrix, e.g., V_{ub}, V_{ts}, V_{td} and R-ratios for LUV tests .
(f) QED and Isospin breaking effects	Better determination of quark masses Proton-Neutron Mass Difference	A step towards sub-% precision groundwork for $(g-2)_\mu$
(g) Muon Anomalous Magnetic Moment $(g-2)_\mu$	Hadronic Vacuum Polarization contribution Light-by-Light contribution	$(g-2)_\mu$ experiments at BNL, FNAL, J-PARC
(h) Nucleon calculations for HEP	Vector/Axial form factors of nucleon Proton decay matrix element Nucleon EDM and $F_3(q^2)$ from vacuum angle θ and quark's (Chromo) EDM Parton Distribution Function	DUNE, Super-K, T2K GUT EDM experiments incl. ORNL, LANL Origin of matter in Universe LHC, Electron-Ion Colliders

Members

Group Leader

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Special Postdoctoral Researchers

Akio TOMIYA
Enrico RINALDI

RBRC Researchers

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Stefan MEINEL (RHIC Physics Fellow)
Sergey SYRITSYN (RHIC Physics Fellow)
Luchang JIN (RHIC Physics Fellow)

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Chulwoo JUNG (BNL)
Shigemi OHTA (KEK)
Tomomi ISHIKAWA (Shanghai Jiao-Tong Univ.)
Christoph LEHNER (BNL)
Meifeng LIN (BNL)
Robert MAWHINNEY (Columbia Univ.)
Hiroshi OKI (Nara Women's Univ.)
Christopher KELLY (Columbia Univ.)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

E. Rinaldi, S. Syritsyn, M. L. Wagman, M. I. Buchoff, C. Schroeder, J. Wasem, "Lattice QCD determination of neutron-antineutron matrix elements with physical quark masses," arxiv:1901.07519, submitted to Phys. Rev. D. *

A. Nicholson, E. Berkowitz, H. Monge-Camacho, D. Brantley, N. Garron, C. C. Chang, E. Rinaldi, C. Monahan, C. Bouchard, M. A. Clark, B. Joo, T. Kurth, B. Tiburzi, P. Vranas, A. Walker-Loud, "Symmetries and interactions from lattice QCD," arxiv:1812.11127. *

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T. Blum, P. A. Boyle, V. Gülpers, T. Izubuchi, L. Jin, C. Jung, A. Jüttner, C. Lehner, A. Portelli, J. T. Tsang (RBC and UKQCD Collaborations), "Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment," Phys. Rev. Lett. **121**, 022003 (2018). * [Editors' suggestion]

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T. Izubuchi, X. Ji, L. Jin, I. W. Stewart, Y. Zhao, "Factorization theorem relating Euclidean and light-cone parton distributions," Phys. Rev. D **98**, 056004 (2018). *

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S. Meinel, "$\Lambda_c \to N$ form factors from lattice QCD and phenomenology of $\Lambda_c \to n\ell^+\nu_\ell$ and $\Lambda_c \to pu^+\mu^-$ decays," Phys. Rev. D **97**, 034511 (2018). *

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J. -W. Chen, L. Jin, H. -W. Lin, Y. -S. Liu, Y. -B. Yang, J. -H. Zhang, Y. Zhao, "Lattice calculation of parton distribution function from LaMET at physical pion mass with large nucleon momentum," Phys. Rev. Lett. **121**, 242003 (2018). *

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[Proceedings]

(Original Papers) *Subject to Peer Review

USQCD Collaboration (V. Cirigliano, T. Izubuchi, S. Syritsyn *et al.*,), "The role of lattice QCD in searches for violations of fundamental symmetries and signals for new physics," arXiv:1904.09704 [hep-lat].

K. Maltman, T. Izubuchi, H. Ohki *et al.*, "Current status of inclusive hadronic τ determinations of $|V_{us}|$," SciPost Phys. Proc. **1**, 006 (2019).

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M. Bruno, T. Izubuchi, C. Lehner, A. Meyer, "On isospin breaking in τ decays for $(g-2)_\mu$ from lattice QCD," Proc. Sci. **LATTICE2018**, 135 (2018).

S. Syritsyn, T. Izubuchi, H. Ohki, "Progress in the nucleon electric dipole moment calculations in lattice QCD," arXiv:1810.03721.

P. Boyle, R. J. Hudspith, T. Izubuchi, A. Jüttner, C. Lehner, R. Lewis, K. Maltman, H. Ohki, A. Portelli, M. Spraggs, "$|V_{us}|$ determination from inclusive strange tau decay and lattice HVP," EPJ Web Conf. **175**, 13011 (2018).

S. Hashimoto, B. Colquhoun, T. Izubuchi, T. Kaneko, H. Ohki, "Inclusive B decay calculations with analytic continuation," EPJ Web Conf. **175**, 13006 (2018).

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T. Izubuchi, Y. Kuramashi, C. Lehner, E. Shintani, "Lattice study of finite volume effect in HVP for muon $g-2$," EPJ Web Conf. **175**, 06020 (2018).

S. Syritsyn, "Nucleon EDM on a lattice at the physical point," LATTICE 2018, July 22–28, 2018; to be published in Proc. Sci. Confinement.

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G. Rendon, L. Leskovec, S. Meinel, J. Negele, S. Paul, M. Petschlies, A. Pochinsky, G. Silvi, S. Syritsyn, "$K\pi$ scattering and the $K*(892)$ resonance in 2 + 1 flavor QCD," Proc. Sci. **LATTICE2018**, 073 (2018).

L. Leskovec, C. Alexandrou, S. Meinel, J. W. Negele, S. Paul, M. Petschlies, A. Pochinsky, G. Rendon, S. Syritsyn, "Calculating the ρ radiative decay width with lattice QCD," Proc. Sci. **LATTICE2018**, 065 (2018).

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L. Leskovec, C. Alexandrou, S. Meinel, J. W. Negele, S. Paul, M. Petschlies, A. Pochinsky, G. Rendon, S. Syritsyn, "A lattice QCD study of the ρ resonance," CIPANP 2018, (2018).

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S. Aoki, Y. Aoki, G. Cossu, H. Fukaya, S. Hashimoto, K. Suzuki, "Topological susceptibility in $N_f = 2$ QCD at finite temperature," EPJ Web of Conferences **175**, 07024-1–8 (2018).

C. Rohrhofer, Y. Aoki, G. Cossu, H. Fukaya, L. Ya. Glozman, S. Hashimoto, C. B. Lang, S. Prelovsek, "Degeneracy of vector-channel spatial correlators in high temperature QCD," EPJ Web of Conferences **175**, 07029-1–8 (2018).

Y. Aoki, T. Aoyama, E. Bennett, M. Kurachi, T. Maskawa, K. Miura, K. Nagai, H. Ohki, E. Rinaldi, A. Shibata, K. Yamawaki, T. Yamazaki, "Flavor-singlet spectrum in multi-flavor QCD," EPJ Web Conf. **175**, 01008 (2018).

E. Berkowitz, A. Nicholson, C. C. Chang, E. Rinaldi, M. A. Clark, B. Joo, T. Kurth, P. Vranas, A. Walker-Loud, "Calm multi-baryon operators," EPJ Web Conf. **175**, 08023 (2018).

E. Rinaldi, E. Berkowitz, M. Hanada, J. Maltz, P. Vranas, "Toward holographic reconstruction of bulk geometry from lattice simulations," EPJ Web Conf. **175**, 05029 (2018).

Oral Presentations

[International Conference etc.]

T. Izubuchi (invited), "Hadronic contributions to muon $g-2$," Frontiers in Lattice QCD and related topics, Kyoto Univ. Yukawa Institute, April 15–26, 2019.

T. Izubuchi, "Lattice QCD studies of muon $g-2$ and tau decay," 6th KEK Flavor Factory Workshop (KEK-FF 2019), KEK, February 16, 2019.

T. Izubuchi, "Precise calculation of muon $g-2$ based on lattice QCD," Massively parallel programming from Quantum Chemistry and Physics 2019, Kobe, RIKEN AICS, January 16, 2019.

T. Izubuchi (invited seminar), "$|V_{us}|$ from τ," Columbia University, January 28, 2019.

T. Izubuchi, "|Vus| from taus (LQCD)," invited talk, 10th International Workshop on the CKM Unitarity Triangle CKM2018, September 17–21, 2018.

T. Izubuchi (invited seminar), "Hadronic contributions to muon $g-2$ —LQCD confronting the most precise experiments—," Department of Theoretical Physics (DTP), Tata Institute of Fundamental Research (TIFR), Mumbai, India, April 26, 2018.

T. Izubuchi, "Nuclear form factor calculation using DWQCD," 36th International Symposium on Lattice Field Theory (Lattice 2018), at Lansing, MI, July 23–28, 2018.

S. Meinel (invited), "$B \to K^*\ell\ell$ from lattice QCD," 6th KEK Flavor Factory Workshop, Tsukuba, Japan, February 15, 2019.

S. Meinel (Invited parallel talk), "Exclusive semileptonic b baryon decays from lattice QCD," 10th International Workshop on the CKM Unitarity Triangle (CKM 2018), University of Heidelberg, Germany, September 18, 2018.

S. Meinel (Invited), "Form factors for b hadron decays from lattice QCD," Frontiers in Lattice Quantum Field Theory, IFT, Madrid, Spain, May 28, 2018.

S. Meinel, "Flavor physics with charm and bottom baryons, Invited seminar," Cosmology Seminar, Arizona State University, Tempe, AZ, May 2, 2018.

S. Meinel (invited), "Opportunities for lattice QCD in quark and lepton flavor physics," USQCD All Hands Meeting, Fermilab, Batavia, IL, April 20, 2018.

S. Meinel (invited), "$\Lambda_b \to \Lambda_c^{(*)}$ form factors from lattice QCD," Challenges in Semileptonic B Decays, MITP, Mainz, Germany, April 9, 2018.

S. Syritsyn, "Nucleon electric dipole moments from Lattice QCD," Theory Seminar, University of Maryland, October 11, 2018.

S. Syritsyn (invited), "Progress on the nucleon EDM in lattice QCD," XIIIth Quark Confinement and Hadron Spectrum, Maynooth University, Ireland, July 31–August 6, 2018.

Y. Aoki, "QCD phase transition," (invited), International Workshop on Massively Parallel Programming for Quantum Chemistry and Physics 2019, Kobe, Japan, January 15, 2019.

Y. Aoki (invited), "Topology and axial U(1) symmetry in two-flavor hot QCD, lattice and functional techniques for exploration of phase structure and transport properties in quantum chromodynamics," Dubna, Russia, September 5, 2018.

Y. Aoki, "Topological susceptibility in $N_\mathrm{f} = 2$ QCD at finite temperature—volume study," Lattice 2018, East Lancing, MI, USA, July 24, 2018.

Y. Aoki (invited), "Lattice QCD and hadron structure," DIS 2018, Kobe, Japan, April 16, 2018.

L. Jin (plenary), The 36th Annual International Symposium on Lattice Field Theory (LATTICE 2018), July 2018.

L. Jin (invited), Second Plenary Workshop of the Muon $g-2$ Theory Initiative, Mainz, June 2018.

L. Jin (invited), First Workshop of the Muon $g-2$ Theory Initiative, Q Center, June 2017.

L. Jin (invited), QCD Evolution 2017, Jefferson Lab, May 2017.

L. Jin (invited), Lattice PDF Workshop, University of Maryland, April 2018.

E. Neil, "Non-perturbative renormalization in Monte Carlo simulations using gradient flow," CTQM Seminar, University of Colorado, Boulder, CO. February 2019.

E. Neil, "Light composite scalar from $N_\mathrm{f} = 8$ lattice gauge theory," Continuum and Lattice Approaches to the Infrared Behavior of Conformal and Quasi-Conformal Gauge Theories, Simons Center for Geometry and Physics, Stony Brook, NY, January 2018.

E. Rinaldi (invited seminar), "The neutron lifetime with near-Exascale computing," Computational Science Initiative, BNL, Upton, NY, January 2019.

E. Rinaldi (invited seminar), "First- principles lattice QCD calculations of the neutron beta decay: challenges and prospects," Institut für Kernphysik, Forschungzentrum, Jülich, Germany, December 2018.

E. Rinaldi (invited), "First-principles lattice QCD calculations of the neutron beta decay: challenges and prospects," Particle Physics with Neutrons at ESS, Nordita University, Stockholm, Sweden, December 2018.

E. Rinaldi (invited), "Lattice calculations for neutron-antineutron oscillations," Particle Physics with Neutrons at ESS, Nordita University, Stockholm, Sweden, December 2018.

E. Rinaldi (invited seminar), "Illuminating dark matter with supercomputers," York University, Toronto, Canada, November 2018.

E. Rinaldi (invited), "First-principles QCD calculation of the neutron lifetime," Beta Decay as a Probe of New Physics, the Amherst Center for Fundamental Interactions, University of Massachusetts, Amherst, MA, November 2018.

E. Rinaldi (invited seminar), "New results on strongly-coupled theories near the conformal window," University of Rome 3, Rome, Italy, October 2018.

E. Rinaldi (invited seminar), "Beyond the Standard Model physics with lattice simulations," University of Milan Bicocca, Milan, Italy, October 2018.

E. Rinaldi (invited), "Lattice composite dark matter," Interdisciplinary approach to QCD-like composite dark matter, ECT*, Trento, Italy, October 2018.

E. Rinaldi, "Ungauging the gauge/gravity duality," Quantum Gravity meets Lattice QFT, ECT*, Trento, Italy, September 2018.

E. Rinaldi, "Neutron-antineutron oscillations," Lattice 2018, Michigan State University, USA, July 2018.

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E. Rinaldi, "Composite Dark Matter," CIPANP18, Palm Springs, CA, USA, June, 2018.

E. Rinaldi (invited seminar), "How to test the gauge/gravity duality with lattice simulations," New York University, New York, NY, USA, May 2018.

E. Rinaldi (invited), "High-precision tests of the gauge/gravity duality and future applications," Lattice for Beyond the Standard Model Physics (LBSM18), University of Colorado, Boulder, CO, USA, April 2018.

T. Akio, "Towards reduction of autocorrelation in HMC by machine learning," Bielefeld university, October 2018.

T. Akio, "Detection of phase transition via convolutional neural networks," Regenceburg university, October 2018.

T. Akio, “Chiral phase transition of three flavor QCD with nonzero magnetic field using standard HISQ,” Eötvös Loránd University, October 2018.

T. Akio, “Chiral phase transition of three flavor QCD with nonzero magnetic field using standard HISQ,” Oskaka University, November 2018.

T. Akio, “Chiral phase transition of three flavor QCD with nonzero magnetic field using standard HISQ,” Tsukuba University, November 2018.

[Domestic Conference]

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Subnuclear System Research Division
RIKEN Facility Office at RAL

1. Abstract

Our core activities are based on the RIKEN-RAL Muon Facility located at the ISIS Neutron & Muon Source at the Rutherford Appleton Laboratory (UK), which provides intense pulsed-muon beams. The RIKEN-RAL Muon Facility is a significant and long-standing collaboration between RIKEN and RAL in muon science.

Muons have their own spins with 100% polarization, and can detect local magnetic fields and their fluctuations at muon stopping sites very precisely. The method to study the characteristics of materials by observing time dependent changes of muon spin polarization is called "Muon Spin Rotation, Relaxation and Resonance" (μSR method), and is applied to study electro-magnetic properties of insulating, metallic, magnetic and superconducting systems. Muons reveal static and dynamic properties of the electronic state of materials in the zero-field condition, which is the ideal magnetic condition for research into magnetism. For example, we have carried out μSR investigations on a wide range of materials including frustrated pyrochlore systems, which have variety of exotic ground states of magnetic spins, so the magnetism study of this system using muon is quite unique.

The ultra-cold muon beam can be stopped in thin foil, multi-layered materials and artificial lattices, which enables us to apply the μSR techniques to surface and interface science. The development of an ultra-cold muon beam is also very important as a source of pencil-like small emittance muon beam for muon $g-2$/EDM measurement. We have been developing muonium generators to create more muonium atoms in vacuum even at room temperature to improve beam quality compared with the conventional hot-tungsten muonium generator. We have demonstrated a strong increase in the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. We are also developing a high power Lyman-alpha laser in collaboration with the Advanced Photonics group at RIKEN. The new laser will ionize muoniums 100 times more efficiently for slow muon beam generation.

Over the past 2–3 years, a significant development activity in muon elemental analysis has taken place, proton radius experiments have continued and been developed, and chip irradiation experiments have also continued.

2. Major Research Subjects

(1) Materials science by muon-spin-relaxation method and muon site calculation
(2) Development of elemental analysis using pulsed negative muons
(3) Nuclear and particle physics studies via muonic atoms and ultra-cold muon beam
(4) Other muon applications

3. Summary of Research Activity

(1) Material Science at the RIKEN-RAL Muon Facility

Muons have their own spins with 100% polarization, and can detect local magnetic fields and their fluctuations at muon stopping sites very precisely. The μSR method is applied to studies of newly fabricated materials. Muons enable us to conduct (1) material studies under external zero-field condition, (2) magnetism studies with samples without nuclear spins, and (3) measurements of muon spin relaxation changes at wide temperature range with same detection sensitivity. The detection time range of local field fluctuations by μSR is 10^{-6} to 10^{-11} second, which is an intermediate region between neutron scattering method (10^{-10}–10^{-12} second) and Nuclear Magnetic Resonance (NMR) (longer than 10^{-6} second). At Port-2 and 4 of the RIKEN-RAL Muon Facility, we have been performing μSR researches on strong correlated-electron systems, organic molecules, energy related materials and biological samples to study electron structures, superconductivity, magnetism, molecular structures and crystal structures.

Among our scientific activities on μSR studies from year 2016 to 2019, following subjects of material sciences are most important achievements at the RIKEN-RAL muon facility:

(1) Novel superconducting state having the steeper nodal gaps in the quasi two-dimensional organic superconductor λ-$[BETS]_2GaCl_4$
(2) Tiny magnetic moments and spin structures of Ir^{4+} in hole-doped pyrochlore iridates $Y_{1.95-y}Cu_{0.05}Ca_yIr_2O_7$ and $Eu_{2-x}Ca_xIr_2O_7$
(3) Magnetism and spin structure in superoxide CsO_2, RbO_2 and NaO_2
(4) Magnetic properties of the nano-cluster gold in the border of macro- and micro-scale
(5) Novel magnetic properties of nano-size La-based high-T_c superconducting cuprates
(6) Effects of the spatial distributions of magnetic moments and muon positions estimated from density functional theory (DFT) and dipole-field calculations
(7) Measurement of Li and Na ion diffusion in battery materials
(8) Muon as a probe of hydrogen behavior in functional and energy materials
(9) Negative muon SR application to internal field measurement

Result-(1) We developed a novel method to determine the superconducting gap structure in conjunction with the density functional theory calculations. It was concluded that the two-dimensional organic superconductor λ-$[BETS]_2GaCl_4$ has a steeper superconducting gap and clear line nodes showing both the s-wave and d-wave characters. Result-(2) Doped hole effects on the magnetic properties of corner-shared magnetic moments on pyrochlore systems gave us new interpretations to understand exotic phenomena, like the quantum criticality of magnetic moments and a quasi-magnetic monopole state. Result-(3) In CsO_2, we confirmed a novel coexisting state of the so-called spin-liquid state and a magnetically ordered state of magnetic moment which are on the π-orbital of oxygen atoms.

We also observed the spin-gap state in NaO_2. Those findings open a new scheme of quantum magnetic properties of π electrons on light elements. Result-(4) and (5) The nano-size effect show a new scheme of electronic properties of metallic element. The gold is the most typical example to have a possibility to possess magnetic properties due to the nano-size effect. We confirmed that the nano-gold cluster can have free electronic moment on one nano-cluster. The same nano-size effect was tested on the La-based high-T_c superconducting oxide. The severe restriction on the magnetic interaction is expected to provide novel effects on the magnetic and superconducting properties of the high-T_c superconducting oxide. We confirmed the reduction in the magnetic interaction and the disappearance of the superconducting state .by decreasing the size of the particle size. Result-(6) Well known and deeply investigated La_2CuO_4 has opened a new scheme of the Cu spin. Taking into account quantum effects to expand the Cu-spin orbital and muon positions, we have succeeded to explain newly found muon sites and hyperfine fields at those sites. Result-(7) Movement of ions is an essential requirement for an efficient battery. The μSR has been actively used to measure the ion hopping rate in microscopic level in Li- and Na-ion batteries. We also started a study of macroscopic Li movement from its depth dependent concentration using negative muons. Result-(8) Muon shows similar behavior as hydrogen in materials and its behavior can be measured even at very low concentration. Thus μSR was applied to understand energy and functional materials such as graphene, TiO_2 catalyst and hydrogen storage materials. Result-(9) Recently a clear Kubo-Toyabe-type relaxation was observed for negative muons captured by Mg. This will open the door to studying the dynamic behavior of light elements in solids with μ^-SR from a fixed viewpoint of the nucleus.

We have been developing muon activities in Asian countries. We enhanced international collaborations to organize new μSR experimental groups and to develop muon-site calculation groups using computational method. We renewed MOU with Universiti Sains Malaysia (USM) in order to develop activities on the muon-site calculation. We are also continuing collaborations in μSR experiments on strongly correlated systems with researchers from Taiwan and Korea including graduate students. We are starting to collaborate with the new Chinese muon group who are developing the Chinese Muon Facility and trying to develop more muon activities in the Asian area.

(2) Development of elemental analysis using pulsed negative muons

There has been significant development of elemental analysis using negative muons on Port 4 and Port 1 over the past couple of years. Currently, elemental analysis commonly uses X-ray and electron beams, which accurately measure surfaces. However a significant advantage of muonic X-rays over those of electronic X-rays is their higher energy due to the mass of the muon. These high energy muonic X-rays are emitted from the bulk of the samples without significant photon self-absorption. The penetration depth of the muons can be varied by controlling the muon momentum, providing data from a thin slice of sample at a given depth. This can be over a centimetre in iron, silver and gold or over 4 cm in less dense materials such as carbon.

Some techniques for elemental analysis are destructive or require the material under investigation to undergo significant treatment and some of the techniques are only sensitive to the surface. Therefore, negative muons offer a unique service in which they can measure inside, beyond the surface layer and completely non-destructively.

The areas of science that have used negative muons for elemental analysis have been very diverse. The largest area is the cultural heritage community as the non-destructive ability is particularly important and will become more so. This community have investigated swords from different eras, coins (Roman gold and silver, Islamic silver and from the Tudor Warship Mary Rose), Bronze Age tools and cannon balls. In addition, energy materials (Li composition for hydrogen storage), bio-materials (search for iron to potentially help understand Alzheimer's), engineering alloys (manufacturing processes for new materials for jet engines), and functional materials (surface effects in piezo electrics) have also been investigated.

(3) Ultra-cold (low energy) Muon Beam Generation and Applications

Positive muon beam with thermal energy has been produced by laser ionization of muonium (bound system of μ^+ and electron) emitted from a hot tungsten surface with stopping surface muon beam at Port-3. The method generates a positive muon beam with acceleration energy from several 100 eV to several 10 keV, small beam size (a few mm) and good time resolution (less than 8 nsec). By stopping the ultra-cold muon beam in thin foil, multi-layered materials and artificial lattices, we can precisely measure local magnetic field in the materials, and apply the μSR techniques to surface and interface science. Since there has been no appropriate probe to study magnetism at surface and interface, the ultra-cold muon beam will open a new area of these research fields. In addition, the development of ultra-cold muon beam is very important as the source of ultra-cold (pencil-like small emittance) muon beam for muon $g-2$/EDM measurement. It is essential to increase the slow muon beam production efficiency by 100 times for these applications. There are three key techniques in ultra-cold muon generation: production of thermal muonium, high intensity Lyman-alpha laser and the ultra-cold muon beam line.

A high-power Lyman-alpha laser was developed in collaboration with the Advanced Photonics group at RIKEN. The new laser system is used at J-PARC U-line and, upon completion, will ionize muoniums 100 times more efficiently for slow muon beam generation. In this development, we succeeded to synthesize novel ceramic-based Nd:YGAG crystal, which realized a highly efficient and stable laser system. However, larger size crystal than presently available is needed for full design power, and we are working hard to improve the crystal.

We also succeeded in developing an efficient muonium generator, laser ablated silica aerogel, which emits more muoniums into vacuum even at room temperature. In 2013 at TRIUMF, by utilizing positron tracking method of muon decay position, we demonstrated at least 10 times increase of the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. Further study was carried out in 2017 to find the optimum fabrication that will maximize the muonium emission. An alternative detection method using muonium spin rotation, which will be sensitive even to muoniums near the surface, was tested at RIKEN-RAL in 2018 and was found successful.

In RIKEN-RAL Port 3, the ultra-cold muon beam line, which had been designed with hot tungsten, was completely rebuilt to use advantage of the new room temperature silica aerogel target. The equipment was tested with surface muon beam and basic data such as muon stopping in aerogel were taken. We are waiting the laser crystal development in order to proceed to ultra-cold muon generation. A similar target design will be adopted in the ultimate cold muon source planned for muon $g-2$/EDM at J-PARC.

(4) Other Fundamental Physics Studies

A measurement of the proton radius using muonic hydrogen at PSI revealed that the proton charge radius is surprisingly smaller than the radius measured using normal hydrogen spectroscopy and e-p scattering by more than 5 times their experimental precision. In contrast to the conventional measurement by means of electron, the PSI experiment utilized muonic hydrogen atom, and measured two different allowed transitions from one of the 2S levels to one of the 2P levels. The muonic atom has larger sensitivity to the proton radius because the negative muon orbits closer to the proton, although there is no reason why these measurements can yield inconsistent results if there exists no exotic physics or unidentified phenomenon behind. The cause of the discrepancy is not understood yet, thus a new measurement with independent method is much anticipated.

We proposed the measurement of the proton radius by using the hyperfine splitting of the muonic hydrogen ground state. This hyperfine splitting is sensitive to the Zemach radius, which is a convolution of charge and magnetic-dipole distributions inside proton. We are planning to re-polarize the muonic hydrogen by a circularly polarized excitation laser (excites one of the $F = 1$ states and regenerates the muon spin polarization), and detect the recovery of the muon decay-asymmetry along the laser.

At RIKEN, we are developing dedicated laser system (mid-infrared high-power pulse laser system at around 6 μm). We have tested the efficiency of our wavelength conversion scheme. We are going to test band-width narrowing using a seed laser of (Quantum Cascade Laser) and the laser reflection cavity. Preparation using muon beam is also in progress. We measured the muon stopping distribution in low-density hydrogen-gas cell, which gave us consistent results with beam simulation. The study of the beam originated background level gives us reasonably small level, in which we can conduct a precision measurement. Another key is the lifetime of the polarized triplet muonic hydrogen state. We successfully observed the muon spin precession of muonic deuterium atom in 2018 for the first time in the world, from which we can set limit on the lifetime. The measurement with muonic protium is planned in 2019.

(5) Other topics

RIKEN and ISIS have signed a new collaboration agreement for the period 2018–2023. This is the fourth in a continuous series of agreements, the first being signed in 1990, resulting in a partnership which will have lasted over 30 years. Under the new agreement, ownership and operation of the facility pass to ISIS, a refurbishment programme of the facility will be undertaken, a user programme for Japanese scientists will continue, and the partnership between RIKEN and ISIS will be continued. The RIKEN-RAL collaboration is regularly highlighted as a good example of UK-Japanese science partnership at the UK-Japan Joint Committee on Science and Technology (chaired by the UK Chief Scientific Advisor to Government and a counterpart from Japan) — for example, Dr. King and Dr. Watanabe presented RIKEN-RAL at the November 2016 meeting of the Committee. The RIKEN-RAL collaboration has also enabled the development of collaborative activity between RIKEN and other Asian universities, *e.g.* through several MoUs with Indonesian and Malaysian universities.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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K. Ishida, “Future opportunities in mu-p atoms,” FAMU meeting, Trieste, Italy, June, 2018.

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Safety Management Group

1. Abstract

The RIKEN Nishina Center for Accelerator-Based Science possesses one of the largest accelerator facilities in the world, which consists of two heavy-ion linear accelerators and five cyclotrons. This is the only site in Japan where uranium ions are accelerated. The center also has electron accelerators of microtron and synchrotron storage ring. Our function is to keep the radiation level in and around the facility below the allowable limit and to keep the exposure of workers as low as reasonably achievable. We are also involved in the safety management of the Radioisotope Center, where many types of experiments are performed with sealed and unsealed radioisotopes.

2. Major Research Subjects

(1) Safety management at radiation facilities of Nishina Center for Accelerator-Based Science
(2) Safety management at Radioisotope Center
(3) Radiation shielding design and development of accelerator safety systems

3. Summary of Research Activity

Our most important task is to keep the personnel exposure as low as reasonably achievable, and to prevent an accident. Therefore, we daily patrol the facility, measure the ambient dose rates, maintain the survey meters, shield doors and facilities of exhaust air and wastewater, replenish the protective supplies, and manage the radioactive waste. Advice, supervision and assistance at major accelerator maintenance works are also our task.

The entrance and exit management system for which is the part of the radiation control system developed for the RILAC upgrade was installed and started to operate. Interlock system will be set in the next year.

Minor improvements of the radiation safety systems were also done. The radiation monitors at the Nishina building has been replaced annually from 2015 because they get older, which were installed in 1986.

Members

Group Director
Yoshitomo UWAMINO (–March 31, 2018)
Kanenobu TANAKA (April 1, 2018–)

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Hisao SAKAMOTO (Technical Scientist)

Expert Technician
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Research Consultant
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Visiting Scientists
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Masayuki HAGIWARA (KEK)
Nobuhiro SHIGYO (Kyushu Univ.)
Hiroshi YASHIMA (Kyoto Univ.)
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Arim LEE (Pohang Accelerator Laboratory POSTECH)

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Eunji LEE (Kyushu Univ.)
Shougo IZUMITANI (Kyushu Univ.)

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Tomoyuki DANTSUKA (concurrent: Cryogenic Technology Team)

Temporary Staffing
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Part-time Workers
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Naoko USUDATE (Administrative Part-time Worker II)
Shin FUJITA (Part-time Worker)
Hiroshi KATO (Part-time Worker)
Satomi IIZUKA (Administrative Part-time Worker II)
Yukiko SHIODA (Administrative Part-time Worker II)
Hiroko AISO (Part-time Worker)

Assistant

Tomomi OKAYASU

List of Publications & Presentations

Publications

Oral Presentations

[Domestic Conference]

田中鐘信, 「理化学研究所 RIBF 加速器施設の火災時対応と個人線量管理について」, 第 6 回加速器施設安全シンポジウム, 東海村, 2018 年 1 月.

杉原健太, 李恩智, 執行信寛, 田中鐘信, 赤塩敦子, 佐波俊哉, 「Bi に対する 7 MeV/u α 入射による中性子生成量測定」, 日本原子力学会 2019 年春の年会, 水戸, 2019 年 3 月.

User Liaison Group

1. Abstract

The essential mission of the User Liaison Group is to maximize the research activities of RIBF by attracting users in various fields with a wide scope. The Group consists of two teams. The RIBF User Liaison Team provides various supports to visiting RIBF users through the RIBF Users Office. Managing RIBF beam time and organizing the Program Advisory Committee Meetings to review RIBF experimental proposals are also important mission of the Team in order to enhance collaborative-use of the RIBF. The Outreach Team has created various information materials, such as pamphlets, posters, and homepages, to introduce the research activities in the RNC. On the homepage, we provide information on usage of the RIBF facility. The team also participate in science introduction events hosted by public institutions. In addition, the User Liaison Group also takes care of laboratory tours for RIBF visitors from public. The numbers of visitors amounts to 2,300 per year.

Members

Group Director

Hideyuki SAKAI (–March 31, 2018)
Hideki UENO (April 1, 2019–)

Senior Visiting Scientists

Ikuko HAMAMOTO (Lund Univ.)
Munetake ICHIMURA (Univ. of Tokyo)

Assistants

Tomomi OKAYASU (Concurrent: Safety Management Grp.)
Yoko FUJITA
Yu NAYA
Midori YAMAMOTO

User Liaison Group
RIBF User Liaison Team

1. Abstract

To enhance synergetic common use of the world-class accelerator facility, the Radioisotope Beam Factory (RIBF), it is necessary to promote a broad range of applications and to maximize the facility's importance. The facilitation and promotion of the RIBF are important missions charged to the team. Important operational activities of the team include: i) the organization of international Program Advisory Committee (PAC) meetings to review experimental proposals submitted by RIBF users, ii) RIBF beam-time operation management, and iii) promotion of facility use by hosting outside users through the RIBF Independent Users program, which is a new-user registration program begun in FY2010 at the RIKEN Nishina Center (RNC) to enhance the synergetic common use of the RIBF. The team opened the RIBF Users Office in the RIBF building in 2010, which is the main point of contact for Independent Users and provides a wide range of services and information.

2. Major Research Subjects

(1) Facilitation of the use of the RIBF
(2) Promotion of the RIBF to interested researchers

3. Summary of Research Activity

(1) Facilitation of the use of the RIBF

The RIBF Users Office, formed by the team in 2010, is a point of contact for user registration through the RIBF Independent User program. This activity includes:

- registration of users as RIBF Independent Users,
- registration of radiation workers at the RIKEN Wako Institute,
- provision of an RIBF User Card (a regular entry permit) and an optically stimulated luminescence dosimeter for each RIBF Independent User, and
- provision of safety training for new registrants regarding working around radiation, accelerator use at the RIBF facility, and information security, which must be completed before they begin RIBF research.

The RIBF Users Office is also a point of contact for users regarding RIBF beam-time-related paperwork, which includes:

- contact for beam-time scheduling and safety review of experiments by the In-House Safety Committee,
- preparation of annual Accelerator Progress Reports, and
- maintaining the above information in a beam-time record database.

In addition, the RIBF Users Office assists RIBF Independent Users with matters related to their visit, such as invitation procedures, visa applications, and the reservation of on-campus accommodation.

(2) Promotion of the RIBF to interested researchers

- The team has organized an international PAC for RIBF experiments; it consists of leading scientists worldwide and reviews proposals in the field of nuclear physics (NP) purely on the basis of their scientific merit and feasibility. The team also assists another PAC meeting for material and life sciences (ML) organized by the RNC Advanced Meson Laboratory. The NP and ML PAC meetings are organized twice a year.
- The team coordinates beam times for PAC-approved experiments and other development activities. It manages the operating schedule of the RIBF accelerator complex according to the decisions arrived at by the RIBF Machine Time Committee.
- To promote research activities at RIBF, proposals for User Liaison and Industrial Cooperation Group symposia/mini-workshops are solicited broadly both inside and outside of the RNC. The RIBF Users Office assists in the related paperwork.
- The team is the point of contact for the RIBF users' association. It arranges meetings at RNC headquarters for the RIBF User Executive Committee of the users' association.
- The Team conducts publicity activities, such as arranging for RIBF tours, development and improvement of the RNC official web site, and delivery of RNC news via email and the web.

Members

Team Leader

Ken-ichiro YONEDA

Contract Researcher

Tadashi KAMBARA (Concurrent: Industrial Application Research Team)

User Liaison Group
Outreach Team

1. Abstract

The Outreach Team has created various information materials to introduce research activities in the RNC. For instance, the team makes brochures introducing the RNC and the RIBF accelerator facility, posters of symposia and the summer school hosted by RNC, the center homepage containing information such as details of RNC and the procedure for the use of the RIBF facility, and images of equipment and facilities available for researchers inside and outside RIKEN, among the others. Furthermore, the team also participates in science introduction events hosted by public institutions.

2. Major Work Contents

The major work contents of the Outreach Team is to promote the publicity of RNC, through the creation of various materials such as brochures, websites, posters, and videos, among the others. The arrangement of tours of the RIBF facility and the exhibition and introduction of the RIBF facility at science events are also conducted independently or in cooperation with RIKEN Public Relations Office.

3. Summary of Work Activity

The specific work contents performed by the team are as follows:

- [Website] The Team creates/manages the RNC official website (`http://www.nishina.riken.jp`), which introduces the organization and its research activities. This website plays an important role in providing information to researchers who visit RNC to conduct his/her own research.
- [Brochures] The Team has produced various brochures introducing the organization and the studies performed at RNC. The brochures named "Your body is made of star scraps" explaining element synthesis in the universe and "Introduction of RIBF Facility" in a cartoon style for children are among them.
- [Posters] Conference/Symposium posters connected with RNC were prepared on the request of organizers. For general purpose, a special poster featuring the nuclear chart has been prepared for distribution. In commemoration of the discovery of nihonium, brochures and posters dedicated to the ceremony were made.
- [RIBF Cyclopedia] In April 2012, the permanent exhibition hall (RIBF Cyclopedia) located at the entrance hall of the RIBF building was set up in cooperation with RIKEN Public Relations Office. Explanatory illustrations on nuclear science, research at RIBF, RIBF history, a 3D nuclear chart built with LEGO blocks, and a 1/6-size GARIS model are displayed to help understanding through visual means. The Team is also working on updating the exhibits.
- [RIBF facility tour] The Team arranges RIBF facility tour for over 2000 visitors per year. The tour is guided by a researcher.
- [Science event participation] In 2010, 2012, 2013, 2015, and 2016, the sub-team opened an exhibition booth of RNC to introduce the latest research activities on the occasion of the "Science Agora" organized by Japan Science and Technology Agency (JST). From time to time, the sub-team was invited to participate in scientific events by MEXT, Wako city, and Nissan global foundation. One attraction targeting children is the hands-on work of assembling "Iron-beads" to create a nuclear chart or a shape of nihonium.

In addition to the above-noted work contents, the Team conducts a variety of works, such as taking pictures of meetings organized by RNC, cooperation in the production of a 3D video to explain the accelerators and the research at RIBF, among the others.

Members

Team Leader
Hideki UENO

Deputy Team Leader
Yasushi WATANABE (concurrent: Senior Research Scientist, Radiation Laboratory)

Technical Staff I
Narumasa MIYAUCHI (concurrent: Research Administrator, Office of the Center Director)

List of Publications & Presentations

Outreach Activities

Hokkaido Science Festival 2018, Sapporo, Japan, August 6–7, 2018.

Partner Institutions

The Nishina Center established the "Research Partnership System" in 2008. This system permits an external institute to develop its own projects at the RIKEN Wako campus in equal partnership with the Nishina Center. At present, two institutes, the Center for Nuclear Study, the University of Tokyo (CNS); and the Wako Nuclear Science Center (WNSC), Institute of Particle and Nuclear Studies (IPNS), High-energy Accelerator Research Organization (KEK) are conducting research activities under the Research Partnership System.

CNS and the Nishina Center signed the partnership agreement in 2008. Until then, CNS had collaborated in joint programs with RIKEN under the "Research Collaboration Agreement on Heavy Ion Physics" (collaboration agreement) signed in 1998. The partnership agreement redefines procedures related to the joint programs while keeping the spirit of the collaboration agreement. The joint programs include experimental nuclear-physics activities using CRIB, SHARAQ, and GRAPE at RIBF, accelerator development, and activities at RHIC PHENIX.

KEK started low-energy nuclear physics activity at RIBF in 2011 under the Research Partnership System. The joint experimental programs are based on KISS (KEK Isotope Separator). After the R&D studies on KISS, it became available for users from 2015.

The experimental proposals that request the use of the above-noted devices of CNS and KEK together with the other RIBF key devices are screened by the Program Advisory Committee for Nuclear Physics experiments at RI Beam Factory (NP-PAC) The NP-PAC meetings are co-hosted together with CNS and KEK.

The activities of CNS and KEK are reported in the following pages.

Partner Institution
Center for Nuclear Study, Graduate School of Science
The University of Tokyo

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. We added a new group for fundamental symmetry by using heavy RIs. 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 line to CRIB. In 2017, the operating time of the HyperECR was 2414 hours, which is 61% of the total operating time of the AVF cyclotron. The beam extraction system of the HyperECR is under development to realize a high intensity and low emittance beam. We have succeeded to suppress $^{12}C^{4+}$ beam which contaminated $^{18}O^{6+}$ beam by measuring the light intensity of the CIV line spectrum. The calculation model of injection beam orbit of the AVF cyclotron was completed and the adjustment of the positon and angle deviation between the measured beam orbit and the calculated beam orbit is carried on. The detailed studies on ion optics of the beamline to CRIB from AVF cyclotron were performed with beam diagnosis system and simulation code, and it turned out the loss of the beam intensity is occurred at the entrance of the vertical deflection bending magnet.

(2) Nuclear Astrophysics

The main activity of the nuclear astrophysics group is to study astrophysical reactions and special nuclear clustering using the low-energy RI beam separator CRIB. Several experimental projects on big-bang nucleosynthesis (BBN) are currently under way. To give a solution to the cosmological ^{7}Li abundance problem, $^{7}\mathrm{Be}(n,\alpha)/(n,p)$ astrophysical reactions were studied with the Trojan Horse method, and the rate of $^{7}\mathrm{Be}(n,p_1)$, the (n,p) reaction with ^{7}Li excitation, is evaluated at the BBN temperature for the first time. $^{7}\mathrm{Be}(d,p)$ measurement with a ^{7}Be-implanted target was carried out in 2018, in collaboration with RCNP, Osaka Univ. and JAEA. $^{8}\mathrm{Li}(\alpha,n)$ reaction has been considered as responsible to the production of nuclei heavier than boron in some models of the BBN. To solve the discrepancy between the previous measurements of $^{8}\mathrm{Li}(\alpha,n)$, a new experiment with γ-ray measurement was performed at CRIB in Sep. 2018. To confirm the exotic linear-chain cluster structure in ^{14}C nucleus indicated in the previous $^{10}\mathrm{Be}+\alpha$ resonant scattering measurement at CRIB, a new measurement was carried out at INFN-LNS, Catania, Italy, under the collaboration of CNS, INFN, Univ. Edinburgh and other institutes, in Oct. 2018. A measurement on $^{25}\mathrm{Al}+p$ resonant scattering was performed at CRIB in Feb. 2019, to study the resonances relevant for the astrophysical $^{22}\mathrm{Mg}(\alpha,p)$ reaction in X-ray bursters.

(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. In 2017, the following progress has been made. Experimental data taken under the EURICA collaboration has been analyzed for studying octupole deformation in neutron-rich Ba isotopes and preparing publication. A new experiment measuring the $^{4}\mathrm{He}(^{8}\mathrm{He},{}^{8}\mathrm{Be})4n$ reaction was performed for better statistics and better accuracy in order to verify a candidate of the ground state of the tetra neutrons just above the 4n threshold, which is under analysis.

(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 and p-Pb collisions, J/ψ measurements in p-Pb collisions, long range two particle correlations in p-Pb collisions, and searches for thermal photons in p-Pb collisions. The group has involved in the ALICE-TPC upgrade using a Gas Electron Multiplier (GEM). Development of the new data readout system for the upgrade, which aims online data processing by utilizing FPGA and GPU, has been ongoing in 2017.

(5) Nuclear Theory

The nuclear theory group participates a project, "Priority Issue 9 to be tackled by using the Post-K Computer" and promotes computational nuclear physics utilizing supercomputers. In FY2017, we performed the Monte Carlo shell model calculations of the Sn isotopes and revealed that the anomalous enhancement of the B(E2) transition probabilities in the neutron-deficient region is caused by the proton excitation from the $1g_{9/2}$ orbit, and found that the second-order quantum phase transition occurs around $N = 66$. We also investigated the double Gamow-Teller strength distribution of double-beta decay emitters, such as ^{48}Ca. We theoretically predict a linear relation between the nuclear matrix elements of the double Gamow-Teller transition and the neutrinoless double beta decay. In parallel, we have been promoting the CNS-RIKEN collaboration project on large-scale nuclear structure calculations and performed shell-model calculations under various collaborations with many experimentalists for investing the exotic structure of neutron-rich nuclei, such as ^{35}Mg, ^{136}Ba, ^{138}Ce, and ^{135}La.

(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 successfully reaches calcium isotopes beyond $N = 34$, ^{55,57}Ca, and the preparation of publication is ongoing. The experimental study of 0^- strength in nuclei using the parity-tansfer charge exchange (^{16}O, ^{16}F) is on progress and the data analysis is on the final stage. The OEDO beamline, which was an upgrade of the high-resolution beamline to produce low-energy RI beams, has started the operation in June and has successfully achieved the designed ion-optical performance. The first and second experiments were performed in October and November, and new data for nuclear transmutation of long lived fission products (LLFPs) were successfully obtained.

(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) reaction. In 2017 a set of neutron counters PANDORA was used for the first time at HIMAC facility for the study of the ^{6}He(p, n) reaction. Candidate nuclei to study are high spin isomers such as ^{52}Fe(12^+). Development of isomer beam was carried out.

(8) Low Energy Nuclear Reaction Group

A recoil particle detector for missing mass spectroscopy, named TiNA, had been developed under the collaboration with RIKEN and RCNP. TiNA consists of 6 sector telescopes. Each of which as a stripped-type SSD and 2 CsI(Tl) crystals. After the test experiment at the tandem facility of Kyushu Univ., TiNA was employed at the physics experiment with OEDO. Development of the tritium target is still on-going. Several deuterium doped Ti targets were fabricated at the Toyama Univ. They were tested by using d(^{12}C, d) reaction at the tandem facility at Kyushu. The amount of deuterium was found to be scattered. The optimum condition to make the target will be sought for. The production cross section ^{178m2}Hf was evaluated for the mass production in the future. The digital signal processing devices for the GRAPE have been developed to measure the cascade transitions from the isomeric state. After chemical separation of Hf at the hot laboratory at RIBF. The week cascade decay was successfully measured.

(9) Active Target Development

Two types of gaseous active target TPCs called CAT's and GEM-MSTPC are developed and used for the missing mass spectroscopy. 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. In 2017, we developed a larger active target called CAT-M, which has 10-times larger active volume than that of CAT-S. The CAT-M was commissioned at HIMAC and the excitation energy spectrum of ^{136}Xe for proton scattering was measured. 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

Although the Standard Model of particle physics is being steadily and successfully verified, the disappearance of the antimatter in the universe could not be sufficiently explained; a more fundamental framework is required and has to be studied. In order to understand the mechanism of matter-antimatter symmetry violation, we are developing the next generation experiments employing ultracold atoms to search for the electron electric dipole moment (EDM) using heavy element francium (Fr) in an optical lattice at RIBF. The developments of a high intensity surface ionizer to produce Fr and a magneto-optical trap (MOT) are in progress, and Fr-MOT experiments are going on at present at CYRIC.

Members

Director

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Shinsuke OTA (Assistant Professor)
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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

T. Nishi, K. Itahashi, G. P. A. Berg, H. Fujioka, N. Fukuda, N. Fukunishi, H. Geissel, R. S. Hayano, S. Hirenzaki, K. Ichikawa, N. Ikeno, N. Inabe, S. Itoh, M. Iwasaki, D. Kameda, S. Kawase, T. Kubo, K. Kusaka, H. Matsubara, S. Michimasa, K. Miki, G. Mishima, H. Miya, H. Nagahiro, M. Nakamura, S. Noji, K. Okochi, S. Ota, N. Sakamoto, K. Suzuki, H. Takeda, Y. K. Tanaka, K. Todoroki, K. Tsukada, T. Uesaka, Y. N. Watanabe, H. Weick, H. Yamakami, K. Yoshida, "Spectroscopy of pionic atoms in ^{122}Sn(d, ^{3}He) reaction and angular dependence of the formation cross sections," Phys. Rev. Lett. **120**, 152505 (2018). *

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[Proceedings]

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N. Imai, “Nuclear reaction data of low-energy LLFP produced by OEDO,” Proceedings of the 2017 Symposium on Nuclear Data, JAEA-Conf2018-001, 39–44 (2018). *

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N. Tsunoda, T. Otsuka, N. Shimizu, “Structure of exotic nuclei based on nuclear force,” Proceedings of the Ito International Research Center Symposium “Perspectives of the Physics of Nuclear Structure,” **23**, 012014. (2018). *

T. Abe, “Advances in the Monte Carlo Shell Model for Understanding Nuclear Structure,” JPS Conf. Proc. **23**, 012009 (2018). *

J. Menéndez, “Towards reliable nuclear matrix elements for neutrinoless $\beta\beta$ decay,” Proceedings of the “Symposium on Perspectives of the Physics of Nuclear Structure,” JPS Conf. Proc. **23**, 012036 (2018). *

T. Miyagi, T. Abe, M. Kohno, P. Navrátil, R. Okamoto, T. Otsuka, N. Shimizu, S. R. Stroberg, "Nuclear Ab Initio Calculations with the Unitary-Model-Operator Approach," JPS Conf. Proc. **23**, 013007 (2018). *

Oral Presentations

[International Conference etc.]

S. Shimoura (Invited), "Tetra-neutron and few-body correlations studied by RI-beam experiments," New Frontiers in Nuclear Physics and Astrophysics (NNPA), Antalya, Turkey, June 1–May 28, 2018.

S. Shimoura (Invited), "Tetraneutron system populated by double-charge exchange reactions using RI beam," The 13th International Conference on Hypernuclear and Strange Particle Physics (HYP2018), Portsmouth, Virginia, USA, June 24–29, 2018.

S. Shimoura (Invited), "Tetra-neutron system populated by RI-beam induced reactions," The 22nd International Conference on Few-Body Problems in Physics (FB22), Caen, France, July 9–13, 2018.

S. Shimoura (Invited), "Nuclear Reaction Data for Long-Lived Fission Products," ImPACT International Symposium on "New Horizons of Partitioning and Transmutation Technologies with Accelerator System," The University of Tokyo, December 2–3, 2018.

S. Shimoura (Invited), "Tetra-neutron system populated by exothermic double-charge exchange reaction," 13th International Conference on Nucleus-Nucleus Collisions (NN2018), Omiya, Saitama, December 4–8, 2018.

N. Imai (Invited), "Experimental studies with the energy-degraded RI beams," 20th Northeastern Asia symposium, Nagoya, Japan, September 19, 2018.

S. Michimasa (Invited), "Overview of OEDO," International OEDO Workshop 2018, Wako, Japan, June 11, 2018.

M. Dozono (Invited), "Status report of ImPACT17-02-01/02," International OEDO Workshop 2018, Wako, Japan, June 11, 2018.

N. Imai (Oral), "Measurement of ^{77,79}Se(d,p) reactions in inverse kinematics at OEDO," The 10th international conference on Direct Reaction with Exotic Beams (DREB2018), Matsue, Japan, June 4–8, 2018.

S. Michimasa (Oral), "New energy-degrading beam line for in-flight RI beams, OEDO," The International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS), CERN Geneva, Switzerland, September 16–21, 2018.

S. Michimasa (Oral), "Construction of Low-energy RI Beam Line at RIBF and Nuclear Reaction Data on Low-energy LLFPs," Fifteenth NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Manchester Hall, Manchester, UK, September 30–October 3, 2018.

S. Michimasa (Invited), "Recent Achievements using OEDO-SHARAQ at RIBF," The 10th China-Japan Joint Nuclear Physics Symposium (CJNP2018), Sheraton Bailuhu Resort Hotel, Houzhou, China, November 18–23, 2018.

S. Ota (Invited), "Active target technique with medium-energy high-intensity heavy-ion beams," The 10th China-Japan Joint Nuclear Physics Symposium (CJNP2018), Sheraton Bailuhu Resort Hotel, Huizhou, China, November 18–23, 2018.

N. Imai (Invited), "Surrogate reaction of ^{79}Se(n,γ)," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

S. Michimasa (Oral), "Direct mass measurements of very neutron-rich calcium isotopes beyond $N = 34$," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

M. Dozono (Oral), "Nuclear reaction study for long-lived fission products in nuclear waste: Proton-and deuteron-induced reactions on ^{107}Pd and ^{93}Zr at 20–30 MeV/u," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

S. Ota (Invited), "Experimental study of the isospin dependence of nuclear incompressibility," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

S. Masuoka (Oral), "Re-measurement of ^{4}He(^{8}He, ^{8}Be) reaction," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

R. Tsunoda (Oral), "Proton resonance scattering of a shape-coexistence nucleus ^{118}Sn," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

K. Kawata (Oral), "Production of isomers around ^{52}Fe nucleus via projectile fragmentation," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

L. Stuhl (Oral), "Study of spin-isospin responses of radioactive nuclei with background free neutron spectrometer, PANDORA International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS2018)," CERN, Geneva, Switzerland, September 16–21, 2018.

L. Stuhl (Invited), "Detector development for (p,n) measurements at RIKEN RIBF," Nuclear Physics In Stellar Explosions Workshop, Debrecen, Hungary, September 12–14, 2018.

L. Stuhl (Oral), "Overview of campaign type experiments at SAMURAI—The ^{18}O campaign," SAMURAI International Workshop 2018, RIKEN Nishina Center, Wako, Japan, September 3–4, 2018.

L. Stuhl (Oral), "Status of (p, n) measurements at SAMURAI," SAMURAI International Workshop 2018, RIKEN Nishina Center, Wako, Japan, September 3–4, 2018.

L. Stuhl (Oral), "Study of spin-isospin responses of light nuclei along the drip line with PANDORA," The 10th international conference on Direct Reactions with Exotic Beams (DREB2018), Matsue, Japan, June 4–8, 2018.

H. Tokieda (Oral), "CNS Active Target (CAT) for high-intensity heavy-ion beam experiment," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

C. Iwamoto (Oral), "Performance evaluation of Dual Gain Multi-layer Thick GEM for CAT with high-intensity heavy-ion beams," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

S. Ota (Oral), "Giant resonances in Tin-region nuclei," 6th International Conference on Collective Motion in Nuclei under Extreme Conditions, Cape town, South Africa, October 29–November 2, 2018.

Y. Sekiguchi (Oral), "Long-range two-particle correlations," Second internal workshop on Collectivity in Small Collision Systems (CSCS2018), Wuhan, China, June 13–15, 2018.

Y. Sekiguchi for the ALICE Collaboration (Oral), "Long range angular correlations in p-Pb collisions with ALICE," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

S. Hayashi for the ALICE Collaboration (Oral), "J/ψ production in p-Pb collisions with the ALICE detector," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

S. Hayashi for the ALICE Collaboration (Oral), "J/ψ production in p-Pb collisions with the ALICE detector," The 7th Asian Triangle Heavy Ion Conference (ATHIC2018), Hefei, China, November 3–6, 2018.

Y. Sekiguchi for the ALICE Collaboration (Oral), "Two-particle correlations with ALICE," The 7th Asian Triangle Heavy Ion Conference (ATHIC2018), Hefei, China, November 3–6, 2018.

S. Hayashi for the ALICE Collaboration (Oral), "Quarkonium production in pp, pA, and AA collisions," Quark and Nuclear Physics 2018 (QNP2018), Tsukuba, Japan, November 13–17, 2018.

T. Gunji (Oral), "Extension of Forward Physics beyond 2030," International workshop on Forward Physics and Forward Calorimeter upgrade in ALICE, Tsukuba, Japan. March 7–9, 2019.

L. Yang (Oral), "Reaction mechanisms of ^{17}F + ^{58}Ni at energies around the Coulomb barrier," DREB2018, Kunibiki Messe, Matsue, Shimane, Japan, June 4–8, 2018.

H. Yamaguchi (Oral), "Study on explosive nuclear synthesis with low-energy RI beams at CRIB," 15th International Symposium on Nuclei in the Cosmos, LNGS, Assergi, Italy, June 24–29, 2018.

S. Hayakawa (Oral), "Cross section measurements of the ^{7}Be$(n, p)^{7}$Li and the ^{7}Be$(n, \alpha)^{4}$He reactions covering the Big-Bang nucleosynthesis energy range by the Trojan Horse method at CRIB," 15th International Symposium on Nuclei in the Cosmos, LNGS, Assergi, Italy, June 24–29, 2018.

H. Yamaguchi (Oral), "Activities at the low-energy RI beam separator CRIB," RIBF Users Meeting 2018, RIKEN, Wako, Saitama, Japan, September 5–6, 2018.

H. Yamaguchi (Invited), "Indirect method application for RI-beam experiments," ECT* Workshop "Indirect Methods in Nuclear Astrophysics," ECT*, Trento, Italy, November 5–9, 2018.

H. Yamaguchi (Invited), "Studies on nuclear astrophysics and nuclear clustering with low-energy RI beams at CRIB," 13th International Conference on Nucleus-Nucleus Collisions (NN2018), Omiya, Saitama, Japan, December 4–8, 2018.

H. Yamaguchi (seminar), "Study on cluster states in unstable nuclei with alpha-resonant scattering," RIBF Nuclear Physics Seminar, RIKEN, Wako, Saitama, Japan, January 8, 2019.

K. Harada (Oral), "Magneto-optical trapping of radioactive francium atoms: toward search for electron electric dipole moment," 11th Fundamental Physics using Atoms, OIST, Okinawa, Japan, March 1–4, 2019.

H. Nagahama (Oral), "A new approach to high-precision measurements of the electron EDM using francium atoms," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

H. Nagahama (Invited), "High-precision measurements for testing CP and CPT symmetry," 3rd ETH Zurich-The University of Tokyo Strategic Partnership Symposium on the UN Sustainable Development Goals and Innovation, The University of Tokyo, Japan, January 21–22, 2019.

T. Abe (Oral), "Recent advances of the no-core Monte Carlo shell model," GANIL Workshop on Nuclear Structure and Reactions for the 2020s, GANIL, Caen, France, July, 2018.

T. Abe (Oral), "Large-scale computation of the no-core Monte Carlo shell model for nuclear many-body problems," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

T. Abe (Oral), "Recent results and implications of no-core MCSM calculations for nuclear structure," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

T. Abe (Oral), "No-core Monte Carlo shell model calculations with Daejeon16 NN interaction," International Conference "Nuclear Theory in the Supercomputing Era – 2018" (NTSE-2018), IBS, Daejeon, Korea, November, 2018.

T. Abe (Oral), "Recent advances in the no-core Monte Carlo shell model for the alpha clustering nature in light nuclei," International workshop on "Recent advances in nuclear structure physics 2018" (RANSP2018), YITP, Kyoto, Japan, November 2018.

T. Abe (Oral), "Alpha-cluster structure from no-core Monte Carlo shell model (oral)," The 50th Reimei workshop on Universal Physics in Many-Body Quantum Systems —From Atoms to Quarks—, JAEA, Ibaraki, Japan, December 2018.

T. Abe (Oral), "Alpha-cluster structure from no-core Monte Carlo shell model," TRIUMF Theory Workshop on "Progress in Ab Initio Techniques in Nuclear Physics," TRIUMF, Vancouver, Canada, March 2019.

N. Shimizu (Oral), "Large-scale shell model calculations and chiral doublet of ^{128}Cs," International Conference, Nuclear Theory in the Supercomputing Era 2018 (NTSE-2018), November 2018.

N. Shimizu (Oral), "Double Gamow Teller transition and its relation to neutrinoless double beta decay matrix element," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

N. Shimizu (Oral), "Shell-model study in $A \sim 130$ nuclei and chiral doublet of ^{128}Cs," The 9th international workshop "Quantum Phase Transitions in Nuclei and Many-body Systems," Padova, Itally, May, 2018.

角田佑介 (Invited), "Shapes of Medium-mass Nuclei Studied by Monte Carlo Shell Model Calculations," Nuclear Structure 2018

(NS2018), Michigan State University, Michigan, USA, August 2018.

角田佑介 (Invited), "Large-scale shell model calculations for structure of Ni and Cu isotopes," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

N. Tsunoda (Oral), "Physics in the island of inversion starting from the first principle," Shapes and Symmetries in Nuclei: from Experiment to Theory (SSNET'18 conference), Gif-Sur Yvette, France, October 2018.

N. Tsunoda (Oral), "Study of neutron-rich nuclei via nuclear force and microscopic theory," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

J. Menéndez (Invited), "Double Gamow-Teller transitions in connection to neutrinoless double-beta decay," ECT* Workshop "Exploring the role of electro-weak currents, in Atomic Nuclei," Trento, Italy, April 2018.

J. Menéndez (Invited), "Current status of neutrinoless double beta decay matrix elements," 13th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2018), Indian Wells, USA, May 2018.

J. Menéndez (Invited), "Neutrinoless double-beta decay and direct dark matter detection," INT Workshop "From nucleons to nuclei: enabling discovery for neutrinos, dark matter and more," Seattle, USA, June 2018.

J. Menéndez (Invited), "Double charge exchanges for double beta decays," Symposium "Neutrinos and Dark Matter in Nuclear Physics (NDM18)," Daejeon, South Korea, July 2018.

J. Menéndez (Invited), "Recent progress on neutrinoless double-beta decay nuclear matrix elements," "Double-Beta Decay and Underground Science," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

J. Menéndez (Invited), "Nuclear observables to constrain neutrinoless double-beta decay," The 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, October 23–27, 2018.

J. Menéndez (Invited), "Nuclear matrix elements to unveil the nature of neutrinos and dark matter," Conference "Shapes and Symmetries in Nuclei: from Experiment to Theory (SSNET'18)," Gif-sur-Yvette, France, November 2018.

T. Miyagi (Oral), "Recent progress in the unitary-model-operator approach," TRIUMF workshop on Progress in Ab Initio Techniques in Nuclear Physics, Vancouver, Canada, February–March 2018.

[Domestic Conference]

下浦享 (Oral), 「核変換：新たな核変換の方法を探る」, ImPACT プログラム「核変換による高レベル放射性廃棄物の大幅な低減・資源化」公開成果報告会—新たな選択肢の提案, 未来に向けて—品川インターシティホール, 2019 年 3 月 9 日.

D. Dozono (Invited), "r-process study with OEDO," 研究会「重力波観測時代の r プロセスと不安定核」, Wako, Japan, June 20, 2018.

S. Michimasa (Invited), "Closed-shell property at $N = 34$ seen in the masses of neutron-rich Ca isotopes," 日本物理学会第 74 回年次会, 九州大学, 伊都キャンパス, 福岡, 2019 年 3 月 14 日–17 日.

M. Dozono (Oral), 「低速 RI ビームを用いた ^{107}Pd の陽子・重陽子誘起反応測定」, 日本物理学会第 7 回年次会, 九州大学, 伊都キャンパス, 福岡, 2019 年 3 月 14 日–17 日.

S. Masuoka (Oral), 「二重荷電交換反応 ^{4}He(^{8}He, ^{8}Be) 反応の再測定 (II)」, 日本物理学会第 74 回年次会, 九州大学, 伊都キャンパス, 福岡, 2019 年 3 月 14 日–17 日.

J. W. Hwang (Oral), "Angle-tunable Degrader for a low-energy beamline," 日本物理学会第 74 回年次会, 九州大学, 伊都キャンパス, 福岡, 2019 年 3 月 14 日–17 日.

M. Dozono (Oral), 「低速 RI ビームを用いた LLFP 核の核反応データ測定」, 日本原子力学会 2018 年秋の大会, 岡山大学, 津島キャンパス, 岡山, 2018 年 9 月 5 日–7 日.

N. Imai (Oral), 「核変換による高レベル放射性廃棄物の大幅な低減・資源化 (4-2) 代理反応を用いた ^{79}Se$(n,\gamma)^{80}$Se 反応断面積評価," 日本原子力学会 2019 年春の年会, 茨城大学, 水戸キャンパス, 水戸, 2019 年 3 月 20 日–22 日.

M. Dozono (Oral), 「核変換による高レベル放射性廃棄物の大幅な低減・資源化 (4-3) 低速 RI ビームを用いた LLFP 核の陽子・重陽子誘起反応測定」, 日本原子力学会 2019 年春の年会, 茨城大学, 水戸キャンパス, 水戸, 2019 年 3 月 20 日–22 日.

Y. Sekiguchi (Oral), 「$p + p$ や p/d/He + A 衝突（小さい系）における集団運動」, 35th Heavy Ion Café and 27th Heavy Ion Pub, June 30, 2018. Nagoya, Japan.

T. Gunji (Oral), 「EM プローブ」, 35th Heavy Ion Café and 27th Heavy Ion Pub, Nagoya, Japan, June 30, 2018.

Y. Sekiguchi for the ALICE Collaboration (Oral), "Pseudorapidity dependence of anisotropic flow in *p*-Pb collisions with the ALICE detector," The Physical Society of Japan 2019 annual meeting, Fukuoka, Japan, March 14–17, 2019.

T. Gunji for the ALICE Collaboration (Oral), "Low mass dielectron measurements in *pp* and Pb-Pb collisions at LHC-ALICE," The Physical Society of Japan 2019 annual meeting, Fukuoka, Japan, March 14–17, 2019.

酒見泰寛 (Invited), 「人工 RI 結晶による基本対称性の研究」, 超重元素研究の新展開（研究会）, 九州大学, 福岡, 2018 年 7 月 30–31 日.

酒見泰寛 (Invited), 「光格子重元素干渉計による基本対称性の研究」, 物質階層原理&ヘテロ界面（研究報告会）, 理化学研究所, 和光キャンパス, 和光, 2019 年 2 月 5–6 日.

酒見泰寛 (Invited), "Fundamental physics with laser cooled heavy elements," 2019 重元素化学ワークショップ, 理化学研究所, 和光キャンパス, 和光, 2019 年 3 月 27–28 日.

長濱弘季 (Invited), 「基本対称性の高精度検証」, RIBF 若手放談会：エキゾチック核物理の将来, 理研神戸, 日本, 2019 年 2 月.

早水友洋 (Oral), 「電子の永久電気双極子モーメント探索へ向けたフランシウム原子の生成とトラップ」, 日本物理学会第 74 回年次会, 伊都キャンパス, 九州大学, 福岡, 2019 年 3 月 14 日–17 日.

角田佑介 (Oral), 「モンテカルロ殻模型による中重核の構造の研究」, 素粒子・原子核・宇宙「京からポスト京に向けて」シンポジウム, 筑波大学東京キャンパス文京校舎, 東京, January 2019.

N. Tsunoda (Oral), "Physics in neutron-rich nuclei with the effective interaction for the shell model based on nuclear force," 日本物理学会第 73 回年次大会, 福岡, 2019 年 3 月.

角田直文, 「原子核殻模型の統計力学的理解」, 若手放談会：エキゾチック核物理の将来, 理研神戸, 2019 年 2 月,

角田直文, 「中性子過剰原子核の存在限界とその新しい原理—核力に基づく大規模計算による解析」, 素粒子・原子核・宇宙「京からポスト京に向けて」シンポジウム, 筑波大学東京キャンパス文京校舎, 東京, 2019 年 1 月.

阿部喬 (Invited), 「大規模数値計算の現在と未来」, RIBF 若手放談会:エキゾチック核物理の将来, 理研神戸, 2019 年 2 月.

清水則孝 (Oral), 「制限ボルツマンマシンによる殻模型波動関数の記述」, 日本物理学会第 73 回年次大会, 福岡, 2019 年 3 月.

清水則孝 (Oral), 「殻模型計算による中重核高スピン状態の記述とカイラル二重項バンド」, 素粒子・原子核・宇宙「京からポスト京に向けて」シンポジウム, 東京, 2019 年 1 月.

大城幸光 (Oral), 「CNS イオン源の現状」, 第 16 回 AVF 合同打ち合わせ, 2018 年 10 月 30–31 日. 高崎量子応用研究所.

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Posters Presentations

[International Conference etc.]

M. Dozono (Poster), "Proton- and deuteron-induced reactions on ^{107}Pd and ^{93}Zr at 20–30 MeV/nucleon," The 10th international conference on Direct Reaction with Exotic Beams (DREB2018), Matsue, Japan, June 4–8, 2018.

J. W. Hwang (Poster), "Study on performance of the OEDO beamline," The 10th international conference on Direct Reaction with Exotic Beams (DREB2018), Matsue, Japan, June 4–8, 2018.

S. Shimoura (Poster), "Reduction and resource recycling of high-level liquid radioactive wastes through nuclear transmutation-Nuclear Reaction Data of long-lived fission products," Fifteenth NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Manchester Hall, Manchester, UK, September 30–October 3, 2018.

K. Kawata (Poster), "Production of isomer beam around ^{52}Fe nucleus via projectile fragmentation," The 10th international conference on Direct Reaction with Exotic Beams (DREB2018), Matsue, Japan, June 4–8, 2018.

S. Hayashi for the ALICE Collaboration (Poster), "Inclusive J/ψ measurement at mid-rapidity in p-Pb collisions with the ALICE detector," Quark Matter 2018 (QM2018), Venice, Italy, May 13–19, 2018.

H. Shimizu (Poster), "Isomeric RIB Production of Aluminum-26," 15th International Symposium on Nuclei in the Cosmos, LNGS, Assergi, Italy, June 24–29, 2018.

N. Ozawa (Poster), "Development of a New Surface Ionizer for the FrEDM Experiment," The 11th International Workshop on Fundamental Physics Using Atoms, OIST, Okinawa, Japan, March 1–4, 2019.

[Domestic Conference]

下浦享 他 (Poster), 「PJ2-1 低速 RI ビーム開発」, ImPACT プログラム「核変換による高レベル放射性廃棄物の大幅な低減・資源化」公開成果報告会—新たな選択肢の提案, 未来に向けて—, 品川インターシティホール, 東京, 2019 年 3 月 9 日.

T. Abe, "Alpha-cluster structure from no-core Monte Carlo shell model (poster)," The 1st R-CCS International Symposium on K and Post-K: Simulation, Big Data and AI supporting Society 5.0, Kobe, Japan, February 2019.

阿部喬, "Alpha-cluster structure from no-core Monte Carlo shell model（ポスター発表）," 新学術領域「量子クラスターで読み解く物質の階層構造」, キックオフシンポジウム, 東工大, 2018 年 11 月.

Awards

大津秀暁, 藤田玲子, 松崎禎市郎, 櫻井博儀, 下浦享, 水口浩司, 大井川宏之, 小澤正基, 仁井田浩二, 平成 30 年度全国発明表彰「21 世紀発明賞」,「放射性廃棄物の処理方法の発明」,（特許第 6106892 号）, 2018 年 6 月.

Partner Institution
Wako Nuclear Science Center, IPNS (Institute of Particle and Nuclear Studies)
KEK (High Energy Accelerator Research Organization)

1. Abstract

The Wako Nuclear Science Center (WNSC) of KEK aims to promote low-energy nuclear physics and nuclear astrophysics research as well as interdisciplinary studies using short-lived radioactive nuclei. WNSC operates the KEK Isotope Separation System (KISS) which is an electro-magnetic isotope separator featuring elemental selectivity from the use of resonance laser ionization in a gas catcher. The KISS facility provides various neutron-rich nuclei via multinucleon transfer reactions. Of particular significance is its provision of nuclei in the vicinity of the neutron magic number $N = 126$. Optical and β-γ spectroscopy have been applied to these neutron-rich nuclear beams, for nuclear structure and nuclear astrophysical studies. Several new developments—a rotating target, a donut-shaped gas cell, and in-jet laser ionization scheme—have been performed to improve the performance of KISS facility. The WNSC has also developed multi-reflection time of flight mass spectrographs (MRTOF-MS) for precision mass measurements of short-lived nuclei in collaboration with the RIKEN SLOWRI team and the Institute of Basic Science (IBS), Korea. After successful mass measurements in combination with the GARIS-II at RILAC, the existing MRTOF-MS setup has been renewed for use with the GARIS-II relocated after the ring cyclotron, and additional MRTOF-MS setups are being fabricated and placed at KISS and at F11 of the ZeroDegree Spectrometer for comprehensive mass measurements of more than one thousand nuclides.

2. Major Research Subjects

(1) Production and manipulation of radioactive isotope beams for nuclear experiments.
(2) Explosive nucleosynthesis (r- and rp-process).
(3) Heavy ion reaction mechanism for producing heavy neutron-rich nuclei.
(4) Development of MRTOF mass spectrographs for short-lived nuclei.
(5) Comprehensive mass measurements of short-lived nuclei including superheavy elements.

3. Summary of Research Activity

KISS is an element-selective isotope separator, combining the use of a magnetic mass separator with in-gas-cell resonant laser ionization. The gas cell, filled with argon gas at 75 kPa, is a central component of KISS, from which only the elements of interest are extracted as an ion beam, and subsequently mass separated. In the cell, nuclei primarily produced by low-energy heavy-ion reactions are stopped (thermalization and neutralization), transported by a buffer gas (gas flow of $\sim$ 75 kPa argon in the present case), and then re-ionized by laser irradiation just before the exit. The gas cell was fabricated to efficiently collect the reaction products produced by multi-nucleon transfer (MNT) reactions. For higher primary beam intensities and a higher extraction efficiency, a doughnut-shaped gas cell with a rotating target wheel setup has been developed. The mass separated isotope beams are guided to a tape transport setup where a low-background beta telescope counter is setup and surrounded by an array of germanium detectors consisting of four super-clover germanium crystals. The system has successfully performed β-γ spectroscopy of isotopes of Pt, Ir and Os.

An important feature of KISS is the capability to perform laser spectroscopy by scanning the resonant ionization laser frequency. The hyperfine structure constants of ^{196,197,198}Ir and ^{199}Pt have been measured at KISS. However, due to pressure broadening of the resonance line in the gas cell, the linewidths were as large as 12 GHz. To determine electromagnetic moments and isotope shifts with much higher precision, an “in-gas-jet” laser ionization method has been implemented at KISS. A high repetition rate, narrowband laser radiation irradiates the atoms within the gas jet after the nozzle of the cell and an S-shaped radiofrequency quadrupole structure guides resonantly ionized ions toward the mass separator. With this new setup, a narrow line width of 0.6 GHz has been achieved for the hyperfine splitting spectrum of ^{194}Pt.

The multi-reflection time-of-flight mass spectrograph (MRTOF-MS) has been developed for direct mass measurements of short-lived heavy nuclei. After successful mass measurements of more than 80 nuclides, including short-lived ($T_{1/2}$ = 10 ms) isotopes of Ra and several isotopes of the trans-uranium elements Es and Md at GARIS-II in collaboration with the SLOWRI team and the Super Heavy Element Synthesis team of RIKEN, multiple MRTOF setups are being installed at different facilities of RIBF.

The first MRTOF was connected directly to the new GARIS-II in the E6 experimental room (after the ring cyclotron) in a manner expected to yield a total efficiency of more than 10%. This device will used for precise mass measurements of Db isotopes produced in cold fusion reactions, as well for measurements of Mc and Nh isotopes produced in hot fusion reactions. In 2018, a short online commissioning experiment was performed for testing the newly developed “alpha-ToF” detector which can correlate the time-of-flight signal to alpha-decay signals. The test experiment with a Ra isotope showed that the background rate was highly reduced and, in addition, the life-time of the isotope could be determined from the correlation data.

A mini-MRTOF with a so-called “gas-cell cooler buncher” setup has been installed at KISS and offline commissioning is in progress. Efficient trapping of a 30 keV ion beam from KISS has been confirmed. A third-prototype SLOWRI gas catcher with a “gutter structure” RF-carpet has been developed for a new MRTOF setup, referred to as the ZD-MRTOF, for use at the beam dump of the ZeroDegree spectrometer. This setup will be used for “symbiotic” experiments with other experimental groups who use the ZeroDegree spectrometer to perform efficient mass measurements in parallel to the other experiments.

Members

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

Y. Watanabe, Y. Hirayama, H. Miyatake, "KEK Isotope Separation System (KISS)," Nucl. Phys. News **28**, 2–28 (2018).

M. Reponen, V. Sonnenschein, T. Sonoda, H. Tomita, M. Oohashi, D. Matsui, M. Wada, "Towards in-jet resonance ionization spectroscopy: An injection-locked Titanium: Sapphire laser system for PALIS-facility," Nucl. Instrum. Methods Phys. Res. A **908**, 236–243 (2018). *

P. Schury, Y. Ito, M. Rosenbusch, H. Miyatake, H. Wollnik, "Improving wide-band mass measurements in a multi-reflection time-of-flight mass spectrograph by usage of a concomitant measurement scheme," Int. J. Mass Spectrom. **433**, 40–46 (2018). *

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M. La Commara, M. Mazzocco, A. Boiano, C. Boiano, C. Manea, C. Parascandolo, D. Pierroutsakou, C. Signorini, E. Strano, D. Torresi, H. Yamaguchi, D. Kahl, P. Di Meo, J. Grebosz, N. Imai, Y. Hirayama, H. Ishiyama, N. Iwasa, S. C. Jeong, H. M. Jia, Y. H. Kim, S. Kimura, S. Kubono, C. J. Lin, H. Miyatake, M. Mukai, T. Nakao, M. Nicoletto, Y. Sakaguchi, A. M. Sánchez-Benítez, F. Soramel, T. Teranishi, Y. Wakabayashi, Y. X. Watanabe, L. Yang, Y. Y. Yang, "^{8}B + ^{208}Pb elastic scattering at Coulomb barrier energies," J. Phys. Conf. Ser. **966**, 012010 (2018). *

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S. Kimura, Y. Ito, D. Kaji, P. Schury, M. Wada, H. Haba, T. Hashimoto, Y. Hirayama, M. MacCormick, H. Miyatake, J. Y. Moon, K. Morimoto, M. Mukai, I. Muary, A. Ozawa, M. Rosenbusch, H. Schatz, A. Takamine, T. Tanaka, Y. X. Watanabe, H. Wollnik, "Atomic masses of intermediate-mass neutron-deficient nuclei with relative uncertainty down to 35-ppb via multireflection time-of-flight mass spectrograph," Int. J. Mass Spectrom. **430**, 134–142 (2018). *

E. Strano, M. Mazzocco, A. Boiano, C. Boiano, M. La Commara, C. Manea, C. Parascandolo, D. Pierroutsakou, C. Signorini, D. Torresi, H. Yamaguchi, D. Kahl, L. Acosta, P. Di Meo, J. P. Fernandez-Garcia, T. Glodariu, J. Grebosz, A. Guglielmetti, N. Imai, Y. Hirayama, H. Ishiyama, N. Iwasa, S. C. Jeong, H. M. Jia, N. Keeley, Y. H. Kim, S. Kimura, S. Kubono, J. A. Lay, C. J. Lin, G. Marquinez-Duran, I. Marte, H. Miyatake, M. Mukai, T. Nakao, M. Nicoletto, A. Pakou, K. Rusek, Y. Sakaguchi, A. M. Sanchez-Benitez, T. Sava, O. Sgouros, C. Stefanini, F. Soramel, V. Soukeras, E. Stiliaris, L. Stroe, T. Teranishi, N. Toniolo, Y. Wakabayashi, Y. X. Watanabe, L. Yang, Y. Y. Yang, "^{7}Be and ^{8}B reaction dynamics at Coulomb barrier energies," J. Phys. Conf. Ser. **184**, 02015 (2018).

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M. Mukai, Y. Hirayama, Y. X. Watanabe, P. Schury, H. S. Jung, M. Ahmed, H. Haba, H. Ishiyama, S. C. Jeong, Y. Kakiguchi, S. Kimura, J. Y. Moon, M. Oyaizu, A. Ozawa, J. H. Park, H. Ueno, M. Wada, H. Miyatake, "High-efficiency and low-background multi-segmented proportional gas counter for be-ta-decay spectroscopy," Nucl. Instrum. Methods Phys. Res. A **884**, 1–10 (2018).*

T. Sonoda, H. Iimura, M. Reponen, M. Wada, I. Katayama, V. Sonnenschein, T. Takamatsu, H. Tomita, T. M. Kojima, “The laser and optical system for the RIBF-PALIS experiment,” Nucl. Instrum. Methods Phys. Res. A **877**, 118–123 (2018) .*

[Proceedings]

(Original Papers) *Subject to Peer Review

M. Mazzocco, A. Boiano, C. Boiano, M. La Commara, C. Manea, C. Parascandolo, D. Pierroutsakou, C. Signorini, E. Strano, D. Torresi, H. Yamaguchi, D. Kahl, L. Acosta, P. Di Meo, J. P. Fernandez-Garcia, T. Glodariu, J. Grebosz, A. Guglielmetti, N. Imai, Y. Hirayama, H. Ishiyama, N. Iwasa, S. C. Jeong, H. M. Jia, N. Keeley, Y. H. Kim, S. Kimura, S. Kubono, J. A. Lay, C. J. Lin, G. Marquinez-Duran, I. Martel, H. Miyatake, M. Mukai, T. Nakao, M. Nicoletto, A. Pakou, K. Rusek, Y. Sakaguchi, A. M. Sánchez-Benítez, T. Sava, O. Sgouros, F. Soramel, V. Soukeras, E. Stiliaris, L. Stroe, T. Teranishi, N. Toniolo, Y. Wakabayashi, Y. X. Watanabe, L. Yang, Y. Y. Yang, “^{8}B + ^{208}Pb elastic scattering at Coulomb barrier energies,” J. Phys. Conf. Ser. **1078**, 012013 (2018).*

Oral Presentations

[International Conference etc.]

M. Wada, “Mass measurements with MRTO at RIKEN RIBF,” NUSTAR Week 2018, Milan, Italy, September 27, 2018.

M. Wada, “Mass measurements of heavy elements at GARIS,” SSNET18 Conference, Paris, France, November 5–11, 2018.

M. Wada, “MRTOF mass spectrographs at RIKEN RIBF — toward comprehensive mass measurements of >1000 nuclides including superheavy nuclides —,” 13th Int. Conf. on Nucleus Nucleus Collisions (NN2018), Omiya, Japan, December 4, 2018.

P. Schury, “KISS and MRTOF project of KEK,” 10th China Japan Joint Nuclear Physics Symposium (CJNP2018), Huizhou, China, November 18–23, 2018.

Y. Hirayama, “Nuclear spectroscopy of r-process nuclei using KEK isotope separation system,” International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS2018), CERN Geneva, Switzerland, September 16–21, 2018.

M. Mukai, “Development of a multi-segmanted proportional gas counter for beta-decay sepectroscopy at KISS,” International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS2018), CERN Geneva, Switzerland, September 16–21, 2018.

Y. X. Watanabe, “Production of neutron-rich nuclei by multinucleon transfer reactions at KISS project,” IX Int. Symp. On Exotic Nuclei (EXON2018), Petrozavodsk, Russia, September 10–15, 2018.

[Domestic Conference]

H. Miyatake, 「r-過程の第三ピークと終焉領域–KEK-WNSC のアプローチ」, 重力波観測時代の r プロセスと不安定核研究会, 2018 年 6 月 20–22 日.

H. Miyatake, “RNB project on the astrophysical element synthesis,” TGSW2018, 筑波大学, 2018 年 9 月 21 日.

M. Wada, 「核データと重元素合成を中心とする宇宙核物理研究会, 札幌, 2019 年 3 月 6–8 日.

Y. Hirayama, “Nuclear spectroscopy of r-process nuclei in the vicinity of N = 126 at KISS,” 日本物理学会年次大会 Joint Symposium on Nuclear structure studies through the magic numbers, 九州大学, 福岡, 2019 年 3 月 14–17 日.

Events (April 2018 — March 2019)

RNC

Apr. 21	Wako Open Campus
Jun. 12	The 24th RBRC Management Steering Committee (MSC)
Jun. 29	The 8th Industrial Program Advisory Committee (In-PAC)
Jul. 20	The 16th Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)
Jul.24–Aug.3	Nishina School
Nov.29–Dec.3	The 19th Program Advisory Committee for Nuclear Physics Experiments at RI Beam Factory (NP-PAC)
Jan	The 17th Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)P-PAC)
Jan. 11	Interim Review of the Chief Scientist, Tomohiro UESAKA

CNS

Aug. 22–28	17th CNS International Summer School CNSSS18 https://indico2.cns.s.u-tokyo.ac.jp/event/30/

KEK

Sept. 4	2018 SSRI-PNS Collaboration meeting. http://research.kek.jp/group/wnsc/workshop/2018_SSRI-PNS_201809/

Press Releases (April 2018−March 2019)

RNC

Apr. 13	Spectroscopy of pionic atoms in 122Sn(d,3He) reaction and angular dependence of the formation cross sections	T. Nishi, Spin isospin Laboratory K. Itahashi, Meson Science Laboratory
May. 24	Most Strange Dibaryon from Lattice QCD	S. Gongyo, T. Doi, Quantum Hadron Physics Laboratory
May. 29	Termination of Electron Acceleration in Thundercloud by Intra/Inter-cloud Discharge	Y. Wada, High Energy Astrophysics Laboratory
May. 31	A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics	E. Rinaldi, Computing Group, RIKEN BNL Research Center
Jul. 10	Magic Nature of Neutrons in 54Ca: First Mass Measurements of 55-57Ca	T. Uesaka, Spin isospin Laboratory
Jul. 12	Discovery of 60Ca and Implications For the Stability of 70Ca	O. B. Tarasov, D. Ahn, N. Suzuki, BigRIPS Team
Aug. 3	Development of Ferromagnetic Fluctuations in Heavily Overdoped (Bi, Pb)2Sr2CuO6＋δ Copper Oxides	I. Watanabe, Meson Science Laboratory
Aug. 11	Novel shape evolution in Sn isotopes from magic numbers 50 to 82	T. Otsuka, Nuclear Spectroscopy Laboratory
Oct. 2	Characterization of the shape-staggering effect in mercury nuclei	T. Otsuka, Nuclear Spectroscopy Laboratory
Oct. 19	Extraction of the Landau-Migdal Parameter from the Gamow-Teller Giant Resonance in 132Sn	M. Sasano, T. Uesaka, Spin isospin Laboratory
Dec. 11	Creation of quark-gluon plasma droplets with three distinct geometry	Y. Akiba, Experimental Group, RIKEN BNL Research Center
Jan. 30	Interplay between nuclear shell evolution and shape deformation revealed by the magnetic moment of 75Cu	Y. Ichikawa, H. Ueno, Nuclear Spectroscopy Laboratory
Feb. 28	First spectroscopy of the Near Drip-line Nucleus 40Mg	P. Doornenbal, H. Sakurai, Radioactive Isotope Physics Laboratory

CNS

Jul. 10	希少原子核の高効率・高分解能質量測定による新しい魔法数 34 の確証	道正新一郎、小林幹、下浦亨、他