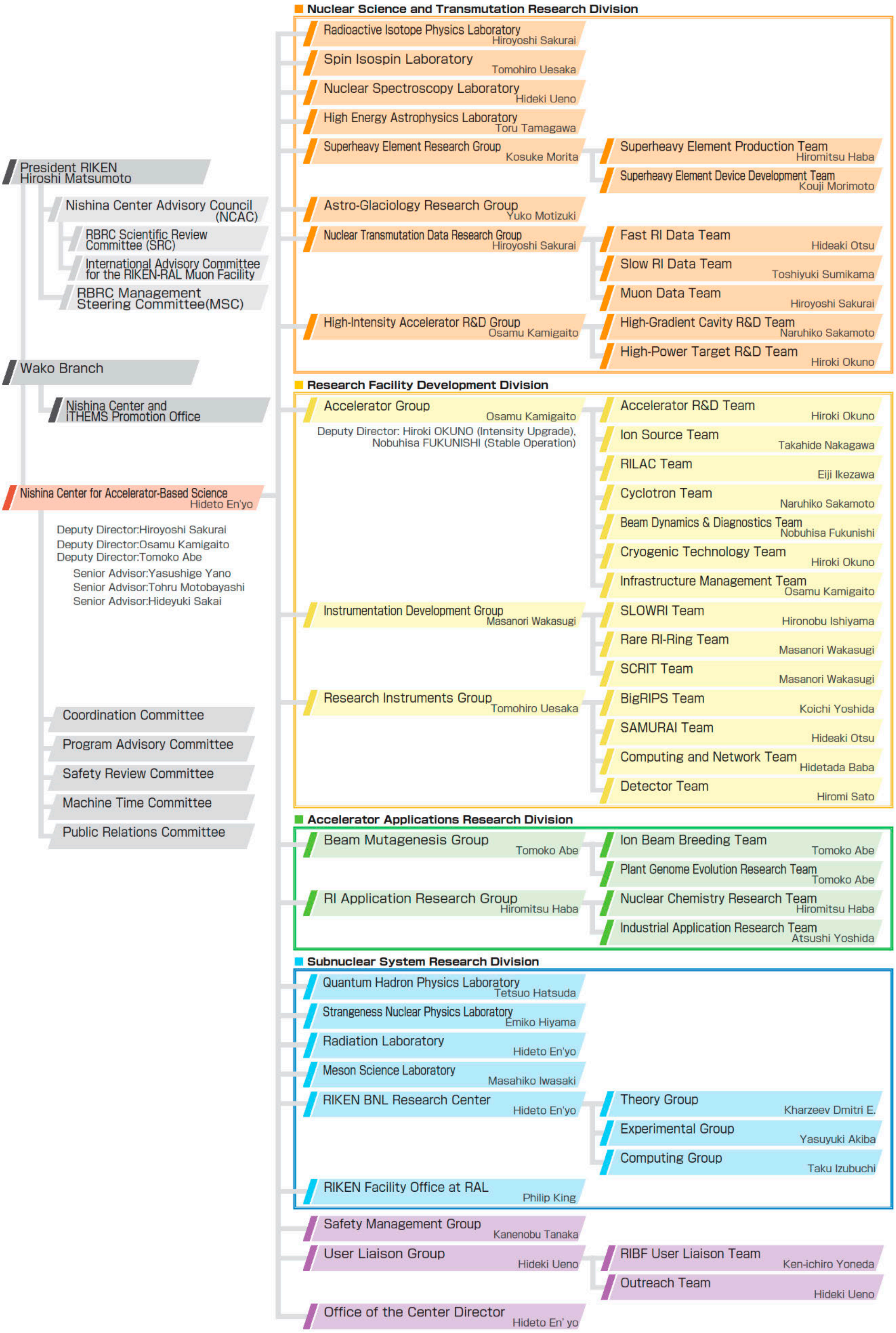
1. Organization

1.1 Organization Chart as of March 31, 2020 （End of FY2019）

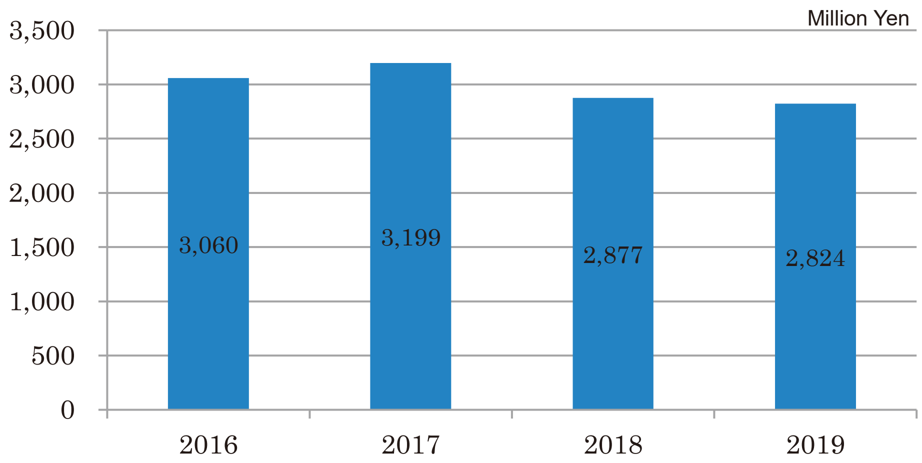


1.2 Topics in FY2019

Year	Date	Topics in Management
2019	Apr. 1	Newly appointed: Deputy Director of RIKEN BNL Research Center: David MORRISON
2019	Apr. 1	Newly appointed: Team Leader of Plant Genome Evolution Research Team: Tomoko ABE

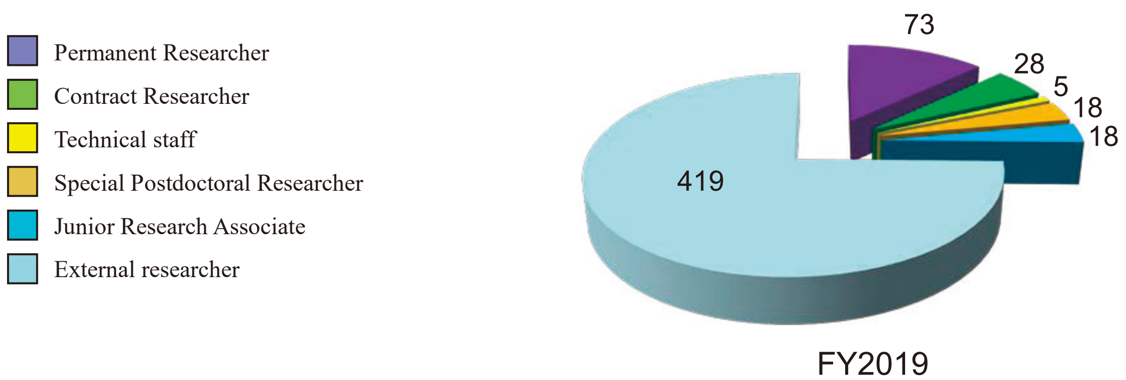
2. Finances

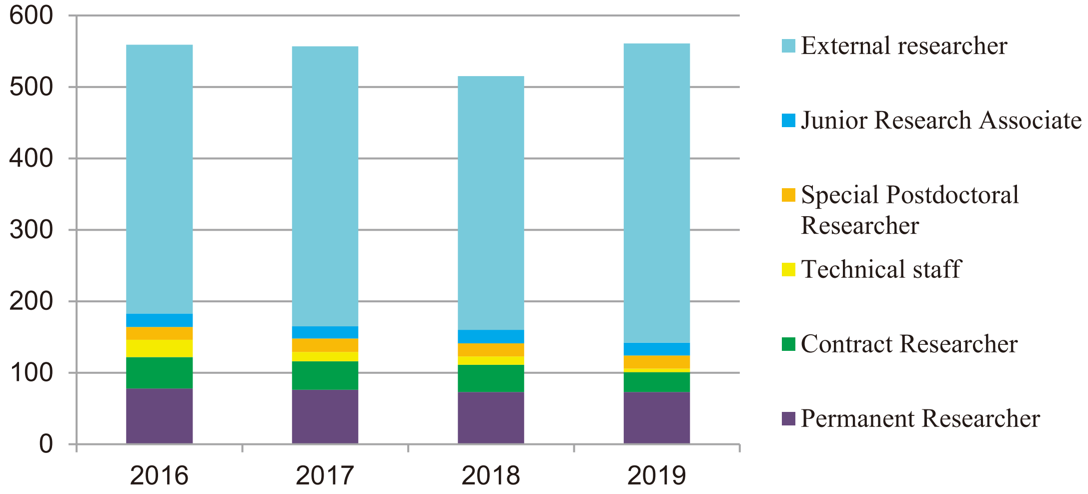
A transition of the RNC budget for the past four years is shown in following graph.



3. Staffing

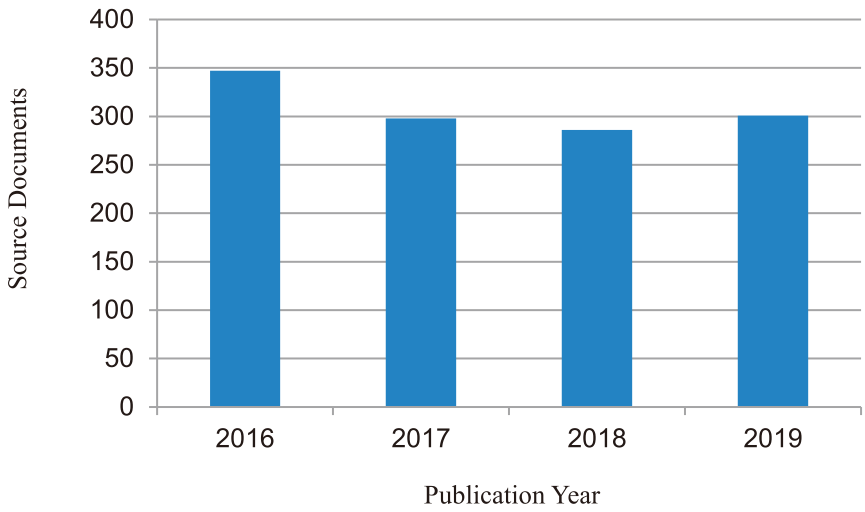
At the start of FY 2019, there were 142 personnel affiliated with RNC and 419 researchers visiting RNC for research purpose. The following graphs show a breakdown of personnel into six categories as of April 1, 2019, and a transition of the number of each category.





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 April 2020

Indicators \ Year	2016	2017	2018	2019
Total number of papers	347	298	286	301
Percentage of papers in top 10%	15.85	16.78	20.63	9.63
Percentage of papers in top 1%	1.44	2.68	4.20	1.00

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 FY2019. 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, 2020)

Hideto EN'YO	Director
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, 2020)

Hideto EN'YO	Director, RNC; Director, Radiation Laboratory
Hiroyoshi SAKURAI	Deputy Director, RNC; Director, Radioactive Isotope Physics Laboratory and Nuclear Transmutation Data Research Group; Team Leader, Muon Date Team
Osamu KAMIGAITO	Deputy Director, RNC; Director, Accelerator Group and High-Intensity Accelerator R&D Group; Team Leader, Infrastructure Management Team
Tomoko ABE	Deputy Director, RNC; Director, Beam Mutagenesis Group; Team Leader, Ion Beam Breeding Team and Plant Genome Evolution Research Team
Yasushige YANO	Senior Advisor, RNC
Tohru MOTOBAYASHI	Senior Advisor, RNC
Hideyuki SAKAI	Senior Advisor, RNC
Tomohiro UESAKA	Director, Spin Isospin Laboratory and Research Instruments Group
Hideki UENO	Director, Nuclear Spectroscopy Laboratory and User Liaison Group; Team Leader, Outreach Team
Toru TAMAGAWA	Director, High Energy Astrophysics Laboratory
Kosuke MORITA	Director, Superheavy Element Research Group
Yuko MOTIZUKI	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	Director, Instrumentation Development Group; Team Leader, Rare RI-Ring Team and SCRIT Team
Hiromitsu HABA	Director, RI Application Research Group; Team Leader, RI Application Team and Superheavy Element Production Team
Tetsuo HATSUDA	Director, Quantum Hadron Physics Laboratory
Emiko HIYAMA	Director, Strangeness Nuclear Physics Laboratory
Masahiko IWASAKI	Director, Meson Science Laboratory
Kanenobu TANAKA	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
Atsushi YOSHIDA	Team Leader, Industrial Application Research Team
Ken-ichiro YONEDA	Team Leader, RIBF User Liaison Team
Yasuyuki AKIBA	Group Leader, Experimental Group, RIKEN BNL Research Center
Taku IZUBUCHI	Group Leader, Computing Group, RIKEN BNL Research Center
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
Koichi ABE	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 20th NP-PAC was held on December 16−18, 2019 at RIBF.

Members (as of March 31, 2020)

Robert V.F. JANSSENS (Chair)	University of North Carolina at Chapel Hill
Dieter ACKERMANN	GANIL
Nori AOI	Osaka University
Maria J.G. BORGE	Consejo Superior de Investigaciones Científicas
Robert CHARITY	Washington University in St. Louis
Augusto O. MACCHIAVELLI	Lawrence Berkeley National Laboratory
Gabriel MARTINEZ-PINEDO	Technische Universität Darmstadt, GSI Helmholtzzentrum für Schwerionenforschung
Iain MOORE	University of Jyväskylä
David J. MORRISSEY	Michigan State University
Hitoshi NAKADA	Chiba University
Alexandre OBERTELLI	Technische Universität Darmstadt
Takehiko SAITO	RIKEN Cluster for Pioneering Research
Kimiko SEKIGUCHI	Tohoku University
Philip J. WOODS	University of Edinburgh
Andrea VITTURI	Universita' di Padova
Xiaohong ZHOU	Institute of Modern Physics, CAS

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

The 18th and 19th ML-PAC was held on June 28, 2019 and January 24, 2020 at RIBF, respectively.

Members (as of March 31, 2020)

Adrian HILLIER (Chair)	ISIS, RAL (UK)
Philippe MENDELS	Laboratorie de Physique des Solides, Universite Paris (SUD)
Zhi QIN	Institute of Modern Physics, CAS
Toshiyuki AZUMA	RIKEN Cluster for Pioneering Research
Ryosuke KADONO	Institute of Materials Structure Science (KEK)

Atsushi KAWAMOTO	Hokkaido University
Shigeyuki KAWANO	The University of Tokyo
Kenya KUBO	International Christian University
Hiroyuki YAMASE	Research Center for Functional Materials, NIMS
Xu-Guang ZHENG	Saga University
Robert V.F. JANSSENS	University of North Carolina at Chapel Hill

Industrial Program Advisory Committee (In-PAC)

The 9th In-PAC was held on July 10, 2019 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, 2020)

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
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Koichi YOSHIDA	Team Leader, BigRIPS Team
Naoki FUKUDA	Technical Scientis, BigRIPS Team
Naruhiko SAKAMOTO	Team Leader, Cyclotron Team
Daisuke SUZUKI	Research Scientist, Radioactive Isotope Physics Laboratory
Masaki SASANO	Senior Research Scientist, Spin Isospin Laboratory
Yuichi ICHIKAWA	Senior Research Scientist, Nuclear Spectroscopy Laboratory

External members

Shinichiro MICHIMASA	Assistant Professor, 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

Ex officio members

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

Hot-Lab Safety Review Committee

Members (as of March 31, 2020)

Kazuya TAKAHASHI (Chair)	Senior Research Scientist, Nuclear Chemistry Research Team
Kanenobu TANAKA	Director, Safety Management Group
Hisao SAKAMOTO	Technical Scientist, Safety Management Group
Hiroki MUKAI	Technical Staff I, Safety Management Group
Eriko HIGURASHI	Technical Scientist, Safety Management Group
Hiromitsu HABA	Team Leader, RI Application Team
Tetsuya OHNISHI	Senior Research Scientist, SCRIT 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, 2020)

Hideki UENO (Chair)	Director, User Liaison Group and Nuclear Spectroscopy Laboratory
Osamu KAMIGAITO	Director, Accelerator Group
Masanori WAKASUGI	Director, Instrumentation Development Group
Tomohiro UESAKA	Director, Research Instruments Group and Spin Isospin Laboratory
Nobuhisa FUKUNISHI	Deputy Group Director, Accelerator Group
Hiroki OKUNO	Deputy Group Director, Accelerator Group
Hiroyoshi SAKURAI	Director, Radioactive Isotope Physics Laboratory
Tomoko ABE	Director, Beam Mutagenesis Group

Hiromitsu HABA	Director, RI Application Research Group
Kanenobu TANAKA	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
Yutaka WATANABE	Associate Professor, High Energy Accelerator Research Organization, KEK

Observers

Hideto EN'YO	Director, RNC
Susumu SHIMOURA	Director, Center for Nuclear Study, University of Tokyo
Michiharu WADA	Director, KEK Wako Nuclear Science Center
Kosuke MORITA	Director, Superheavy Element Research Group
Hideaki OTSU	Team Leader, SAMURAI Team
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Tohru MOTOBAYASHI	Senior Advisor, RNC
Hideyuki SAKAI	Senior Advisor, RNC
Kathrin WIMMER	Lecturer, University of Tokyo; Chair, The RIBF Users Executive Committee (RIBF-UEC)
Yasuhiro SAKEMI	Professor, Center for Nuclear Study, University of Tokyo
Koichi ABE	Director, Nishina Center and iTHEMS Promotion Office
Kazushige FUKUSHIMA	Manager, Nishina Center and iTHEMS 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, 2020)

Koichi ABE (Chair)	Director, Nishina Center and iTHEMS Promotion Office
Hiroyoshi SAKURAI	Deputy Director, RNC; Director, Radioactive Isotope Physics Laboratory
Osamu KAMIGAITO	Deputy Director, RNC; Director, Accelerator Group
Tomoko ABE	Deputy Director, RNC; Director, Beam Mutagenesis Group
Tetsuo HATSUDA	Director, Quantum Hadron Physics Laboratory
Masahiko IWASAKI	Director, Meson Science Laboratory
Tomohiro UESAKA	Director, Spin Isospin Laboratory and Research Instruments Group
Hideki UENO	Director, Nuclear Spectroscopy Laboratory and User Liaison Group
Toru TAMAGAWA	Director, High Energy Astrophysics Laboratory
Emiko HIYAMA	Director, Strangeness Nuclear Physics Laboratory
Kosuke MORITA	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 25th MSC was held on May 24, 2019.

Members (as of May 24, 2019)

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

6. International Collaboration

Country	Partner Institute	Objects	RNC contact person

Austria	Stefan Meyer Institute for Subatomic Physics	Framework	Masahiko IWASAKI, Director, Meson Science Laboratory
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	Tomohiro UESAKA, Director, Spin Isospin Laboratory
	Normandy University	Framework	Tomohiro UESAKA, Director, Spin Isospin Laboratory
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
	Hasanuddin University	Agricultural science and related fields involving heavy-ion beam mutagenesis using Indonesian crops	Tomoko ABE, Director, Beam Mutagenesis Group
Italy	Applied Physics Division, National Institute for New Technologies, Energy and Environment (ENEA)	Framework	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
	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
	University of Bucharest	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
USA	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	Hiroyoshi SAKURAI, Director, Radioactive Isotope Physics Laboratory
Europe	European Nuclear Science and Application Research2	Framework	Tomohiro UESAKA, Director, Spin Isospin Laboratory
	The European Organization for Nuclear Research (CERN)	R&D and application of micro-pattern gas detectors (MPGD) technology (RD51 Collaboration)	Hideto EN'YO, Director, Radiation Laboratory
	The European Organization for Nuclear Research (CERN)	Collaboration in the ALICE Experiment	Hideto EN'YO, Director, Radiation Laboratory

7. Awards

Awardee, Laboratory / Team	Award	Organization	Date
Emiko HIYAMA, Director, Strangeness Nuclear Physics Laboratory	The FY 2019 Prize for Science and Technology, the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology	The Minister of Education, Culture, Sports, Science and Technology	Apr. 17
Daiki MORI, Technical Staff, Nuclear Chemistry Research Team	Young Scientist Oral Presentation Award at 56th Annual Meeting on Radioisotopes and Radiation Researchers	Japan Radioisotope Association	Jul. 4
Nozomi SATO, Research Part-time Worker, Nuclear Chemistry Research Team	IUPAC Periodic Table of Younger Chemists	IUPAC	Jul. 8
Yasushi ABE, Visiting Scientist, Instrumentation Development Group	The 16th PASJ Annual Award for poster presentation	Particle Accelerator Society of Japan	Aug. 3
Akio TOMIYA, Special Postdoctoral Researcher, Computing Group	The 13th Particle Physics Medal (FY2019): Young Scientist Award in Theoretical Particle Physics	Particle Theory Committee	Sep. 19
Kosuke MORITA, Director, Superheavy Element Research Group	The 2019 Kimura Award	The Japan Society of Nuclear and Radiochemical Sciences (JNRS)	Sep. 25

Koichi YOSHIDA, Team Leader, BigRIPS Team	The Saitama prefecture High-pressure Gas Chairman Commendation	The Saitama prefecture High-pressure Gas Committee	Oct. 23
A joint research group of RNC's Safety Management Group and the Neutron Beam Technology Team of RIKEN Center for Advanced Photonics	2019 Symposium on Nuclear Data Poster Presentation Award	Atomic Energy Society of Japan Nuclear Data Division	Nov.28
Tomoya NAITO, Student Trainee, Quantum Hadron Physics Laboratory	2020 CAEN Best Young Speaker Award	Organizing Comettee of "Vth Topical Workshop on Modern Aspects in Nuclear Structure"	Feb. 8
Hiromitsu HABA, Director, the RI Application Group	Open Innovation Prize (President of Science Council of Japan Prize)	Cabinet Office, Government of Japan	Feb. 27

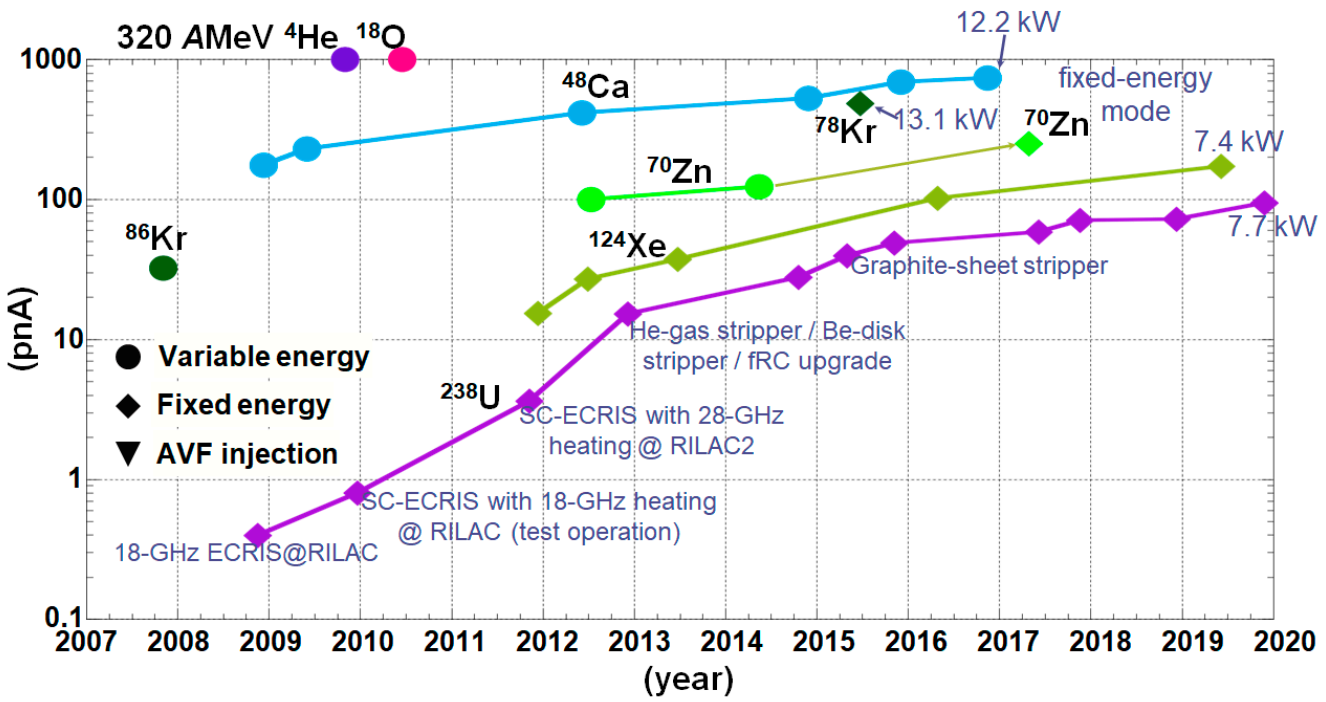
8. Brief overview of the RI Beam Factory

Intensity of Primary Beams

Achieved beam intensities (as of March 2019)

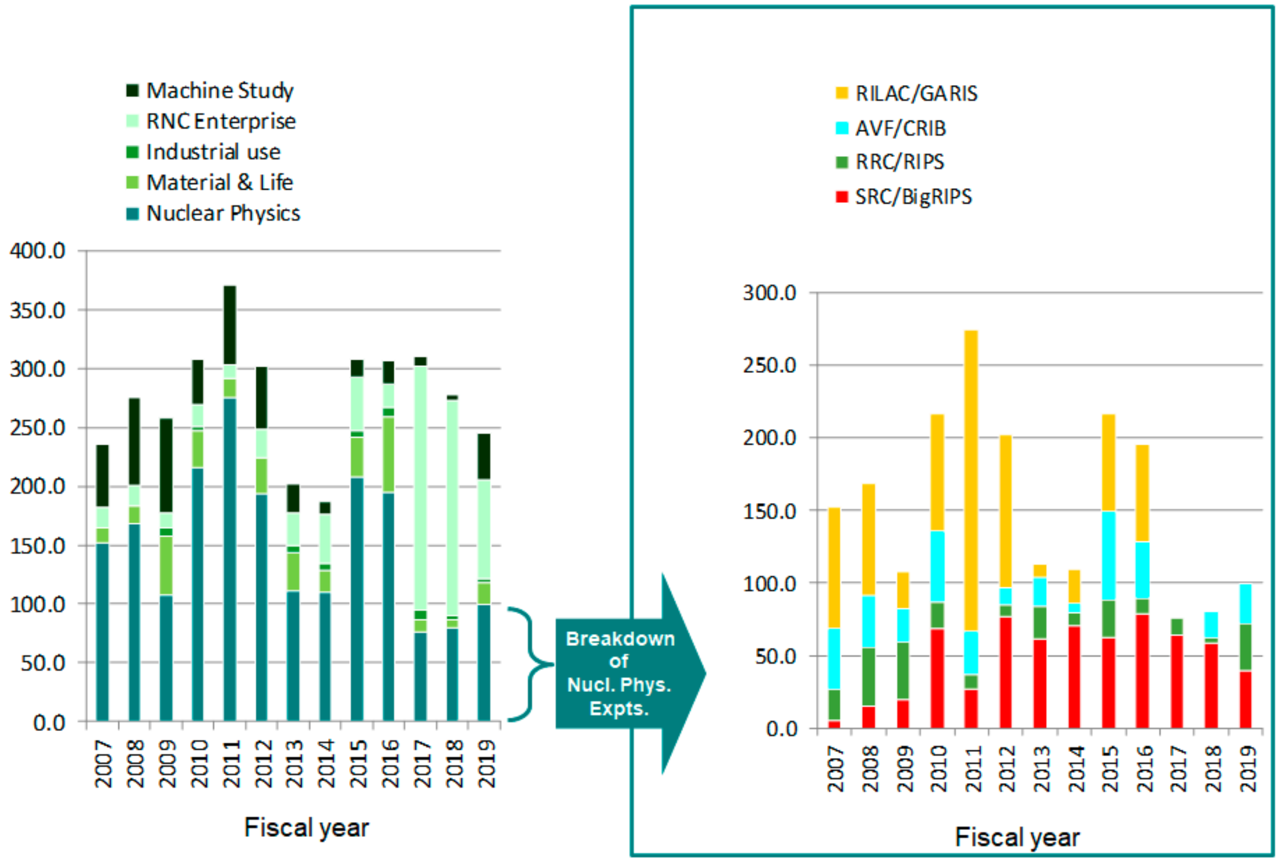
^{238}U	94 pnA (345 MeV/nucleon, Nov. 2019)
^{124}Xe	173 pnA (345 MeV/nucleon, Jun. 2019)
^{86}Kr	30 pnA (345 MeV/nucleon, Nov. 2007)
^{78}Kr	486 pnA (345 MeV/nucleon, May. 2015)
^{70}Zn	250 pnA (345 MeV/nucleon, May 2017)
^{48}Ca	730 pnA (345 MeV/nucleon, Nov. 2016)
^{18}O	1000 pnA (345 MeV/nucleon, 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

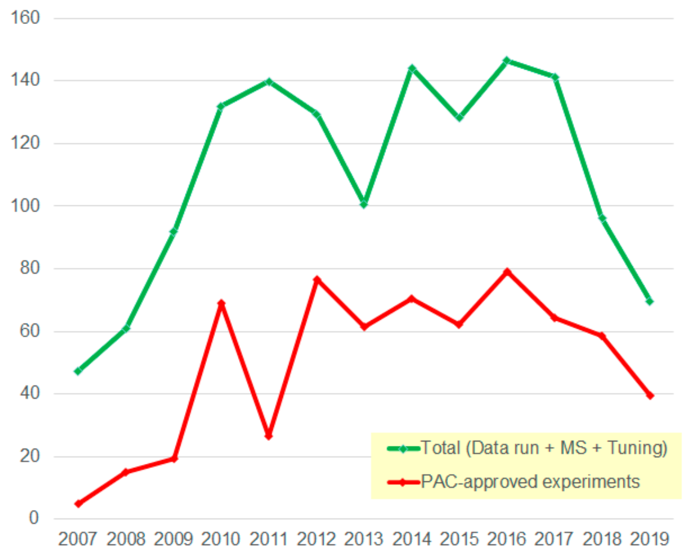


Beam energies of the beams without explicitly indicated are 345 AMeV.

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-ray 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. In 2019, results of the first spectrosocpy of ^{40}Mg was published in PRL, to demonstrate the exotic structure which is very different from in other neutron-rich Mg isotopes.

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. In 2019, the result of the first spectroscopy was published in Nature.

A new project of high resolution gamma spectroscopy with fast beams "HiCARI" has been proposed at PAC 2018 and the campaign programs are scheduled in 2020. MINIBALL and several Ge tracking detectors from Japan, Europe, the USA and Korea 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 two workshops were organized in 2019, and the machine time of 43.5 days in total was approved at PAC 2019.

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 had been conducted for programs approved to survey nuclei of interest as many as possible, such as Ni-78, Pd-128, Sn-100. The EURICA collaboration finished its physics programs in summer 2016. So far, 54 papers including 14 PRL's and 13 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.

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 2017–2019.

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

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List of Publications & Presentations

Publications

[Original papers]

T. Lokotko, S. Leblond, J. Lee, P. Doornenbal, A. Obertelli, A. Poves, F. Nowacki, K. Ogata, K. Yoshida, G. Authelet, H. Baba, D. Calvet, F. Chateau, S. Chen, A. Corsi, A. Delbart, J. Gheller, A. Gillibert, T. Isobe, V. Lapoux, M. Matsushita, S. Momiyama, T. Motobayashi, M. Niikura, H. Otsu, C. Peron, A. Peyaud, E. Pollacco, J. Rousse, H. Sakurai, C. Santamaria, Z. Xu, M. Sasano, Y. Shiga, S. Takeuchi, R. Taniuchi, T. Uesaka, H. Wang, V. Werner, F. Browne, L. Chung, Z. Dombradi, S. Franchoo, F. Giacoppo, A. Gottardo, K. Hadynska-Klek, Z. Korkulu, S. Koyama, Y. Kubota, M. Lettmann, C. Louchart, R. Lozeva, K. Matsui, T. Miyazaki, S. Nishimura, L. Olivier, S. Ota, Z. Patel, E. Sahin, C. Shand, P. Soderstrom, I. Stefan, D. Steppenbeck, T. Sumikama, D. Suzuki, Z. Vajta, and J. Wu, "Shell structure of the neutron-rich isotopes ^{69,71,73}Co," Phys. Rev. C **101**, 034314 (2020).

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Presentations

[International conferences/workshops]

H. Sakurai (invited), "In-flight radioactive isotope beam facilities and nuclear physics at RIKEN," The First African Nuclear Physics Conference (ANPC), Kruger, South Africa, July 1–5, 2019.

S. Nishimura (invited), "r-process studies at RIBF," Nuclear and astrophysics aspects for the rapid neutron capture process in the era of multimessenger observations, ECT*, Trento, Italy, July 1–5, 2019.

S. Nishimura (invited), "Decay properties of exotic nuclei" China-Japan Collaboration Workshop on Nuclear Mass and Life for Unraveling Mysteries of R-process, ITP-CAS, Beijing, China, October 9–13, 2019.

S. Nishimura (invited), "Ukakuren" JINA-CEE IReNA/NAOJ Workshop, National Astronomy Observation of Japan, Mitaka, Japan, December 3-4 (2019).

T. Isobe (poster), "Measurement of Th-229 low lying isomeric state with MRTOF+TES system at RIKEN-RIBF," 18th International Workshop on Low Temperature Detectors (LTD18), Milano, Italy, July 22–26, 2019.

T. Isobe (invited), "Latest update on RIKEN facilities," 9th International Symposium on Nuclear Symmetry Energy (NuSym2019), Danan, Vietnam, September 30–October 4, 2019.

T. Isobe (oral), "Experimental study of hydrogen isotopes production in Sn+Sn RI collisions at 270 AMeV," 9th International Symposium on Nuclear Symmetry Energy (NuSym2019), Danan, Vietnam, September 30–October 4, 2019.

P. Doornenbal (invited), "Structure of exotic Calcium and Nickel isotopes," 14th Asia Pacific Physics Conference, Kuching, Malaysia, November 17–22, 2019.

P. Doornenbal (invited), "Exploring the terra incognita of exotic nuclei at RIKEN: past achievements and future endeavors," VINANST-13, Reu Island, Vietnam, August 7–9, 2019.

P. Doornenbal (invited), "Towards high-resolution in-beam Gamma-ray spectroscopy at the RIBF," 27th International Nuclear Physics Conference (INPC), Glasgow, UK, July 29–August 2, 2019.

P. Doornenbal (invited), "In-beam gamma-ray spectroscopy at RIKEN," 1st African Nuclear Physics Conference (ANPC), Kruger National Park, South Africa, July 1–5, 2019.

P. Doornenbal (oral), "High resolution spectroscopy of ^{78}Ni," High Resolution Gamma-ray Spectrosocpy at the RIBF Workhsop, Darmstadt, Germany, April 10–12, 2019.

P. Doornenbal (oral), "Technical Considerations," High Resolution Gamma-ray Spectrosocpy at the RIBF Workhsop, Darmstadt, Germany, April 10–12, 2019.

D. Suzuki (invited), "Present and future of in-beam spectroscopy at RIBF," Workshop on RI-beam Spectroscopy by Innovative Gaseous Active Targets, Osaka, Japan, December 19–20, 2019.

D. Suzuki (invited), "Present and future of in-beam spectroscopy at RIBF," Workshop on RI-beam Spectroscopy by Innovative Gaseous Active Targets, Osaka, Japan, December 19–20, 2019.

D. Suzuki (oral), "Coulomb and quantum bubbles in heavy nuclei," High Resolution Gamma-Ray Spectroscopy at the RIBF, Darmstadt, Germany, April 10–12, 2019.

D. Suzuki (oral), "rp-process study at OEDO," OEDO collaboration workshop, Wako, Japan, September 2, 2019.

D. Suzuki (oral), "Recent results from SUNFLOWER and future perspectives," JSPS/NRF/NSFC A3 Foresight Program "Nuclear Physics in the 21st Century" Joint Kickoff Meeting, Kobe, Japan, December 6–7, 2019.

D. Suzuki (invited), "Present and future of in-beam spectroscopy at RIBF," Workshop on RI-beam Spectroscopy by Innovative Gaseous Active Targets, Osaka, Japan, December 19–20, 2019.

D. Suzuki (invited), "Present and future of in-beam spectroscopy at RIBF," Workshop on RI-beam Spectroscopy by Innovative Gaseous Active Targets, Osaka, Japan, December 19–20, 2019.

D. Suzuki (oral), "Coulomb and quantum bubbles in heavy nuclei," High Resolution Gamma-Ray Spectroscopy at the RIBF, Darmstadt, Germany, April 10–12, 2019.

D. Suzuki (oral), "rp-process study at OEDO," OEDO collaboration workshop, Wako, Japan, September 2, 2019.

W. Horiuchi, S. Hatakeyama, A. Kohama (oral), "Nuclear "diffuseness" probed by proton-nucleus diffraction," The 27th International

Nuclear Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019. (INPC 2019)

S. Kubono (invited), "Heavy element synthesis under explosive burning on neutron stars," The 10th European Summer School on Experimental Nuclear Astrophysics Catania, INFN-LNS, June 16–23, 2019.

S. Kubono (invited), "Experimental approach to explosive H-burning in X-ray bursts and SNeII," Workshop on origin of Elements and Cosmic Evolution: From Big-Bang to Supernovae and Mergers, Beihang University, China, November 27–29, 2019.

K. Asahi (invited), "Experiment on nuclear EDMs," KEK Workshop on Nucleon EDMs and Spin Structure 2020, KEK Tokai Campus, Tokai, Ibaraki, Japan, January 11, 2020.

R. Taniuchi (oral), "Approaching the fifth island of inversion from the north" High Resolution Gamma-Ray Spectroscopy at the RIBF, TU Darmstadt, Germany, April 10–12, 2019.

R. Taniuchi (oral), "In-beam gamma-ray spectroscopy of ^{78}Ni reveals its doubly magic character," 27th International Nuclear Physics Conference (INPC 2019), Glasgow, United Kingdom, July 29–August 2, 2019.

R. Taniuchi (oral), "Quest for shell quenching of N = 50 in doubly magic ^{78}Ni" 8th SUNFLOWER Workshop/HiCARI Workshop, Osaka, September 26–28, 2019.

V. Phong (oral), "β-decay measurements of very neutron-rich isotopes around Mass A = 130 within the BRIKEN project at RIBF," 15th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG15), Kyoto, Japan, July 2–5, 2019.

V. Phong (oral), "Measurement of very neutron-rich beta delayed neutron emitters around mass A = 130 relevant to the astrophysical r-process," 9th International Symposium on Nuclear Symmetry Energy (NuSYM2019), Danang, Vietnam, September 30–October 4, 2019.

H. Shimizu (poster), "Study on ^{26m}Al(p,γ) reaction at the SNe temperature," Symposium on Origin of Matter and Evolution of Galaxies (OMEG15), Kyoto, Japan, July 2–5, 2019.

H. Shimizu (poster), "Isomeric ^{26}Al beam production with CRIB," Nuclear Physics School For Young Scientists (NUSYS-2019), Lanzhou, China, August 12–17, 2019.

T. Koiwai (oral), "Single-particle structure of ^{55}Ti and ^{57}Ti," Workshop on high-resolution gamma-ray spectroscopy at the RIBF, Darmstadt, Germany, April 2019

T. Koiwai (oral), "In-beam γ-ray spectroscopy of ^{55}K and ^{55}Ca via neucleon knockout reactions," International Nuclear Physics Conference (INPC 2019), Glasgow, UK, July–Augsut 2019

T. Koiwai (oral), "N = 34 beyond ^{54}Ca: Single-particle structure of ^{55,57}Ti," 8th SUNFLOWER Workshop and HiCARI Workshop (JSPS A3Foresight), Osaka, Japan, August 2019.

[Domestic conferences/workshops]

櫻井博儀（招待講演），「RIBF での核物理研究」, 研究会「シミュレーションによる宇宙の基本法則と進化の解明に向けて（QUCS2019）」, 京都大学基礎物理学研究所, 京都, 2019 年 12 月.

西村俊二（口頭発表），「r プロセスの研究: 実験的検証と挑戦」, 研究会「原子核物理でつむぐ r プロセス」, 京都大学基礎物理学研究所, 京都, 2019 年 5 月 22–24 日.

P. Doornenbal (invited), "Recent results from SUNFLOWER and future plans," RIBF Week, Wako, Japan, September 2–4, 2019.

P. Doornenbal (invited), "Results from SEASTAR III," SAMURAI Workshop, Tokyo, Japan, August 30–31, 2019.

P. Doornenbal (oral), "Sunflower Status," SUNFLOWER/HiCARI Workshop, Osaka, Japan, August 26–28, 2019.

P. Doornenbal (invited), "Probing the Nuclear Shell Closures far off Stability with In-Beam Gamma-Ray Spectroscopy," JPS Spring Meeting, Kyushu, Japan, March 14–17, 2019.

槇口雄仁（口頭発表）, 堀内渉, 小濱洋央, 「反陽子-原子核散乱による希薄核密度領域の探索」, 日本物理学会第 75 回年次大会, 名古屋大学東山キャンパス, 名古屋, 2020 年 3 月 16 日–20 日.

F. Browne (oral), "Coulomb excitation study of Se isotopes beyond N = 50," 8th SUNFLOWER Workshop/HiCARI Workshop (JSPS A3Foresight), Osaka, Japan, August 26–28, 2019.

谷内稜（招待講演），「核変形に対して二重閉殻を堅持する 78Ni」, 日本物理学会第 75 回年次大会, 名古屋大学（オンライン開催）, 2020 年 3 月 16–19 日.

旭 耕一郎（招待講演），「原子の EDM と時間反転対称性の破れ—反磁性原子の EDM を中心に」, 電子 EDM 研究会, 東京大学駒場キャンパス, 目黒, 2019 年 12 月 11 日.

[Seminars]

T. Isobe, "Overview of the RI Beam Facility (RIBF)," CNS Summer School 2019 (CNSSS19), Nishina Hall Riken Wako, August 21–27, 2019.

T. Isobe, "Experimental study of asymmetric dense nuclear matter Equation Of State by using heavy RI collisions at RIBF-SπRIT," CNS Summer School 2019 (CNSSS19), Nishina Hall Riken Wako, August 21–27, 2019.

S. Kubono, "Special lectures on nuclear astrophysics," Department of Physics, Hong Kong University, April 15–18, 2019.

K. Asahi, "Electric dipole moments of diamagnetic atoms—Present status of experiments," CNS Seminar, Hongo, Tokyo, Japan, June 13, 2019.

R. Taniuchi, "^{78}Ni revealed as a doubly magic stronghold against nuclear deformation," 276th RIKEN RIBF Nuclear Physics Seminar, Saitama, Japan, May 28, 2019.

R. Taniuchi, "In-beam gamma-ray spectroscopy of ^{78}Ni revealed its double magicity and shape-coexistence," The RIBF Users Group Thesis Award lecture, RIBF Week 2019, Saitama, September 3, 2019.

Awards

P. Doornenbal, RIKEN BAIHO Award 2020, Achievement: In-beam γ-ray spectroscopy of the neutron-rich doubly-magic nucleus ^{78}Ni

R. Taniuchi, The RIBF Users Group Thesis Award, September 3, 2019.

谷内稜, 第 14 回（2020 年）日本物理学会若手奨励賞, 2020 年 3 月 18 日.

谷内稜, 第 26 回原子核談話会 新人賞, 2020 年 3 月 18 日.

V. Phong, ANPhA(and AAPPS DNP) award for Young Scientists at 9th International Symposium on Nuclear Symmetry Energy (NuSYM2019): 2nd prize.

Press releases

「魔法数研究に金字塔—ついに中性子過剰なニッケル原子核の二重魔法性に結論—」, 2019 年 5 月 2 日.

「新魔法数 34 の新たな証拠—中性子ノックアウト反応で探るカルシウム-54 の閉殻構造—」, 2019 年 10 月 18 日.

「急激に膨れる原子核—カルシウム同位体で見つかった異常な核半径増大現象—」, 2020 年 3 月 13 日.

Outreach activities

櫻井博儀, 「元素の進化と変換」, 2019 年度芦屋公民館サイエンス講座, 2019 年 4–6 月.

磯部忠昭, 「科学者になるという事〜世界最先端の研究と未来〜」, 細田学園講演会, 細田学園高等学校, 志木, 2019 年 6 月 24 日.

Others

[Software package]

A. Kohama, K. Iida, K. Oyamatsu, H. Iwase, Release of “kurotama0” update (ver. 3.0), Contribution of PHITS update to ver. 3.20, March 2020.

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:

(a) Polarized proton target (described in (4))
(b) Thin solid hydrogen target
(c) MINOS (developed at Saclay and hosted by the Spin Isospin Laboratory)

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List of Publications & Presentations

Publications

[Original papers]

Z. Elekes, Á. Kripkó, D. Sohler, K. Sieja, K. Ogata, K. Yoshida, P. Doornenbal, A. Obertelli, G. Authelet, H. Baba, D. Calvet, F. Château, A. Corsi, A. Delbart, J. -M. Gheller, A. Gillibert, T. Isobe, V. Lapoux, M. Matsushita, S. Momiyama, T. Motobayashi, H. Otsu, C. Péron, A. Peyaud, E. C. Pollacco, J. -Y. Roussé, H. Sakurai, C. Santamaria, Y. Shiga, S. Takeuchi, R. Taniuchi, T. Uesaka, H. Wang, K. Yoneda, F. Browne, L. X. Chung, Zs. Dombrádi, F. Flavigny, S. Franchoo, F. Giacoppo, A. Gottardo, K. Hadyńska-Klęk, Z. Korkulu, S. Koyama, Y. Kubota, J. Lee, M. Lettmann, C. Louchart, R. Lozeva, K. Matsui, T. Miyazaki, M. Niikura, S. Nishimura, L. Olivier, S. Ota, Z. Patel, E. Sahin, C. Shand, P. -A. Söderström, I. Stefan, D. Steppenbeck, T. Sumikama, D. Suzuki, Zs. Vajta, V. Werner, J. Wu, and Z. Xu, "Nuclear structure of ^{76}Ni from the $(p, 2p)$ reaction," Phys. Rev. C **99**, 014312 (2019).

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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

[Original papers]

M. Tajima, N. Kuroda, C. Amsler, H. Breuker, C. Evans, M. Fleck, A. Gligorova, H. Higaki, Y. Kanai, B. Kolbinger, A. Lanz, M. Leali, V. Mäckel, C. Malbrunot, V. Mascagna, Y. Matsuda, D. Murtagh, Y. Nagata, A. Nanda, B. Radics, M. Simon, S. Ulmer, L. Venturelli, E. Widmann, M. Wiesingerc, and Y. Yamazaki, "Antiproton beams with low energy spread for antihydrogen production," J. Instrum. **14**, P05009 (2019).

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[Review article]

Y. Ichikawa, "Nuclear shell evolution with shape deformation—Structure of exotic nuclei investigated by the magnetic moment—（「変形しながら殻進化—磁気モーメントで探るエキゾチック核の『中身』」）," Isotope News **765**, 26–29 (2019).

Presentations

[International conferences/workshops]

H. Ueno (invited), "Nuclear-physics research based on RI spin orientation technique," XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2019.

A. Takamine (invited), "Recent progress in the development of gas cells, SHE results combining GARIS with GASCELL+MRTOF," Expert Meeting on Next-Generation Fragment Separators 2019, Darmstadt, Germany, September 30–October 3, 2019.

Y. Ichikawa (invited), "Magnetic-moment measurement of exotic nuclei using spin-oriented RI beams at RIBF," 14th Asia-Pacific Physics Conference (APPC 2019), Sarawak, Malaysia, November 17–22, 2019.

T. Otsuka (invited), "Self-organization of quantum systems and the structure of heavy nuclei," Workshop Physics between lead and uranium: In preparation of new experimental campaigns at ISOLDE, Leuven, Bergium, April 16–18, 2019.

T. Otsuka (invited), "Alpha clustering in nuclei and the shell model," Theoretical Nuclear Physics in Padova: A Meeting in Honor of Prof. Andrea Vitturi, Padova, Italy, May 20–21 2019.

T. Otsuka (invited), "Self-organization in nuclear structure and its impact to heavy nuclei—A challenge to Bohr-Mottelson's picture and a future prospect—," LXIX International Conference on Nuclear Spectroscopy and Nuclear Structure "Fundamental Problems of Nuclear Physics, Nuclei at Borders of Nucleon Stability, High Technologies," (Nucleus-2019) , Dubna, Russia, July 1–5, 2019.

T. Otsuka (invited), "Nuclear matrix elements with advanced shell model methods," Workshop on Progress and Challenges in Neutrinoless Double Beta Decay, Trento, Italy, July 15–19, 2019.

T. Otsuka (invited), "Ab initio studies on the dripiline of the Island-of-Inversion nuclei," Workshop on Ab initio Nuclear Theory from Breakthroughs to Applications, Guildford, UK, July 24–26, 2019.

T. Otsuka (oral), "Self-organization in atomic nuclei and nuclear collectivity," 27th International Nuclear Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019.

T. Otsuka (invited), "Precision nuclear structure via the Monte-Carlo shell model," ESNT Workshop Laser Spectroscopy as a Tool for Nuclear Theories, Saclay, France, October 7–11, 2019.

T. Otsuka (invited), "Evolution of shape and shell of atomic nuclei and the self-organization," 2XVII International Meeting on "Selected topics in nuclear and atomic physics," Fiera di Primiero, Italy, September 30–October 4, 2019.

T. Otsuka (invited), "Olaf gets into shapes," Symposium on "Particles, photons, and fields: Messengers of violent events from the nucleus, through the sky, to the cosmos," Groningen, the Netherlands, November 21, 2019.

T. Otsuka (invited), "Self-organization of quantum systems and nuclear collectivity," International Symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2020), Beppu, Japan, January 23–24, 2020.

T. Otsuka (invited), "Self-organization in nuclear collective bands," Fifth Topical Workshops on Modern Aspects of Nuclear Structure, Bormio, Italy, February 4–9, 2020.

T. Otsuka (invited), "Nuclear matrix elements of neutrinoless double beta decay calculated by Monte Carlo shell model for ^{76}Ge and ^{136}Xe," International Conference on Neutrino and Nuclear Physics 2020 (CNNP2020), Cape Town, South Africa, February 24–28, 2020.

T. Otsuka (invited), "Structure of F-Ne-Na-Mg isotopes and new mechanism of driplines," Workshop on Progress in Ab Initio Techniques in Nuclear Physics, Vancouver, Canada, March 3–6, 2020.

[Domestic conferences/workshops]

市川雄一,「原子核励起状態の磁気モーメント測定」, 2019 年度「物質階層原理研究」&「ヘテロ界面研究」合同春合宿, 御殿場, 2019 年 5 月 10–11 日.

上野秀樹, "Highly Spin-polarized RI beams and the application to nuclear and condensed-matter physics ," 新学術領域「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。」第 1 回領域全体会議, 東京大学 Kavli IPMU, 柏市, 2019 年 7 月 15–16 日.

高峰愛子, "Development of an RF ion guide gas cell for universal ultra slow RI beams," 新学術領域「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。」, 第 1 回領域全体会議, 東京大学 Kavli IPMU, 柏, 2019 年 7 月 15–16 日.

今井康貴, 藤枝亮, 植竹智, 笹尾登, 吉村太彦, 吉村浩司, 吉見彰洋, 宮本祐樹, 増田孝彦, 原秀明, 今村慧, 上垣外修一, 中川孝秀, 金井保之, 市川雄一, 長友傑, 本田洋介, 坂上和之,「量子イオンビーム(QIB)分光に向けた Yb ドープファイバーを用いた 987 nm 光の増幅」, 日本物理学会 2019 年秋季大会, 岐阜大学柳戸キャンパス, 岐阜, 2019 年 9 月 10–13 日.

今井伸明, 堂園昌伯, 道正新一郎, 炭竃聡之, 大田晋輔, J. W. Hwang, 岩本ちひろ, 川瀬頌一郎, 川田敬太, 北村徳隆, 増岡翔一朗, 中野敬太, P. Schrock, 鈴木大介, 角田理恵子, K. Wimmer, for ImPACT17-02-02 collaboration,「逆運動学 ^{79}Se(d, p) 反応による中性子捕獲反応断面積の評価」, 日本物理学会 2019 年秋季大会, 山形大学小白川キャンパス, 山形, 2019 年 9 月 17–20 日.

川田敬太, 大田晋輔, 堂園昌伯, 銭廣十三, 岩本ちひろ, 北村徳隆, 酒井英行, 笹野匡紀, 増岡翔一朗, 道正新一郎, 横山輪, 矢向謙太郎, Laszlo STUHL, 坂口治隆, 原田知也, 寺嶋知, 西畑洸希, 角田理恵子, 今井伸明, Ningtao Zhang, Jongwon Hwang, 遠藤史隆,「入射核破砕反応による ^{52}Fe 周辺核の高スピンアイソマーの生成」, 日本物理学会 2019 年秋季大会, 山形大学小白川キャンパス, 山形, 2019 年 9 月 17–20 日.

庭瀬暁隆, 和田道治, P. Schury, 伊藤由太, 木村創太, 加治大哉, M. Rosenbusch, 渡辺裕, 平山賀一, 宮武宇也, J. Y. Moon, 石山博恒, 森本幸司, 羽場宏光, 田中泰貴, 石澤倫, 高峰愛子, 森田浩介, H. Wollnik,「MRTOF-MS を用いた ^{207}Ra の精密質量—崩壊特性測定」, 日本物理学会 2019 年秋季大会, 山形大学小白川キャンパス, 山形, 2019 年 9 月 17–20 日.

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小澤直也, 長濱弘季, 早水友洋, 中村圭佑, 小高康照, 田中香津生, 大塚未来, 小森有希子, 市川雄一, 羽場宏光, 上野秀樹, 酒見泰寛,「フランシウム原子の電気双極子能率探索のための表面電離イオン源の開発」, 日本物理学会第 75 回年次大会, 名古屋(名古屋大学現地開催中止), 2020 年 3 月 16–19 日.

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"Basic principles of nuclear shape and self-organization in quantum systems (「原子核の形の基本原理と量子系での自己組織化」)," joint press-release from the University of Tokyo and RIKEN, November 26, 2019.
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"Research group lead by RIKEN and the University of Tokyo succeeded in measuring excited-state nuclear magnetic moment of a neutron-rich copper isotope（「理研と東大など, 中性子過剰な銅同位体原子核の励起状態の磁気モーメント測定に成功」）," Nikkei Shinbun Newspaper Online, January 30, 2019.

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Outreach activities

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A. Takamine, Interactive Event "RIKEN DAY: Let's talk with researchers!"（理研 DAY：研究者と話そう！「原子核を捕まえて光でみる」）, Tokyo Science Museum, December 15, 2019.

H. Ueno, RIKEN Osaka Campus Open Day 2019, Suita, November 23, 2019.

H. Ueno, Kagakudo 100 Books 2019 Selection Committee（科学道 100 冊 2019 選書委員会).

Nuclear Science and Transmutation Research Division
High Energy Astrophysics Laborarory

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) XRISM

We have contributed to the XRISM (X-ray imaging and spectroscopy mission) mission for the launch in 2022. XRISM is the recovery mission of the ASTRO-H/Hitomi satellite, which was launched in February 2016 but lost by an accident one month after the launch. 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. We hoped to use SXS to discover many previously-unknown elemental lines in the universe and to measure the abundance of these elements, but this was not possible with Hitomi. The XRISM satellite carries almost identical X-ray detectors as the Hitomi satellite, and is expected to carry out scientific observations that were not done with the Hitomi mission.

(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 the second half of 2021. We have already provided the flight qualified GEMs to the project in FY2018, and have contributed to the detector calibrations in FY2019.

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.

As an successor of the MAXI mission, we are also verifying the principle of a new concept, multiplexing lobster-eye (MuLE) optics, to monitor the entire sky with a wide field-of-view for detecting and immediate reporting transient objects such as a neutron star merger.

Members

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Yuto YOSHIDA (Tokyo University of Science)
Yuuki WADA (Univ. of Tokyo)

List of Publications & Presentations

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T. Kitaguchi (Poster), "A machine learning approach for reconstructing X-ray polarization information acquired with micro-pattern gas polarimeters," The 6th International Conference on Micro Pattern Gaseous Detectors (MPGD19), La Rochelle, France, May 5–10, 2019.

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内山慶祐 (口頭発表), 「IXPE 衛星搭載 GEM の宇宙線重イオンへの耐性試験」, 日本物理学会第 75 回年次大会, 名古屋大学, オンライン開催, 名古屋, 2020 年 3 月 16–19 日.

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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)$^{296\text{-}x}$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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Nuclear Science and Transmutation Research Division
Superheavy Element Research Group
Superheavy Element Production Team

1. Abstract

The elements with atomic number $Z \geq 104$ are called as trans-actinide or superheavy elements (SHEs). Superheavy Element Production Team investigates synthesis mechanisms 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

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 International Union of Pure and Applied Chemistry (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. In 2019, we continued to search for element 119 in the $^{248}Cm + ^{51}V$ reaction. We also developed the new separator GARIS III on the beam line of the upgraded RILAC, *i.e.* Superconducting RIKEN heavy-ion Linear ACcelerator (SRILAC). The SRILAC + GARIS III setup will be ready for the SHE experiments in 2020.

(2) Decay spectroscopy of the heaviest nuclei

We developed a novel detector, referred to as an "α-TOF detector," for correlated measurements of atomic masses and decay properties of low-yield, short-lived radioactive isotopes using a multi-reflection time-of-flight mass spectrograph. By correlating measured time-of-flight signals with decay events, it can suppress background events and obtain accurate, high-precision mass and half-life values even in cases of very low event rates. An offline test of the α-TOF detector showed that the time-of-flight detection efficiency for 5.48 MeV α-particles is more than 90% and yields a time resolution of 250.6(68) ps and an α-energy resolution of 141.1(9) keV.

(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. We measured excitation functions for the quasielastic scattering of the $^{248}Cm+^{22}Ne$, $^{248}Cm+^{26}Mg$, and $^{238}U+^{48}Ca$ 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 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. In 2019, we continued to develop an ultra-rapid gas-chromatograph apparatus at the focal plane of GARIS for the gas chemistry of SHEs. This apparatus consists of an RF carpet gas cell and a cryo-gas-chromatograph column with a Si detector array. For the aqueous chemistry, we also developed a flow solvent extraction apparatus which consisted of a continuous dissolution apparatus, a flow extraction apparatus, and a liquid scintillation counter.

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List of Publications & Presentations

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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. In the RIBF facility, three gas-filled recoil ion separators are installed at RILAC and RRC facility. One is GARIS that is designed for a symmetric reaction such as cold-fusion reaction, and the other two are developed for an asymmetric reaction such as hot-fusion reaction, GARIS-II and GARIS-III. New elements $^{278}113$ were produced by $^{70}Zn + {}^{209}Bi$ reaction using GARIS. Further the new element search $Z > 118$ is currently in progress by using GARIS-II and GARIS-III.

2. Major Research Subjects

(1) Maintenance of GARIS, GARIS-II and development of new separator GARIS-III
(2) Maintenance and development of detector and DAQ system for superheavy element research
(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 transmission. A new element search program aiming to element 119 was started using GARIS-II. And new separator GARIS-III was developed and installed into the RILAC experimental hall. It will be ready for operation in the physical 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

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Research/Technical Scientists
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Yuta ITO (JAEA)
Katsuhisa NISHIO (JAEA)
Fuyuki TOKANAI (Yamagata Univ.)

Student Trainees
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Yoshiki TAKAHASHI (Niigata Univ.)
Hiroki TSUNODA (Niigata Univ.)

List of Publications & Presentations

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I. Murakami (poster), S. Sakaguchi, D. Kaji, K. Morimoto, T. Niwase, K. Morita *et al.*, "Development of MCP ToF Detectors at Kyushu University," The 4th International Symposium on Superheavy Elements (SHE2019), Hakone, Japan, December 1–5, 2019.

K. Morimoto (oral), "Discovery of Nh and search for element 119," nSHE RG Collaboration Meeting. Oak Ridge National Laboratory and the University of Tennessee Knoxville, US, May 30–June 1, 2019.

D. Kaji (oral), "GARIS-2/-3 performance," nSHE RG Collaboration Meeting. Oak Ridge National Laboratory and the University of Tennessee Knoxville, US, May 30–June 1, 2019.

P. Brionnett (oral), "Data analysis I," nSHE RG Collaboration Meeting. Oak Ridge National Laboratory and the University of Tennessee Knoxville, US, May 30–June 1, 2019.

S. Ishizawa (oral), "Optimization of ToF system," nSHE RG Collaboration Meeting. Oak Ridge National Laboratory and the University of Tennessee Knoxville, US, May 30–June 1, 2019.

S. Kimura (oral), "Determination of anchor via direct mass measurement with MR-TOF," nSHE RG Collaboration Meeting. Oak Ridge National Laboratory and the University of Tennessee Knoxville, US, May 30–June 1, 2019.

K. Morimoto (oral), "Present status and plans of GARIS, GARIS-II and GARIS-III," SSRI-PNS Collaboration Meeting 2019, Nishina hall, Nishina Bldg. 2F, September 4, 2019.

[Domestic conferences/workshops]

庭瀬暁隆, 和田道治, P. Schury, 伊藤由太, 木村創大, 加治大哉, M. Rosenbusch, 渡辺裕, 平山賀一, 宮武宇也, J. Y. MOON, 石山博恒, 森本幸司, 羽場宏光, 田中泰貴, 石澤倫, 高峰愛子, 森田浩介, H. Wollnik, 「MRTOF-MS を用いた ^{207}Ra の精密質量-崩壊特性測定」, 日本物理学会 2019 年秋季大会, 山形大学, 山形, 2019 年 9 月.

庭瀬暁隆, 和田道治, P. Schury, 伊藤由太, 木村創大, 加治大哉, M. Rosenbusch, 渡辺裕, 平山賀一, 宮武宇也, J. Y. MOON, 石山博恒, 森本幸司, 羽場宏光, 田中泰貴, 石澤倫, 高峰愛子, 森田浩介, H. Wollnik, 「MRTOF+α-TOF を用いた 207Ra の質量-崩壊特性測定」, 日本放射化学会第 63 回討論会 (2019), いわき, 2019 年 9 月.

庭瀬暁隆, 和田道治, P. Schury, 伊藤由太, 木村創大, 加治大哉, M. Rosenbusch, 渡辺裕, 平山賀一, 宮武宇也, J. Y. MOON, 石山博恒, 森本幸司, 羽場宏光, 田中泰貴, 石澤倫, 飯村俊, 高峰愛子, 森田浩介, H. Wollnik, 「MRTOF+α-TOF を用いた短寿命 α 崩壊核種の質量-崩壊特性測定」, 日本物理学会 第 75 回年次大会 (2020 年), 名古屋大学, 名古屋, 2020 年 3 月.

Awards

庭瀬暁隆, 日本放射化学会第 63 回討論会 (2019), 若手優秀発表賞 2019 年 9 月

Others

森本幸司, 理化学研究所仙台地区 一般公開, 「新元素「ニホニウム」の発見と新たな展開」, 理化学研究所 仙台地区, 2019 年 07 月 27 日.

Nuclear Science and Transmutation Research Division
Astro-Glaciology Research Group

Summary of Research Activities

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, glaciology, and climate science.

On the experimental side, we measure isotopic and ionic concentrations in ice cores drilled at Dome Fuji station, Antarctica, in collaboration with the National Institute of Polar Research (NIPR, Tokyo). Here, the ice cores are time capsules which preserve atmospheric information of the past. In particular, the ice cores obtained around the Dome Fuji site are very unique, because they contain much more information on the stratosphere than any other ice cores obtained from elsewhere on Earth. This means that we have significant advantages in using Dome Fuji ice cores if we wish to study the Universe, since UV photons, gamma-rays, and high-energy protons emitted by astronomical phenomena affect the atmosphere of the stratosphere. Our principal aim is thus to acquire and interpret information preserved in ice cores regarding:

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

Moreover, we are promoting experimental projects on:

- Development of an automated laser melting sampler for analyzing ice cores with high depth resolution and high through-put;
- Development of precise analytical techniques of high sensitivity for analyzing ice cores;
- The application of analytical methods to measure isotopes developed for ice cores to archaeological artifacts;
- The evolution of molecules in space.

On the theoretical side, we are simulating numerically:

- Chemical effects of giant solar flares and supernovae on the Earth's atmosphere;
- The explosive and the r-process nucleosynthesis in core-collapse supernovae.

Combining our experimental evidence and theoretical simulations, we are promoting the researches mentioned above. In particular, climate change is the most critical issue facing the world in the 21st century. It is also emphasized that the frequency of supernova explosions in our galaxy has not yet been fully understood, and this is a crucial key to understand of the r-process nucleosynthesis, one of the goals of the Nishina Center. We note that our subjects all will contribute to an understanding relationships between the Universe and Earth.

Members

Director
Yuko MOTIZUKI

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

Technical Staff I
Yu Vin SAHOO

Senior Visiting Scientists
Yasushige YANO (RIKEN/Nishina Memorial Foundation)
Kunihiko KODERA (Meteorological Res. Inst.)

Visiting Scientists
Hideharu AKIYOSHI (Nat'l Inst. for Environmental Studies)
Akira HORI (Kitami Inst. of Tech.)
Kazuho HORIUCHI (Hirosaki Univ.)
Yoshinori IIZUKA (Hokkaido Univ.)
Naoyuki KURITA (Nagoya Univ.)
Hideki MADOKORO (Mitsubushi Heavy Industries, Ltd.)
Hideaki MOTOYAMA (Nat'l Inst. of Polar Res.)
Kenji TANABE (Okayama Univ. of Sci.)

Visiting Technician
Junya HIROSE (Fusion Tech. Co., Ltd.)

Student Trainee
Hisashi HAYAKAWA (Osaka Univ.)

Part-time Worker
Satomi NEGISHI (Part-time Worker I)

List of Publications & Presentations

Publications

[Original papers]

T. Minami, K. Hatanaka, Y. Motizuki, Y. Nakai, and K. Takahashi, "A method of collecting trace amounts of vermilion from artifacts for source estimation by sulfur isotope (δ34S) analysis: use of sulfur-free adhesive," Journal of Archaeological Science: Reports **28**, 102027, (2019).

[Books]

望月優子,「Newton ライト 2.0 周期表」 (協力), ニュートンプレス, 2019 年 12 月.

望月優子,「ニュートン式超図解 最強に面白い!! 周期表」 (協力), ニュートンプレス, 2019 年 7 月.

Presentations

[International conferences/workshops]

Y. Motizuki (invited), "The oxygen isotopic variations in a Dome Fuji (Antarctica) ice core—Relationships of the temperature proxy with solar activity and oceanic variations," WCRP/SPARC SATIO-TCS joint workshop on Stratosphere-Troposphere Dynamical Coupling in the Tropics, Kyoto, February 21–25, 2020.

H. Akiyoshi, Y. Nakai, Y. Motizuki, T. Imamura, and Y. Yamashita, "Ozone change simulations of Halloween event and Carrington event using MIROC3.2 chemistry-climate model," WCRP/SPARC SATIO-TCS joint workshop on Stratosphere-Troposphere Dynamical Coupling in the Tropics, Kyoto, February 21–25, 2020.

Y. V. Sahoo, K. Takahashi, Y. Nakai, Y. Motizuki, and H. Motoyama, "Annually-resolved water isotope measurements in a shallow ice core (DFS10) for 60 meters depth," (A poster paper), The Tenth Symposium on Polar Science, Tachikawa, December 3–5, 2019.

S. Fujita, K. Goto-Azuma, M. Hirabayashi, A. Hori, Y. Iizuka, Y. Motizuki, H. Motoyama, K. Takahashi, H. Enomoto, K. Fukui, Y. Hoshina, F. Nakazawa, S. Sugiyama, and S. Surdylk, "Metamorphism of layered firn at Dome Fuji, Antarctica: Evolution of relations between Near-infrared reflectivity and the other textural/chemical properties," The Tenth Symposium on Polar Science, Tachikawa, December 3–5, 2019.

K. Kanzawa, F. Miyake, Y. Tada, K. Horiuchi, S. Otani, K. Sasa, Y. Motizuki, K. Takahashi, Y. Nakai, H. Motoyama, and H. Matsuzaki, "Variation of cosmogenic 10Be for cosmic ray event in 5480 BC from Antarctic Dome Fuji ice core," The 8th East Asia Accelerator Mass Spectrometry Symposium, Nagoya, Japan, December 3–6, 2019.

Y. Motizuki (invited), "Women in Astronomy: A view from a gender-imbalanced country," IAU Symposium 358: "Astronomy for Equity, Diversity and Inclusion—a roadmap to action within the framework of IAU centennial anniversary," Tokyo, November 12–15, 2019.

Y. Motizuki (invited), "Historical supernova signatures in polar ice cores," International workshop on "Historical supernovae, novae and other transient events," Leiden, the Netherlands, October 14–18, 2019.

[Domestic conferences/workshops]

望月優子, 高橋和也, 中井陽一, Y. V. Sahoo, 本山秀明, 小寺邦彦, 「南極ドームふじアイスコアからさぐる気温変動と太陽活動との相関」, 日本天文学会 2020 年春季年会, つくば, 2020 年 3 月 16–19 日.

中井陽一, 日高宏, 渡辺直樹, 「低エネルギーイオンと低温氷表面との反応実験装置開発の現状」, 日本物理学会第 75 回年次大会, 名古屋, 2020 年 3 月 16 日–19 日.

菅澤佳世, 三宅芙沙, 多田悠馬, 堀内一穂, 大谷昴, 笹公和, 高橋努, 松村真寿美, 落合悠太, 望月優子, 高橋和也, 中井陽一, 本山秀明, 松崎浩之, 「BC5480 年宇宙線イベントにおけるドームふじアイスコア中の 10Be と 36Cl 濃度の変動」, 第 67 回応用物理学会春季学術講演会, 東京, 2020 年 3 月 12–15 日.

三宅芙沙, 堀内一穂, 櫻井敬久, 望月優子, 中井陽一, 高橋和也, 本山秀明, 松崎浩之, 「宇宙線生成核種を用いた紀元前 660 年頃の宇宙線イベント調査」, 第 67 回応用物理学会春季学術講演会, 東京, 2020 年 3 月 12–15 日.

望月優子 (招待講演), 「南極氷中の核種存在比から過去の気候変動をさぐる—宇宙との関連を視野に」, 埼玉大学理学部物理量子力学特別講義, さいたま, 2020 年 1 月 20 日.

高橋和也 (招待講演), 「極微量の硫黄同位体比分析による, 遺跡から出土した水銀朱の産地同定」, 第 370 回ガスクロマトグラフィー研究会特別講演会, 「科学と文化に貢献するガスクロマトグラフィー—人を知る, 地球を知る, 宇宙を知る」, 東京, 2019 年 11 月 22 日.

望月優子 (招待講演), 「ドームふじアイスコアから探る気候変動と太陽活動との関係」, 東京大学大学院理学系研究科 地球惑星科学専攻 佐藤研究室セミナー, 東京, 2019 年 10 月 8 日.

菅澤佳世, 三宅芙沙, 多田悠馬, 堀内一穂, 大谷昴, 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 10Be と 36Cl 濃度の測定による BC5480 年宇宙線イベントの調査」, 日本物理学会 2019 年秋季大会, 山形, 2019 年 9 月 17–20 日.

中井 陽一, 日高宏, 渡部直樹, 「星間塵表面を模擬した低温氷表面と低エネルギーイオンとの反応実験装置の開発」(ポスター発表), 原子衝突学会第 44 回年会, 調布, 2019 年 9 月 5 日.

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」, 公益財団法人山田長満奨学会 30 周年記念講演会, 川崎, 2019 年 7 月 20 日.

Press releases

高橋和也, 望月優子, 南武志, 「超微量硫黄同位体比分析を考古学に応用する—京田遺跡の出土品から赤色顔料を精密分析—」, 2019 年 11 月 26 日. https://www.riken.jp/press/2019/20191126_2/

K. Takahashi and Y. Motizuki, “Sticky tape: A key ingredient for mapping artifact origins,” March 9, 2020. https://www.riken.jp/en/news_pubs/research_news/pr/2019/20191126_2/

RIKEN Science News blog; It Ain’t Magic, “Tape and vermilion: ingredients for mapping artifact origins,” by Adam Phillips, March 9, 2020. https://itaintmagic.riken.jp/hot-off-the-press/tape-and-vermilion-ingredients-for-mapping-artifact-origins/

望月優子 (個別取材受), 「サイエンス View: 地球最古の氷 掘削せよ」読売新聞記事, 2019 年 5 月 26 日.

Outreach activities

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と研究環境を皆で整えていくことの大切さ」, 高松第一高等学校 (香川県) 理研団体見学, 和光, 2019 年 7 月 29 日.

Y. V. Sahoo (Invited talk), “Studying and pursuing research positions in Japan,” Sakura Science High School Program promoted by Department of Japan-Asia Youth Exchange Program in Science, Japan Society and Technology Agency, Wako, June 11, 2019.

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」, KEK-TYL スクール理系女子キャンプ 2019, つくば, 2019 年 4 月 3–4 日.

Others

K. Takahashi, “Detecting traces of sulfur in ice cores—An advanced isotope-measuring system can reveal insights about past environments in shorter time,” RIKEN RESEARCH, SUMMER 2019, November 2019.

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.

Member

Group Director

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

List of Publications & Presentations

Publications

[Original papers]

H. Okuno, H. Sakurai, Y. Mori, R. Fujita, and M. Kawashima, Proceedings of the Japan Academy, Series B **95**, 430–439 (2019).

Presentations

[International conferences/workshops]

H. Sakurai (invited), "A program for accelerator-based transmutation system for LLFP," Fourth International Workshop on Technology and Components of Accelerator-Driven Systems (TCADS-4), Antwerp, Belgium, October 14–17, 2019.

Press releases

「「核のゴミ」問題解決に必要な加速器の概念を提案—既存の 300 倍の高出力重陽子ビームの加速が可能に—」, 2019 年 8 月 9 日.

Patents

Outreach activities

櫻井博儀, 「「核のゴミ」をめぐる元素変換への挑戦」, 三鷹ネットワーク大学, 2019 年 9 月 19 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 a 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 the 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 a collaboration hub on many groups which plan to take data using fast RI beams in RIBF facility.

(2) Concentrating on taking 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)

Visiting Scientists

Takashi TERANISHI (Kyushu Univ.)

Student Trainees

Keita NAKANO (Kyushu Univ.)

List of Publications & Presentations

Publications

[Original papers]

H. Wang, H. Otsu, N. Chiga *et al.*, "Enhancement of element production by incomplete fusion reaction with weakly bound deuteron," Commun. Phys. **2**, 78 (2019).

K. Nakano, Y. Watanabe, S. Kawase, H. Otsu *et al.*, "Isotope production in proton-, deuteron-, and carbon-induced reactions on ^{93}Nb at 113 MeV/nucleon," Phys. Rev. C **100**, 044605 (2019).

S. Michimasa, J. Hwang, K. Yamada, H. Otsu *et al.*, "OEDO, the energy-degrading beamline at RI Beam Factory," Prog. Theor. Exp. Phys. **4**, 043D01 (2019).

J. Hwang, S. Michimasa, S. Ota, H. Otsu *et al.*, "Angle-tunable wedge degrader for an energy-degrading RI beamline," Prog. Theor. Exp. Phys. **4**, 043D02 (2019).

S. Takeuchi, T. Nakamura, M. Shikata, H. Otsu *et al.*, "Coulomb breakup reactions of ^{93,94}Zr in inverse kinematics," Prog. Theor. Exp. Phys. **1**, 013D02 (2019).

[Proceedings]

X. Sun, H. Wang, H. Otsu, H. Sakurai *et al.*, "Cross section measurements in the reactions of ^{136}Xe on proton, deuteron and carbon at 168 MeV/u," Proc. of the 15th Internat. Conf. on Nuclear Reaction Mechanisms, CERN-Proceedings-2019-001 (CERN, Geneva, 2019), pp. 153–157.

Yu. Watanabe, J. Suwa, K. Nakano, H. Otsu *et al.*, "Isotopic production cross sections of residual nuclei in proton- and deuteron-induced reactions on ^{91,92}Y, ^{92,93}Zr, and ^{93,94}Nb around 100 MeV/nucleon," Proc. of the 15th Internat. Conf. on Nuclear Reaction Mechanisms, CERN-Proceedings-2019-001 (CERN, Geneva, 2019), pp. 139–144.

Presentations

[International conferences/workshops]

H. Otsu, “Cross section measurements for LLFP nuclei at RIBF,” Fourth International Workshop on Technology and Components of Accelerator-Driven Systems (TCADS-4), Antwerp, Belgium, October 14–16, 2019.

H. Wang, “Spallation reaction study for long-lived fission products in nuclear waste,” International Nuclear Physics Conference 2019 (INPC2019), Glasgow, UK, July 29–August 2, 2019.

H. Wang, “Spallation reaction study for long-lived fission products in nuclear waste,” International conference on nuclear data and technology (ND2019), Beijing, China, May 19–24, 2019.

K. Nakano, “Isotope-production Cross Sections of Residual Nuclei in Proton- and Deuteron-induced Reactions on ^{93}Zr at 50 MeV/u,” International conference on nuclear data and technology (ND2019), Beijing, China, May 19–24, 2019.

X. Sun, “Cross-section Measurement in the Reactions of ^{136}Xe on Proton, Deuteron and Carbon,” International conference on nuclear data and technology (ND2019), Beijing, China, May 19–24, 2019

Y. Togano *et al.*, “Status report of dipole strength measurement performed in S09 and ImPACT,” SAMURAI International Collaboration Workshop, Rikkyo University, Japan, August 30–31, 2019.

[Domestic conferences/workshops]

大津秀暁 他 4 名, ImPACT-RIBF Collaboration, 「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 (4-1), “LLFP の断面積測定とそのエネルギー依存性”」, 日本原子力学会, 水戸, 2019 年 3 月.

Press releases

ワン・へ (Wang He), 大津秀暁, 櫻井博儀, 「重陽子による元素変換確率の増大—そのまま融合するか, 分裂してから一部だけ融合するか—」, 理化学研究所, 2019 年 7 月 5 日.

Doctor theses

中野敬太, “Study of Isotope Production in Proton- and Deuteron-Induced Spallation Reactions on ^{93}Nb and ^{93}Zr,” 九州大学 大学院総合理工学府.

Bachelor theses

松村理久, 「核分裂生成核種 ^{90}Sr の陽子および重陽子誘起反応に関する研究」, 東邦大学 理学部.

西津美咲, 「Se-79 の核破砕反応データ取得に向けた二次ビームの粒子識別」, 九州大学 総合理工学部.

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.

Members

Team Leader
Toshiyuki SUMIKAMA

Student Trainee
SungHan BAE (Seoul Nat'l Univ.)

List of Publications & Presentations

Publications

[Original papers]

S. Takeuchi *et al*., "Coulomb breakup reactions of ^{93,94}Zr in inverse kinematics," Prog. Theor. Exp. Phys. **2019**, 013D02 (2019).

S. Michimasa *et al*., "OEDO, the energy degrading beamline at RI Beam Factory," Prog. Theor. Exp. Phys. **2019**, 043D01 (2019).

H. Jongwon *et al*., "Angle-tunable wedge degrader for an energy-degrading RI beamline," Prog. Theor. Exp. Phys. **2019**, 043D02 (2019).

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

[Original papers]

S. Wenner, C. D. Marioara, K. Nishimura, K. Matsuda, S. Lee, T. Namiki, I. Watanabe, T. Matsuzaki, and R. Holmestad, "Muon spin relaxation study of solute?vacancy interactions during natural aging of Al-Mg-Si-Cu alloys," Metall. Mater. Trans. A **50**, 3446–3451 (2019).

[Proceedings]

R. Fujita, M. Kawashima, M. Ozawa, and T. Matsuzaki, "Reduction and resource recycling of high-level radioactive wastes through nuclear transmutation—overview and current progress—," Proceeding for the 13th International Conference on Nucleus-Nucleus Collisions (NN2018).

Presentations

[International conferences/workshops]

T. Saito, M. Niikura, T. Matsuzaki, and H. Sakurai for ImPACT muon collaboration, "Neutron emission property after nuclear muon capture of palladium," International Nuclear Physics Conference 2019, Scottish Event Campus, Glasgow, UK, July 29–August 2, 2019.

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

1. Abstract

The High-Intensity Accelerator 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, from FY2014 to FY2018. 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

Research/Technical Scientists
Kazunari YAMADA
Yutaka WATANABE
Kazutaka OZEKI

Research & Development Scientist
Kenji SUDA

List of Publications & Presentations

Publications

[Proceedings]

N. Sakamoto, T. Dantsuka, M. Fujimaki, H. Imao, O. Kamigaito, K. Kusaka, H. Okuno, K. Ozeki, K. Suda, A. Uchiyama, T. Watanabe, Y. Watanabe, K. Yamada, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa, "Development of superconducting quarter-wave resonator and cryomodule for low-beta ion accelerators at RIKEN Radioactive Isotope Beam Factory," Proceedings of the 19th International Conference on RF Superconductivity (SRF2019), (2019), pp. 750–757.

Presentations

[International conferences/workshops]

N. Sakamoto, T. Dantsuka, M. Fujimaki, H. Imao, O. Kamigaito, K. Kusaka, H. Okuno, K. Ozeki, K. Suda, A. Uchiyama, T. Watanabe, Y. Watanabe, K. Yamada, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa (invited), "Development of superconducting quarter-wave resonator and cryomodule for low-beta ion accelerators at RIKEN Radioactive Isotope Beam Factory," 19th International Conference on RF Superconductivity (SRF2019), Dresden, Germany, June 30–July 5, 2019.

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.

2. Major Research Subjects

(1) Liquid lithium target for production of neutron or muon
(2) Beam window without solid structure

3. Summary of Research Activity

(1) Liquid lithium target for production of neutron or muon
(H. Okuno)
(2) Beam window with solid structure
(H. Okuno)

Member

Team Leader
Hiroki OKUNO

List of Publications & Presentations

Publications

[Original papers]

H. Okuno, H. Sakurai, Y. Mori, R. Fujita, and M. Kawashima, “Proposal of a 1-ampere-class deuteron single-cell linac for nuclear transmutation,” Proceedings of the Japan Academy, Series B **95**, 430–439 (2019).

Presentations

[International conferences/workshops]

H. Okuno (oral), “Accelerator and target for transmutation of long-lived fission products in nuclear waste,” Fourth International Workshop on Technology and Components of Accelerator-Driven Systems (TCADS-4), Antwerp, Belgium, October 14–17, 2019.

H. Okuno (oral), “Seeking for a novel fabrication technology to make a large-bore SRF-QWR cavity for 1-ampere class linac,” TTC 2020, Genève, Switzerland, February 4–7, 2020.

Press releases

「「核のゴミ」問題解決に必要な加速器の概念を提案—既存の 300 倍の高出力重陽子ビームの加速が可能に—」, 理研プレスリリース, 2019 年 8 月 9 日.

Research Facility Development Division
Accelerator Group

1. Abstract

The Accelerator Group, consisting of seven teams, pursues various upgrade programs on 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 various 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 govern the development programs that are not dealt with by a single team, 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 70% in the last three years, resulting in the intensity of 94 pnA (7.7 kW) at the exit of the superconducting ring cyclotron. The beam intensity of ^{124}Xe has increased to 173 pnA, corresponding to the beam power of 7.4 kW.

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. The beam commissioning with the upgraded RILAC, which has been named "SRILAC," was started in January 2020. Finally, the SRILAC facility passed the facility inspection by the Nuclear Regulatory Authority on the last day of FY2019. The accelerating cavities of the ring cyclotron, which had been suffered from the low accelerating voltage, were also modified with this supplemantal budget. This modification played a key role in the increase of the beam intensities of uranium and xenon mentioned above. We also started providing intense vanadium beams for the synthesis of a new element [119] at GARIS II in 2017.

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 ^{211}At is under development with RI Application Research Group of RNC in the framework of this project. It will be installed and tested in the SRILAC 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 (CSR)," 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. Design study of the whole CSR is under progress after intensive optical calculations for the circulating beam. The final goal of this plan is to increase the uranium beam intensity by 20 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) Commissioning of the upgraded RILAC (SRILAC) facility
(4) Promotion of the future plan

3. Summary of Research Activity

(1) The maximum intensities of the uranium and xenon beams reached 94 and 173 pnA, respectively, at 345 MeV/nucleon.
(2) 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.
(3) The overall beam availability for the RIBF experiments averaged for 5 years from 2013 to 2017 was 92%. Although the availability fell down to 79% in 2018 because of several hardware troubles, it exceeded 92% in 2019.
(4) 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). The upgraded RILAC (SRILAC) facility passed the facility inspection by the Nuclear Regulatory Authority, as scheduled.
(5) The large infrastructure was properly maintained based on a well-organized cooperation among the related sections.
(6) An intensity-upgrade plan of the RIBF has been further investigated. Design study of the charge-stripper ring (CSR) is under progress.

Members

Group Director

Osamu KAMIGAITO

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

Junior Research Associate
Takahiro KARINO (Utsunomiya Univ.)
Kaori NAKAMURA (The University of Tokyo)

Research Part-time Worker I
Akira GOTO
Masayuki KASE

Research Consultants
Tadashi FUJINAWA
Toshiyuki HATTORI

Visiting Scientists
Eiji KAKO (KEK)
Hirotaka NAKAI (KEK)
Kensei UMEMORI (KEK)
Hiroshi SAKAI (KEK)
Taro KONOMI (KEK)
Noboru SASAO (Okayama Univ.)
Yasutaka IMAI (Okayama Univ.)

Student Trainees
Akira FUJIEDA (Okayama Univ.)
Hiroyuki KAINO (Okayama Univ.)

Assistant
Karen SAKUMA

Administrative Part-time Worker II
Ryoko UMEZAKI

List of Publications & Presentations

Publications

[Original papers]

T. Karino, "Evaluation method of beam instability in laser ion source using solenoid," Rev. Sci. Instrum. **91**, 033316 (2020).

K. Nakamura, N. Nishiura, M. Okamura, T. Kanesue, S. Ikeda, and A. Cannavo, "Feasibility study of a compact heavy ion source for investigation of laboratory magnetospheric plasma," Rev. Sci. Instrum. **91**, 033503 (2020).

[Proceedings]

O. Kamigaito, K. Ozeki, N. Sakamoto, K. Suda, and K. Yamada, "Measurement of mechanical vibration of SRILAC cavities," Proceedings of the 19th International Conference on RF Superconductivity (SRF2019), (Dresden, Germany, TUP042, 2019), pp. 515.

O. Kamigaito, T. Dantsuka, M. Fujimaki, N. Fukunishi, H. Hasebe, Y. Higurashi, E. Ikezawa, H. Imao, M. Kidera, M. Komiyama, K. Kumagai, T. Maie, Y. Miyake, T. Nagatomo, T. Nakagawa, M. Nakamura, T. Nishi, J. Ohnishi, H. Okuno, K. Ozeki, N. Sakamoto, K. Suda, A. Uchiyama, T. Watanabe, Y. Watanabe, and K. Yamada, "Recent progress in RIKEN RI Beam Factory," Proceedings of 22nd International Conference on Cyclotrons and their Applications (CYC2019), (Cape Town, South Africa, MOB01, 2019).

Presentations

[International conferences/workshops]

O. Kamigaito (invited), "Recent progress in RIKEN RI Beam Factory," 22nd International Conference on Cyclotrons and their Applications (CYC2019), Cape Town, South Africa, September 22–27, 2019.

T. Karino (oral), "Evaluation method of beam instability in laser ion source using solenoid," The 18th International Conference on Ion Sources (ICIS2019), Lanzhou, China, September 1–6, 2019.

K. Nakamura (oral), "Feasibility study of a compact heavy ion source for investigation of laboratory magnetospheric plasma," The 18th International Conference on Ion Sources (ICIS2019), Lanzhou, China, September 1–6, 2019.

A. Fujieda (oral), "Ba-ion spectroscopy experiment for high-intensity gamma-ray source using heavy ions," The 12th International Workshop on Fundamental Physics Using Atoms (FPUA2020), Wako, Japan, January 9–10, 2020.

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

Research/Technical Scientists

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

Special Postdoctoral Researcher

Yasuto MIYAKE

Junior Research Associate

Naoya IKOMA

Visiting Scientists

Andreas ADELMANN (Paul Sherrer Inst.)
Noriyosu HAYASHIZAKI (Tokyo Tech)
Hironori KUBOKI (KEK)

Student Trainees

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

Part-time Workers

Taishi SASAKI (Research Part-time Worker II)
Yoshiki SHIKUMA (Research Part-time Worker II)

List of Publications & Presentations

Publications

[Original papers]

N. Ikoma, Y. Miyake, M. Takahashi, H. Okuno, S. Namba, K. Takahashi, T. Sasaki, and T. Kikuchi, "Demonstration of plasma window with diameter of 20 mm and pressure separation for accelerator application," Plasma Fusion Res. **14**, 1206148 (2019).

N. Ikoma, Y. Miyake, M. Takahashi, H. Okuno, S. Namba, K. Takahashi, T. Sasaki, and T. Kikuchi, "Characteristics of plasma window with various channel diameters for accelerator applications," Review of Scientific Instruments **91**, 053503 (2020).

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 (Senior Technical Scientist)
Masanori KIDERA (Technical Scientist)
Yoshihide HIGURASHI (Technical Scientist)

Special Temporary Research Scientist
Yasuyuki KANAI

List of Publications & Presentations

Publications

[Original papers]

T. Nagatomo *et al*., "High intensity vanadium beam for synthesis of new superheavy elements with well-controlled emittance by using "slit triplet"," Rev. Sci. Instrum. ICIS18, 023318 (2020).

A. Uchiyama *et al*., "Control system for the new RIKEN 28-GHz superconducting electron cyclotron resonance ion source for SRILAC," Rev. Sci. Instrum. ICIS18, 025101 (2020).

[Proceedings]

T. Nagatomo *et al*., "Development of RIKEN 28 GHz SC-ECRISs for synthesizing super-heavy elements," Proc. HIAT2018, doi:10.18429/JACoW-HIAT2018-TUZAA01.

Presentations

[International conferences/workshops]

Y. Higurashi (invited), "Status and perspective for high intensity uranium beams from the RIKEN 28 GHz ECRIS," ICIS2019, Lanzhou, China, September 1–6, 2019.

T. Nakagawa (oral), "Production of intense metal ion beam with RIKEN 28 GHz SC-ECRIS," ICIS2019, Lanzhou, China, September 1–6, 2019.

T. Nagatomo (oral), "Well-controlled emittance of the metallic ion beam extracted from the 28 GHz SC-ECRIS adopting the super conducting acceleration cavity for new super heavy elements research," ICIS2019, Lanzhou, China, September 1–6, 2019.

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 28 GHz SC ECR ion source, the frequency-variable RFQ linac, the frequency-variable main linac, and the SC booster linac (SRILAC).

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]

M. Tamura, E. Ikezawa, T. Ohki, H. Yamauchi, K. Oyamada, A. Yusa, K. Kaneko, Y. Watanabe, and O. Kamigaito, "Present status of RILAC," Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan, (2019), pp. 1263.

Presentations

[Domestic conferences]

田村匡史, 池沢英二, 大木智則, 山内啓資, 小山田和幸, 遊佐陽, 金子健太, 渡邉裕, 上垣外修一, （FSPI010),「理研重イオンリニアックの現状報告」, 第 16 回日本加速器学会年会, 京都, 2019 年 7 月 31 日–8 月 3 日.

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 (Senior Technical Scientist)
Kenji SUDA (Technical Scientist)

List of Publications & Presentations

Publications

[Proceedings]

K. Suda, O. Kamigaito, K. Ozeki, N. Sakamoto, Y. Watanabe, K. Yamada, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa, "Fabrication and performance of superconducting quarter-wavelength resonators for SRILAC," Proceedings of the 19th International Conference on RF Superconductivity, (2019), pp. 182–187.

H. Imao, O. Kamigaito, N. Sakamoto, T. Watanabe, Y. Watanabe, K. Yamada, and K. Oyamada, "Non-evaporative getter-based differential pumping system for SRILAC at RIBF," Proceedings of the 19th International Conference on RF Superconductivity (2019), pp. 419–423.

K. Yamada, T. Dantsuka, H. Imao, O. Kamigaito, K. Kusaka, H. Okuno, K. Ozeki, N. Sakamoto, K. Suda, T. Watanabe, Y. Watanabe, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa, "Construction of superconducting linac booster for heavy-ion linac at RIKEN Nishina Center," Proceedings of the 19th International Conference on RF Superconductivity, (2019), pp. 502–507.

O. Kamigaito, K. Ozeki, N. Sakamoto, K. Suda, and K. Yamada, "Measurement of mechanical vibration of SRILAC cavities," Proceedings of the 19th International Conference on RF Superconductivity (2019), pp. 513–517.

月居憲俊, 福澤聖児, 濱仲誠, 石川盛, 小林清志, 小山亮, 仲村武志, 西田稔, 西村誠, 柴田順翔, 矢冨一慎, 大関和貴, 段塚知志, 藤巻正樹, 藤縄雅, 福西暢尚, 長谷部裕雄, 日暮祥英, 池沢英二, 今尾浩士, 上垣外修一, 金井保之, 加瀬昌之, 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, 中村仁音, 大西純一, 奥野広樹, 坂本成彦, 須田健嗣, 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の運転報告」, 第 16 回日本加速器学会年会, 京都大学吉田キャンパス, (京都, 2019), pp.1193–1197.

濱仲誠, 福澤聖児, 石川盛, 小林清志, 小山亮, 仲村武志, 西田稔, 西村誠, 柴田順翔, 月居憲俊, 矢冨一慎, 金子健太, 小山田和幸, 田村匡史, 遊佐陽, 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 16 回日本加速器学会年会, 京都大学吉田キャンパス, (京都, 2019), pp. 1224–1228.

Presentations

[International conferences/workshops]

K. Ozeki (oral), "Power couplers for RIKEN superconducting QWR," World Wide Fundamental Power Coupler meeting #5, Geneva, Switzerland, June 25–26, 2019.

K. Suda, O. Kamigaito, K. Ozeki, N. Sakamoto, Y. Watanabe, K. Yamada, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa (poster), "Fabrication and performance of superconducting quarter-wavelength resonators for SRILAC," 19th International Conference on RF Superconductivity (2019), Dresden, Gernany, June 30–July 5, 2019.

H. Imao, O. Kamigaito, N. Sakamoto, T. Watanabe, Y. Watanabe, K. Yamada, and K. Oyamada (poster), "Non-evaporative getter-based differential pumping system for SRILAC at RIBF," 19th International Conference on RF Superconductivity (2019), Dresden, Gernany, June 30–July 5, 2019.

K. Yamada, T. Dantsuka, H. Imao, O. Kamigaito, K. Kusaka, H. Okuno, K. Ozeki, N. Sakamoto, K. Suda, T. Watanabe, Y. Watanabe, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa (poster), "Construction of superconducting linac booster for heavy-ion linac at RIKEN Nishina Center," 19th International Conference on RF Superconductivity (2019), Dresden, Gernany, June 30–July 5, 2019.

O. Kamigaito, K. Ozeki, N. Sakamoto, K. Suda, and K. Yamada (poster), "Measurement of mechanical vibration of SRILAC cavities," 19th International Conference on RF Superconductivity (2019), Dresden, Gernany, June 30–July 5, 2019.

[Domestic conferences/workshops]

月居憲俊, 福澤聖児, 濱仲誠, 石川盛, 小林清志, 小山亮, 仲村武志, 西田稔, 西村誠, 柴田順翔, 矢冨一慎, 大関和貴, 段塚知志, 藤巻正樹, 藤縄雅, 福西暢尚, 長谷部裕雄, 日暮祥英, 池沢英二, 今尾浩士, 上垣外修一, 金井保之, 加瀬昌之, 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, 中村仁音, 大西純一, 奥野広樹, 坂本成彦, 須田健嗣, 内山暁仁, 渡部秀, 渡邉環, 渡邉裕, 山田一成, 山澤秀行 (ポスター発表), 「理研 RIBF におけるリングサイクロトロンの運転報告」, 第 16 回日本加速器学会年会, 京都大学吉田キャンパス, 京都, 2019 年 7 月 31 日–8 月 3 日.

濱仲誠, 福澤聖児, 石川盛, 小林清志, 小山亮, 仲村武志, 西田稔, 西村誠, 柴田順翔, 月居憲俊, 矢冨一慎, 金子健太, 小山田和幸, 田村匡史, 遊佐陽, 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 (ポスター発表), 「理研 AVF サイクロトロン運転の現状報告」, 第 16 回日本加速器学会年会, 京都大学吉田キャンパス, 京都, 2019 年 7 月 31 日–8 月 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 94-pnA uranium, 173-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

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

Expert Technician
Misaki KOMIYAMA

Postdoctoral Researcher
Takahiro NISHI

Visiting Scientists
Shin-ichiro HAYASHI (Hiroshima Int'l Univ.)
Atsushi KAMOSHIDA (Nat'l Instruments Japan Corporation)
Takuya MAEYAMA (Kitasato Univ.)

Student Trainee
Anri MOCHIZUKI (Kitasato Univ.)

Part-time Worker
Makoto NAGASE (Research Part-time Worker I)

List of Publications & Presentations

Publications

[Original papers]

A. Uchiyama, T. Nagatomo, Y. Higurashi, J. Ohnishi, M. Komiyama, K. Kumagai, M. Fujimaki, H. Yamauchi, M. Tamura, K. Kaneko, N. Fukunishi, and T. Nakagawa, "Control system for the new RIKEN 28-GHz superconducting electron cyclotron resonance ion source for SRILAC," Rev. Sci. Instrum. **91**, 025101 (2020).

[Proceedings]

T. Watanabe, H. Imao, O. Kamigaito, N. Sakamoto, N. Fukunishi, M. Fujimaki, K. Yamada, Y. Watanabe, T. Toyama, T. Miyao, A. Miura, K. Hanamura, T. Kawachi, R. Koyama, and A. Kamoshida, "Calibration of the beam energy and position monitor system for the RIKEN superconducting acceleration cavity," Proceedings of the 2019 International Beam Instrumentation Conference (IBIC2019), Pre-Release 1–3, Malmö, Sweden, September 8–12, 2019.

K. Yamada *et al*., "Construction of superconducting linac booster for heavy-ion linac at RIKEN Nishina Center," Proc. SRF2019, TUP037, Dresden, Germany, 2019-July, p. 504.

R. Koyama, A. Uchiyama, H. Imao, and T. Watanabe, "Upgrade of gas stripper control system for system integration at RIBF," Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan, 865–868, Kyoto, Japan, July 31–August 3, 2019.

A. Uchiyama, M. Komiyama, K. Kumagai, E. Ikezawa, J. Ohnishi, H. Yamauchi, and M. Tamura, "Upgrade of electromagnet power supply control at RILAC," Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan, 869–872, Kyoto, Japan, July 31–August 3, 2019.

T. Watanabe, T. Toyama, K. Hanamura, H. ImaoA, O. Kamigaito, A. Kamoshida, T. Kawachi, R. Koyama, N. Sakamoto, N. Fukunishi, M. Fujimaki, A. Miura, T. Miyao, K. Yamada, and Y. Watanabe, "Mapping measurement for beam energy position monitor system for RIKEN superconducting acceleration cavity," Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan, 1105–1108, Kyoto, Japan, July 31–August 3, 2009.

Presentations

[International conferences/workshops]

K. Yamada *et al*. (poster), "Construction of superconducting linac booster for heavy-ion linac at RIKEN Nishina Center," 19th International Conference on RF Superconductivity (SRF2019), Dresden, Germany, June 30–July 5, 2019.

A. Uchiyama, T. Nagatomo, Y. Higurashi, J. Ohnishi, M. Komiyama, K. Kumagai, M. Fujimaki, H. Yamauchi, M. Tamura, K. Kaneko, N. Fukunishi, and T. Nakagawa (poster), "Control system for the new RIKEN 28-GHz superconducting electron cyclotron resonance ion source for SRILAC," The 18th International Conference on Ion Sources (ICIS2019), Lanzhou, China, September 1–6, 2019.

T. Watanabe, H. Imao, O. Kamigaito, N. Sakamoto, N. Fukunishi, M. Fujimaki, K. Yamada, Y. Watanabe, T. Toyama, T. Miyao, A. Miura, K. Hanamura, T. Kawachi, R. Koyama, and A. Kamoshida, "Calibration of the beam energy and position monitor system for the RIKEN superconducting acceleration cavity," The 2019 International Beam Instrumentation Conference (IBIC2019), Malmö, Sweden, September 8–12.

M. Komiyama *et al*. (poster), "Recent updates of the RIKEN RI Beam Factory control system," The17th Biennial International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 2019), New York, USA, October 5–11, 2019.

K. Yamada (oral), "Cryomodule design, assembly and installation utilizing KOACH system," TESLA Technology Collaboration (TTC) Meeting 2020 at CERN, Geneva, Switzerland, February 4–7, 2020.

[Domestic symposium]

M. Komiyama, A. Uchiyama, and K. Kumagai (poster), "Beam Interlock System of RIKEN RI Beam Factory," 7th Accelerator Facility Safety Symposium, Tokai, Ibaragi, Japan, January 23–24, 2020.

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, M. Kuroiwa, M. Takahashi, H. Okuno).

Members

Team Leader
Hiroki OKUNO

Research/Technical Scientists
Masato NAKAMURA (Senior Technical Scientist)

Expert Technicians
Tomoyuki DANTSUKA
Takeshi MAIE

Part-time Workers
Mamoru TAKAHASHI (Research Part-time Worker I)
Shizuho TSURUMA (Administrative Part-time Worker I)
Mayumi KUROIWA (Administrative Part-time Worker II)

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

Team Leader

Osamu KAMIGAITO (concurrent: Group Director, Accelerator Group)

Deputy Team Leader

Yutaka WATANABE (concurrent: Senior Technical Scientist, RILAC Team.)

Special Temporary Technical Scientist

Shu WATANABE

Special Temporary Employee

Hideyuki YAMASAWA

List of Publications & Presentations

Publications

[Proceedings]

K. Suda, O. Kamigaito, K. Ozeki, N. Sakamoto, Y. Watanabe, K. Yamada, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa, "Fabrication and performance of superconducting quarter-wavelength resonators for SRILAC," Proceedings of the 19th International Conference on RF Superconductivity (SRF2019), Dresden, Germany, MOP055, 182 (2019).

H. Imao, K. Yamada, N. Sakamoto, T. Watanabe, Y. Watanabe, O. Kamigaito, and K. Oyamada, "Non-evaporable getter-based differential pumping system for SRILAC at RIBF," Proceedings of the 19th International Conference on RF Superconductivity (SRF2019), Dresden, Germany, TUP013, 419 (2019).

K. Yamada, T. Dantsuka, H. Imao, O. Kamigaito, K. Kusaka, H. Okuno, K. Ozeki, N. Sakamoto, K. Suda, T. Watanabe, Y. Watanabe, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa, "Construction of superconducting linac booster for heavy-ion linac at RIKEN Nishina Center," Proceedings of the 19th International Conference on RF Superconductivity (SRF2019), Dresden, Germany, TUP037, 504 (2019).

N. Sakamoto, T. Dantsuka, M. Fujimaki, H. Imao, O. Kamigaito, K. Kusaka, H. Okuno, K. Ozeki, K. Suda, A. Uchiyama, T. Watanabe, Y. Watanabe, K. Yamada, E. Kako, H. Nakai, H. Sakai, K. Umemori, H. Hara, A. Miyamoto, K. Sennyu, and T. Yanagisawa, "Development of superconducting quarter-wave resonator and cryomodule for low-beta ion accelerators at RIKEN Radioactive Isotope Beam Factory," Proceedings of the 19th International Conference on RF Superconductivity (SRF2019), Dresden, Germany, WETEB1, 752 (2019).

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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, and an improvement for higher precise mass measurement is now going on. 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) RUNBA project (Beam recycling development)

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 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. Recently, we succeeded in measurement of masses of ^{74,76}Ni, ^{122}Rh, and ^{124}Pd for the first time. 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 will be online-commissioned in this year. Future plans for these projects are described in subsections.

We have started a new project from last year. According to the future plan of Nishina center, we are going to develop a beam re-cycling technique. A circulation 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 losses the 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 growth of the energy-spread and the emittance 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 will construct 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 RUNBA (Recycled-Unstable-Nuclear Beam Accumulator) is equipped by acceleration devices and beam-cooling devices necessary in our R&D study. It was originally constructed as a beam cooler ring (s-LSR) at the Institute for Chemical Research (ICR), Kyoto University more than ten years ago. This has been already moved to RIBF in last year, and will be re-constructed by the SCRIT system in following year. Technical development for key devices required in RUNBA such as a charge breeder, an energy-spread compensator, and an internal target system have been already started under the research cooperation agreement with ICR Kyoto University.

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List of Publications & Presentations

Publications and presentations 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. From April 1st in FY2019, SLOWRI has been started to be co-operated under RNC and WNSC/KEK collaboration.

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. In FY2019, the mass measurement for ^{257}Db has been successfully performed at GARIS-II, and the mass has been directly determined for the first time. At SLOWRI facility, third prototype SLOWRI is under construction, which is a 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.

Parallelly, the on-line commissioning for PALIS has been continuously performed at F2 of BigRIPS. For the optimization of optical components on SLOWRI beam line, which connects between these gas cells installed at BigRIPS and an experimental room, a compact cesium ion source was installed at the upstream of the beam line in FY2019.

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) Commissioning for SLOWRI beam line.

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. 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 (2nd 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 FY2019, we modified the 1st carpet to have a finer pitch which was reduced by 20% compared with the previous version, in order to improve the transport efficiency. We tested the transport performance of the new 1st carpet using Cs^+ ions provided with a surface ionization ion source installed inside the gas cell. As the result, we have successfully achieved 80% transport efficiency in a He gas of 133 mbar. As combined with a transport efficiency on the 2nd carpet, we confirmed more than 70% extraction efficiency from the gas cell for the Cs^+ ions which were collected onto the RF carpets.

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 FY2020. At F11, symbiotic measurements with other BigRIPS experiments such as HiCARI projects 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 (MRTOF) 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 MRTOF. 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. In FY2019, the mass measurement of a super heavt element of ^{257}Db has been successfully performed, and the mass has been dilectly measured for the first time.

A new MRTOF has been assembled in FY2019 to be coupled with the third SLOWRI protype gass cell, which will be installed at F11 of BigRIPS. Using an ion source of K^+, the offline commissioning has been sucessflully performed. As the result, an impressive mass- resolving power of 570,000 has been achived.

(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.

In FY2019, we had two on-line experiments and a part of the experimental result was published in Prog. Theor. Exp. Phys. (See our publication list) Technical developments are under progress in on- and off-line commissioning.

(5) Commissioning for SLOWRI beam line

SLOWRI beam line composes of four dipole magnets, two focal plane chambers, 62 electrostatic quadrupole singlets, 11 electrostatic quadrupole quartets and 7 beam profile monitors. The hardware construction has been almost finished. In order to tune the optical components, a compact ion source, which can be used as a side-inserted type device, has been installed at the upstream of the beam line. We will start the tuning for the beam line using Cs^+ ions provided from the ion source in FY2020.

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List of Publications & Presentations

Publications

[Original papers]

T. Sonoda, I. Katayama, M. Wada, H. Iimura, V. Sonnenschein, S. Iimura, A. Takamine, M. Rosenbusch, T. M. Kojima, D. S. Ahn, N. Fukuca, T. Kubo, S. Nishimura, Y. Shimizu, H. Suzuki, H. Takaeda, M. Tanigaki, H. Tomita, K. Yoshida, and H. Ishiyama, "Conceptual study on parasitic low-energy RI beam production with in-flight separator BigRIPS and the first stopping examination for h igh-energy RI beam in the parasitic gas cell," Progress of Theoretical and Experimental Physics, **2019-11**, 113D02, (2019).

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高峰愛子 (口頭発表), 「核・物質科学研究への応用を目指した高偏極 RI ビーム生成」, 京大複合研専門研究会「短寿命核 RI を用いた核分光と核物性研究 VI」兼「第 11 回停止・低速 RI ビームを用いた核分光研究会」, 京大複合研, 京都, 2020 年 1 月 16–17 日.

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Outreach activities

H. Ishiyama (school master), S. Iimura (school staff), and T. Kojima (school staff), Nishina School 2019, Riken, Wako, Japan, July 30–August 1, 2019.

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. The remaining issues as the R3 facility are further improvement of experimental efficiency and that of mass measurement precision. In 2019, we started efforts to resolve those issues.

2. Major Research Subjects

(1) Further improvement of experimental efficiency and mass measurement precision
(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 a 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 less than 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 2020 or later.

With further improvements in experimental efficiency and mass measurement precision, the R3 enables mass measurement of extremely rare-RIs that are inaccessible for other techniques. In 2019, we started to add one more kicker magnet. More accurate injection and reliable extraction will be possible, the experimental efficiency will be improved about 10 times from the previous experiment. We plan to conduct a beam test in 2020.

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List of Publications & Presentations

Publications

[Original papers]

X. Xu, M. Wang, K. Blaum, J. D. Holt, Yu. A. Litvinov, A. Schwenk, J. Simonis, S. R. Stroberg, Y. H. Zhang, H. S. Xu, P. Shuai, X. L. Tu, X. H. Zhou, F. R. Xu, G. Audi, R. J. Chen, X. C. Chen, C. Y. Fu, Z. Ge, W. J. Huang, S. Litvinov, D. W. Liu, Y. H. Lam, X. W. Ma, R. S. Mao, A. Ozawa, B. H. Sun, Y. Sun, T. Uesaka, G. Q. Xiao, Y. M. Xing, T. Yamaguchi, Y. Yamaguchi, X. L. Yan, Q. Zeng, H. W. Zhao, T. C. Zhao, W. Zhang, and W. L. Zhan, "Masses of neutron-rich $^{52\text{–}54}$Sc and ^{54,56}Ti nuclides: The N = 32 subshell closure in scandium," Phys. Rev. C **99**, 064303 (2019).

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Presentations

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T. Yamaguchi (invited), "New experimental plan and detector R&D at the Rare-RI Ring facility," China-Japan Collaboration Workshop on Nuclear Mass and Life for Unraveling Mysteries of R-process, Beijing, China, October 10–12, 2019.

[Seminars]

T. Yamaguchi, "Charge changing cross section measurement—A possible method to extract point-proton radii of radioactive isotopes," Beihang Univ., Beijing, China, October 14, 2019.

[Domestic conferences/workshops]

向井もも（口頭発表),「薄膜を利用した飛行時間検出器の開発」, 日本物理学会 2019 年秋季大会, 山形大学, 山形, 2019 年 9 月 17–20 日.

稲田康人（口頭発表),「稀少 RI リングのためのファイバーシンチレーション検出器の開発」, 日本物理学会 2019 年秋季大会, 山形大学, 山形, 2019 年 9 月 17–20 日.

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長江大輔（口頭発表),「稀少 RI リングでの粒子蓄積確認の為の飛行時間検出器」, 日本物理学会第 75 回年次大会, 現地開催中止, 2020 年 3 月 16–19 日.

Research Facility Development Division
Instrumentation Development Group
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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 developed 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.

In 2019, we installed a newly designed SCRIT electrodes. The main purpose of the replacement was to lower the background during the measurement due to the electron scattering from the SCRIT electrodes itself but not from the ion targets for the experiment. For that purpose, we employed thin metal wires to construct the electrodes rather than metal plates nor blocks. In addition, we modified the inside structure of the SCRIT chamber to symmetrize the electric ground potential affecting the potential curve inside the electrodes. Currently, we are adjusting the SR2 accelerator and ion source ERIS to be ready for the measurement by means of the new

SCRIT electrodes.

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List of Publications & Presentations

Publications

[Proceedings]

K. Tsukada, K. Adachi, A. Enokizono, T. Fujita, M. Hara, T. Hori, M. Hori, S. Ichikawa, K. Kasama, K. Kurita, K. Namba, T. Ohnishi, T. Suda, T. Tamae, M. Togasaki, M. Wakasugi, M. Watanabe, and K. Yamada, "Electron scattering from ^{208}Pb and ^{132}Xe ions at the SCRIT facility," Hyperfine interact **240**, 1–120 (2019).

Presentations

[International conferences/workshops]

T. Suda (invited), "Proton charge radius by low-energy electron scattering," International Workshop on the Structure of the Proton, Yamagata, February 10–11, 2019.

T. Suda (oral), "Nuclear physics with low-energy and high-intensity electron beam," Neutrino Nuclear Response 2019 (NNR19), RCNP, Osaka, Japan, May 8–9, 2019.

T. Suda (invited), "Electron scattering for short-live nuclei," Gordon Conference on "Exploring simple structural patterns and dynamics of nuclei," New London US, June 16–21, 2019.

T. Suda (invited), "Nuclear physics with electron beam," Connecting Fundamental Physics, Chemistry and the Origins of Biomolecular Homochirality, National Observatory of Japan, June 26–27, 2019.

S. Sato (oral), M. Wakasugi, T. Ohnishi, M. Watanabe, A. Enokizono, and K. Kurita, "Improvement of a dc-to-pulse conversion efficiency of FRAC," The 13th International Conference on Stopping and Manipulation of Ions and related topics (SMI2019), Montreal, Canada, July 16–19, 2019.

T. Suda (plenary/invited), "Electron scattering for short-lived nuclei," International Nuclear Physics Conference (INPC2019), Glasgow UK, July 29–August 2, 2019.

M. Watanabe (poster), A. Enokizono, M. Hara, Y. Honda, T. Hori, S. Ichikawa, K. Kasama, K. Kurita, M. Nakano, K. Namba, T. Oonishi, S. Sato, T. Suda, S. Takayama, T. Tamae, K. Tsukada, M. Wakasugi, and H. Wauke, "Fine optimization of SCRIT facility for short-lived nuclei experiment," International Nuclear Physics Conference (INPC2019), Glasgow, UK, July 29–August 2, 2019.

T. Suda (invited), "Proton radius," The 11th Circum-Pan-Pacific Symposium on High Energy Spin Physics, Miyazaki Japan, August 27–30, 2019.

H. Wauke (poster), T. Aoyagi, A. Enokizono, Y. Honda, T. Suda, S. Takayama, T. Tamae, K. Tsukada, T. Ohnishi, M. Wakasugi, and M. Watanabe, "Precise magnetic field measurement of electron spectrometer for the electron scattering off unstable nuclei experiment," International school for Strangeness Nuclear Physics 2019, Tohoku Univ., Sendai, Japan, September 5–8, 2019.

K. Tsukada (oral), T. Aoyagi, A. Enokizono, M. Hara, Y. Honda, T. Hori, S. Ichikawa, K. Kurita, T Ohnishi, S. Sato, T. Suda, S. Takayama, T. Tamae, M. Wakasugi, and M. Watanabe, "Present status and future prospects of the SCRIT electron scattering facility," 9th International Symposium on Nuclea1r Symmetry Energy (NuSYM2019), Danang City, Vietnam, September 30–October 4, 2019.

T. Suda (invited), "Proton radius," 14th Asia-Pacific Physics Conference (APPC2019), Kuching Malaysia, November 17–22, 2019.

K. Tsukada (oral), T. Aoyagi, A. Enokizono, M. Hara, Y. Honda, T. Hori, S. Ichikawa, K. Kurita, T Ohnishi, S. Sato, T. Suda, T. Tamae, M. Wakasugi, and M. Watanabe, "Present status of SCRIT electron scattering facility," 14th Asia-Pacific Physics Conference (APPC2019), Sarawak, Malaysia, November 17–22, 2019.

T. Suda (invited), "Electron-scattering activities in Japan for nucleon and nuclei," KVI Seminar, KVI Groningen, Netherlands, January 8, 2019.

T. Suda (invited), "ULQ2 project," Collaborative Seminar by REIMEI, RCNP and Clusters, February 2020.

T. Ohnishi (oral), A. Enokizono, M. Hara, T. Hori, S. Ichikawa, K. Kurita, R. Ogawara, S. Sato, T. Suda, S. Takayama, D. Taki, S. Takagi, T. Tamae, K. Tsukada, M. Wakasugi, M. Watanabe, and H. Wauke, "Electron scattering with unstable nuclei at the SCRIT electron scattering facility," Vth Topical Workshop on Modern Aspects in Nuclear Structure—The Many Facets of Nuclear Structure, Bormio, Italy, February 4–9, (2020).

[Domestic conferences/workshops]

須田利美（招待講演),「ガンマ線ビームを用いた原子核・ハドロン物理の新局面と今後の展望」, 低エネルギー・大電流電子ビームと原子核物理, RCNP 研究会, 大阪, 2019 年 3 月 4–5 日.

須田利美（招待講演),「陽子のサイズがおかしい？」, 東京大学物理学教室コロキウム, 東京, 2019 年 11 月 8 日.

和宇慶ひかり（口頭発表),「SCRIT 電子スペクトロメーターの 3 次元磁場測定」, 東北大学理学研究科 6 専攻+生命科学研究科合同シンポジウム 2020, 東北大学, 2020 年 2 月 14 日.

和宇慶ひかり（ポスター発表), 塚田暁, 青柳泰平, 須田利美, 髙山祥太, 瀧大祐, 玉江忠明, 本多佑記,「SCRIT 電子スペクトロメーターの 3 次元磁場測定」, ELPH シンポジウム, 東北大学 ELPH, 仙台, 2019 年 3 月 6 日.

佐藤蒼（口頭発表), 榎園昭智, 大西哲也, 栗田和好, 須田利美, 塚田暁, 和宇慶ひかり, 若杉昌徳, 渡邊正満,「SCRIT 実験のための高効率 RFQ クーラーバンチャーの開発」, 日本物理学会第 75 回年次大会, 名古屋大学, 名古屋, 2020 年 3 月 16–19 日.

和宇慶ひかり（口頭発表), 青柳泰平, 榎園昭智, 大西哲哉, 栗田和好, 佐藤蒼, 須田利美, 高木周, 髙山祥汰, 瀧大祐, 玉江忠明, 塚田暁, 本多佑記, 若杉昌徳, 渡邊正満,「SCRIT 電子スペクトロメーターの 3 次元磁場測定」, 日本物理学会第 75 回年次大会, 名古屋大学, 名古屋, 2020 年 3 月 16–19 日.

塚田暁（口頭発表), 青柳太平, 市川進一, 榎園昭智, 大西哲哉, 栗田和好, 佐藤蒼, 須田利美, 高山祥汰, 瀧大祐, 玉江忠明, 原雅弘, 堀利匡, 本多佑記, 和宇慶ひかり, 若杉昌徳, 渡邊正満,「炭素標的を用いた SCRIT 実験用電子スペクトロメータの性能評価」, 日本物理学会第 75 回年次大会, 名古屋大学, 名古屋, 2020 年 3 月 16–19 日.

[International seminars/lectures]

T. Suda, Lectures: "Electron scattering for nucleon and nuclei," Johannesburg, South Africa, October 19–November 3, 2019.

T. Suda, Public lecture: "Nihonium: 113th element," Johannesburg, South Africa, October 19–November 3, 2019.

[Domestic seminars/lectures]

須田利美,「電子線核物理特論」, 大学院講義, 2019 年 10 月–2020 年 3 月.

須田利美,「宇宙創生物理学概論」, GPPU 講義, 2019 年 6 月.

須田利美,「元素について」, 熊谷高校訪問生への特別講義, 2019 年 8 月 26 日.

須田利美, "Physics Today," 新潟大学集中講義, 2019 年 12 月 3–5 日.

須田利美,「元素と原子核」, 熊谷高校特別授業, 2019 年 12 月 6 日.

須田利美,「日本で発見された 113 番新元素ニホニウム」, 仙台青陵中等学校出前授業, 2019 年 12 月 10 日.

Awards

H. Wauke, SNP School Incentive Prize, "Precise magnetic field measurement of electron spectrometer for the electron scattering off unstable nuclei experiment," International school for Strangeness Nuclear Physics 2019, Tohoku Univ., Sendai, Japan, September 5–8, 2019.

Others

T. Ohnishi, A. Enokizono, M. Hara, T. Hori, S. Ichikawa, K. Kurita, R. Ogawara, S. Sato, T. Suda, S. Takayama, D. Taki, S. Takagi, T. Tamae, K. Tsukada, M. Wakasugi, M. Watanabe, and H. Wauke, "The SCRIT project at RIKEN," NUSTAR Annual Meeting 2020, GSI, Darmstadt, Germany, March 2–6, (2020).

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.

Members

Team Leader

Koichi YOSHIDA

Research/Technical Scientists

Yoshiyuki YANAGISAWA (Senior Research Scientist)
Naohito INABE (Senior Technical Scientist)
Kensuke KUSAKA (Senior Technical Scientist)
Masao OHTAKE (Senior Technical Scientist)
Naoki FUKUDA (Technical Scientist)
Hiroyuki TAKEDA (Technical Scientist)

Contract Researchers

Deuk Soon AHN
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Visiting Scientists

Alan Matthew AMTHOR (Bucknell Univ.)
Daniel P. BAZIN (Michigan State Univ.)
Alfredo ESTRADE VAZ (Central Michigan Univ.)
Michael FAMIANO (Western Michigan State Univ.)
Hans GEISSEL (GSI/Justus-Liebig Univ. Giessen)
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David MORRISSEY (Michigan State Univ.)
Mauricio PORTILLO (Michigan State Univ.)
Bradley M. SHERRILL (Michigan State Univ.)
Oleg TARASOV (Michigan State Univ.)

Student Trainee

Shunki ISHIKAWA (Tohoku Univ.)

Part-time Worker

Tetsuro KOMATSUBARA (Research Part-time Worker I)

List of Publications & Presentations

Publications

[Original papers]

Y. Ichikawa, H. Nishibata, Y. Tsunoda, A. Takamine, K. Imamura, T. Fujita, T. Sato, S. Momiyama, Y. Shimizu, D. S. Ahn, K. Asahi, H. Baba, D. L. Balabanski, F. Boulay, J. M. Daugas, T. Egami, N. Fukuda, C. Funayama, T. Furukawa, G. Georgiev, A. Gladkov, N. Inabe, Y. Ishibashi, T. Kawaguchi, T. Kawamura, Y. Kobayashi, S. Kojima, A. Kusoglu, 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. Tominaga, H. Ueno, H. Yamazaki, and X. F. Yang, "Interplay between nuclear shell evolution and shape deformation revealed by the magnetic moment of ^{75}Cu," Nat. Phys. **15**, 321 (2019).

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[Proceedings]

K. Kusaka, "Long term operation of the superconducting triplet quadrupoles with cryocoolers for BigRIPS in-flight separator at RIKEN," 2019 IOP Conf. Ser.: Mater. Sci. Eng. **502**, 012103(2019).

Presentations

[International conferences/workshops]

H. Suzuki (oral), "Discovery of ^{72}Rb & production of proton-rich RI-beams at RIBF," The International Conference on Proton-Emitting nuclei (PROCON2019), East Lansing, Michigan, USA, June 3–7, 2019.

N. Fukuda (invited), "Observation of new isotopes at RIKEN RI Beam Factory," XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2019.

K. Kusaka (poster), "Long term operation of the superconducting triplet quadrupoles with cryocoolers," EUCAS2019: 14th European Conference on Applied Superconductivity, SEC, Glasgow, UK, September 1–5, 2019.

D. S. Ahn (invited), "Status of RI beam production at BigRIPS," Expert meeting on Next-Generation Fragment Separators 2019, Darmstadt, Germany, September 30–October 2, 2019.

H. Takeda(invited), "Development of various new ion-optics modes at BigRIPS," Expert meeting on Next-Generation Fragment Separators 2019, Darmstadt, Germany, September 30–October 2, 2019.

N. Fukuda (invited), "Observation of new isotopes at RIKEN RI Beam Factory," 14th Asia Pacific Physics Conference, Sarawak, Malaysia, November 17–21, 2019.

N. Fukuda (oral), "Present status of RI production at RIKEN RI Beam Factory and future prospects—RI Production at high energies—," JSPS/NRF/NSFC A3 Foresight Program "Nuclear Physics in the 21st Century," Joint Kickoff Meeting, Kobe, Japan, December 6–7, 2019.

[Domestic conferences/workshops]

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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 a 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

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List of Publications & Presentations

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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 is managed by 5 GTO modules. To improve the data readout speed of VME system, we have successfully developed the MPV system which is a parallel readout extension of the VME system. Data readout sequence is completely parallelized that helps to improve the DAQ deadtime. Thanks to the MPV system, now the DAQ system in RIBF is 10 times faster than in 2007.

(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, some 10 Gbps networks port has been introduced to RIBF experimental area. 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 (Senior Research Scientist)

Junior Research Associate

Fumiya GOTO

Special Temporary Research Scientist

Takashi ICHIHARA

List of Publications & Presentations

Presentations

[International Conferences/Workshops]

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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)
Yuka HIKIMA (Toho University)
Mitsumasa MORI (Toho University)

List of Publications & Presentations

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引間宥花, 池田時浩, 浜垣学, 金衛国 (口頭発表), 「ガラスキャピラリー光学系によるイオンマイクロビームの照射距離とスポットサイズの相関」, 日本物理学会第 75 回年次大会（2020 年）, 名古屋大学, 名古屋, 2020 年 3 月 16–19 日.

Awards

河村俊哉, JSRC Young Scientist Award for 16th International Congress of Radiation Research (ICRR2019), 日本放射線化学会, 2019 年 7 月 12 日.

Accelerator Applications Research Division
Beam Mutagenesis Group

1. Abstract

This group promotes biological 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. Plant Genome Evolution Research Team studies the effect of chromosomal rearrangements on plant genomes and phenotypes.

2. Major Research Subjects

(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) Identification of plant sex-determining genes using mutants and their evolutionary study

3. Summary of Research Activity

Summary of research activities of the two teams are given in the sections of each team.

Member

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 study of ion-beam radiation mutagenesis, genome-wide analyses of mutation, and development of new plants and microbial varieties by heavy-ion irradiation. Thirty new varieties 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). Adjusting the BP to target malignant cells is well known to be effective for cancer therapy. On the other hand, a uniform dose distribution is a key to the systematic study for heavy-ion mutagenesis, thus to the improvement of the mutation efficiency. Plants and microbes therefore, are irradiated 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* and rice (*Oryza sativa* L.). The most effective LET (LETmax) was 30 keV/μm in Arabidopsis and rice dry seeds. LETmax irradiations showed the same mutation rate as that by chemical mutagens, which typically cause high mutation rate. The LETmax of imbibed rice seeds and dry wheat (*Triticum monococcum*) seeds were shown to be 50–63 keV/μm and 50 keV/μm, respectively. In the case of microbe, filamentous fungus (*Neurospora crassa*), the Ar ions at 290 keV/μm demonstrated higher mutagenic activity than the Fe-ions at 640 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

We analyzed the DNA alterations corresponding to morphological mutants in Arabidopsis and rice. In the mutants from C- and Ar-ions irradiations, the majority of the induced mutations were deletions. The proportion of large deletions (>100 bp) increased with increasing LET. We concluded that the size of deletions generated by heavy-ion beam irradiation increased with increasing LET. Whole-genome analysis by high-through put sequencing is a powerful tool used to characterize the nature of induced mutations. We also developed a new pipeline named the Automated Mutation Analysis Pipeline (AMAP), for the rapid detection of whole-genome mutations in Arabidopsis. We comprehensively characterized the mutation effects of ion beams of C (30 keV/μm) and Ar (290 keV/μm) by whole-genome mutational analysis on eight morphological mutants with AMAP. C ions at a dose of 400 Gy mainly induced single-nucleotide variants (SNVs) and small insertions and deletions (InDels) at a rate of 57 sites per mutant genome. LETmax irradiation is effective for breeding because of its very high mutation frequency. Most mutations are SNV and small deletions which are capable of disrupting 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 a dose of 50 Gy showed a mutation spectrum different from that at LETmax. The proportion of SNVs and small InDels was low at a rate of 28 sites per mutant genome, while that of large deletions and chromosomal rearrangements was high (10 sites per mutant genome). 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

In 1999, we formed a consortium for ion-beam breeding consisting of 24 groups. In 2019, the consortium grew to 184 groups from Japan and 20 from overseas. Previously, the ion-beam breeding procedures were carried out using mainly flowers and ornamental plants. We have recently put a new non-pungent and tearless onion, 'Smile ball,' on the market along with 'Kiku Meigetsu,' an edible late flowering chrysanthemum. In addition, a new project was launched to expand the cultivation area of this variety of chrysanthemum in Yamagata prefecture. Beneficial variants have been cultivated for various plant species, such as high yield sea weeds, lipids-hyperaccumulating unicellular alga, large marine plankton and lettuce with a low browning property as a cut vegetable. We collaborate with Miyagi prefectural government and Tohoku University to breed salt-resistant lines in the more delicious commercial rice varieties, 'Hitomebore' and 'Manamusume.' Imbibed seeds were irradiated with the LETmax (C-ions) on 16 April, 2011. We have isolated a candidate line of salt-resistant mutant from 719 M_2 progenies grown in the saline paddy field in 2012. This line grew well after transplantation and had high yield in common paddy field as well. By broadening the target of heavy-ion breeding extending from flowers to crops such as grains, the technology will contribute to solving the global problems of food shortage and environmental destruction.

Members

Team Leader

Tomoko ABE

Research/Technical Scientists

Tokihiro IKEDA (Senior Research Scientist)
Masako IZUMI (Senior Research Scientist)
Teruyo TSUKADA (Senior Research Scientist)
Kazuhide TSUNEIZUMI (Senior Research Scientist)
Ryouhei MORITA (Technical Scientist)

Research & Development Scientist

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Technical Staff I

Yoriko HAYASHI
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Technical Staff II

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Special Temporary Technical Scientists

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Akiko HOKURA (Tokyo Denki Univ.)
Yutaka MIYAZAWA (Yamagata Univ.)
Kazumitsu MIYOSHI (Chiba Univ.)
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Koji MURAI (Fukui Prefectural Univ.)
Kyosuke NIWA (Tokyo Univ. of Marine Sci. and Tech.)
Norihiro OHTSUBO (Kyoto Prefectural Univ.)
Tadashi SATO (Tohoku Univ.)
Yoichi SATO (Riken Food Co., Ltd.)
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Yuta HARUNARI (Tokyo Denki Univ.)

Part-time Worker

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List of Publications & Presentations

Publications

[Original papers]

T. Kashiwabara, K. Tanoi, N. Kitajima, A. Hokura, T. Abe, T. Nakanishi, and I. Nakai, "Comparative *in vivo* imaging of arsenic and phosphorus in *Pteris vittata* gametophyte by synchrotron μ-XRF and radioactive tracer techniques," Chem. Lett. **48**, 319–321 (2019).

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Y. Sawada, M. Sato, M. Okamoto, J. Masuda, S. Yamaki, M. Tamari, Y. Tanokashira, S. Kishimoto, A. Ohmiya, T. Abe, and M. Y. Hirai, "Metabolome-based discrimination of chrysanthemum cultivars for the efficient generation of flower color variations in mutation breeding," Metabolomics **15**, 118–129 (2019).

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[International conferences/workshops]

H. Ichida (invited), R. Morita, Y. Shirakawa, Y. Hayashi, and T. Abe, "A less-biased approach to characterize carbon-ion beam-induced mutations by whole exome sequencing of unselected M2 populations in rice," Rice Functional Genomics Workshop in XXVII Plant & Animal Genome Conference, San Diego, USA, January 12–16, 2019.

K. Niwa (poster), T. Abe, and A. Kobiyama, "Possibility of polyploidy breeding using cryptic species in the marine crop *Pyropia yezoensis* (Bangiales, Rhodophyta)," 23rd International Seaweed Symposium, Jeju, Korea, April 28–May 3, 2019.

T. Abe (invited), H. Ichida, Y. Hayashi, Y. Shirakawa, K. Ishii, and R. Morita, "Ion-beam radiation mutagenesis and plant mutation breeding," 14th Conference of Society for the Advancement of the Breeding Research in Asia and Oceania, Gwangju, Korea, July 2–5, 2019.

H. Murata (oral), S. Nakano, T. Yamanaka, T. Shimokawa, T. Abe, H. Ichida, Y. Hayashi, K. Tahara, and A. Ohta, "Radiation mutagenesis of the ectomycorrhizal fungus *Tricholoma matsutake*," The 10th International Workshop on Edible Mycorrhizal Mushrooms, Nagano, Japan, October 23, 2019.

T. Hioki (oral), H. Kunitake, T. Abe, and T. Hirano, "Analysis of petal size regulatory mechanisms in flower mutant of *Arabidopsis thaliana*," The 14th JKTC Seminar, Qingdao, China, October 18–21, 2019.

[Domestic conferences/workshops]

阿部知子 (招待講演), 林依子, 市田裕之, 「Ion Beam Mutagenesis とイオンビーム品種改良プラットフォーム」, 第 1 回 重・クラスターイオンビーム利用による微生物由来高生産性エネルギー 環境シンポジウム, 筑波大学, つくば, 2019 年 1 月 29 日.

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市田裕之 (口頭発表), 阿部知子, 「効率的な反復配列除去技術の開発とコムギ全ゲノム解析への応用」, 日本育種学会 第 135 回講演会, 千葉大学, 千葉, 019 年 3 月 16–17 日.

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阿部知子 (招待講演), 「イオンビーム育種技術で夢の植物を創る」, 第 6 回ミニシンポ「機能性バイオ」(TIA かけはし研究「機能性バイオ」グループ), 東京大学, 柏, 2019 年 3 月 18 日.

村田宗謙 (口頭発表), 渡川友里恵, 林依子, 阿部知子, 國武久登, 平野智也, 「重イオンビーム照射雄性配偶子が重複受精と胚発生に及ぼす影響」, 園芸学会平成 31 年度春季大会, 明治大学, 川崎, 2019 年 3 月 23–24 日.

常泉和秀 (口頭発表), 山田美恵子, 一瀬勝紀, 市田裕之, 金禧珍, 萩原篤志, 川田実季, 片山貴士, 﨑山一孝, 手塚信弘, 小磯雅彦, 阿部知子, 「重イオンビーム照射によるシオミズツボワムシ大型変異系統の育種」, 日本農芸化学会 2019 年度大会, 東京農業大学, 世田谷, 2019 年 3 月 26–27 日.

村田仁 (口頭発表), 仲野翔太, 山中高史, 下川知子, 阿部知子, 市田裕之, 林依子, 田原恒, 太田明, 「二員培養系で共生パートナーのアカマツ実生苗を枯らすマツタケ変異体の作出」, 日本農芸化学会 2019 年度大会, 東京農業大学, 世田谷, 2019 年 3 月 26–27 日.

阿部知子 (口頭発表), 石井公太郎, 風間裕介, 平野智也, 「重イオンビーム照射により誘発したシロイヌナズナ変異の特徴」, 基礎物理学研究所研究会「放射線の生体影響解明への分野横断による挑戦」, 京都大学, 京都, 2019 年 5 月 23–25 日.

石井公太郎 (口頭発表), 市田裕之, 阿部知子, 「イネの品種特異的高精度リファレンス配列作製手法の開発」, 日本育種学会第 136 回講演会, 近畿大学, 奈良, 2019 年 9 月 6–7 日.

久村麻子 (口頭発表), 諸岡淳司, 阿部知子, 林依子, 平野智也, 「重イオンビーム照射による夏秋小ギク品種「長崎 SWC1」の育成」, 日本育種学会第 136 回講演会, 近畿大学, 奈良, 2019 年 9 月 6–7 日.

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阿部知子（招待講演), 「イオン育種の現状とそれぞれの施設の特徴」, 福井イオンビーム育種研究会, 若狭湾エネルギー研究センター, 敦賀, 2019 年 12 月 13 日.

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市田裕之, 阿部知子, 「効率的な反復配列除去技術の開発とコムギ全ゲノム解析への応用」, 日本育種学会 2019 年春季大会（135 回）千葉大学 記者発表, 2019 年 3 月 7 日.

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久村麻子, 諸岡淳司, 阿部知子, 林依子, 平野智也, 「重イオンビーム商社による夏秋小ギク品種「長崎 SWC1」の育成」, 日本育種学会 2019 年秋季大会（136 回), 近畿大学 記者発表, 2019 年 9 月 3 日.

Patents

阿部知子, 森田竜平, 林依子, 市田裕之, 安部弘, 佐藤雅志, 「種子のサイズが増大した植物の製造方法」, 特許出願番号 2019-000749, 出願日 2019 年 1 月 7 日.

阿部知子, 常泉和秀, 市田裕之, 萩原篤志, キム・ヒジン, 阪倉良孝, 菅向志郎, 小磯雅彦, 手塚信弘, 川田実季, 小林敬典, 「ワムシの変異系統の作出方法, ワムシの変異系統, および重イオンビームの判定方法」特許出願番号 2019-015899, 出願日 2019 年 1 月 31 日.

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落合成光, 阿部知子, 林依子, 「ハイビスカス品種' マザーオレンジ'」, 品種登録出願番号 33885, 出願日 2019 年 4 月 22 日.

Outreach activities

阿部知子, 市田裕之, 山田美恵子, 「重イオンビームに陸上養殖, 「ワカメの革新」進む」日本の縁深き海藻, その歴史と現在（後編), https://jbpress.ismedia.jp/articles/-/55473, 漆原次郎（記者), 現代ビジネス, 食の研究所, 2019 年 2 月 15 日. https://www.foods-ch.com/shokuhin/1556092438588/, フーズチャネル, 2019 年 4 月 25 日（転載）

We established the “Asagao (Morning glory) Club” to deepen the understanding of our technology of mutation breeding. The club distributes the morning glory seeds irradiated with C-ion on request, and collects and compiles the observation reports of their growth. Some reports have been featured in the booklet issued by the club every two years.

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

1. Abstract

Established in May 2018, the plant genome evolution research team studies the effect of heavy-ion induced mutations 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. We develop amd optimize molecular and bioinfoematics techniquws based on the resent progress on genome sequencing technology, to efficiently identify and analyse genomic mutations from model and non-model plant species. we also utilise this heavy-ion's unique capability for plant breeding and evolution studies.

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 former has both stamens and gynoecium, while the latter have no reproductive organs. By whole-genome analysis and RNA seq analysis, we have idetified a gene that is deleted in all 14 of the 14 hermaphroditic mutants. This gene could be a candidate of sex determinant gene with gynoecium suppressing function.

Members

Team Leader

Tomoko ABE

Contract Researcher

Kotaro ISHII

Visiting Scientists

Ali FERJANI (Tokyo Gakugei Univ.)
Yusuke KAZAMA (Fukui Prefectural Univ.)

Student Trainees

Andi M. OKASA (Tohoku Univ.)

Part-time Worker

Yukako ABE (Part-time Worker)

List of Publications & Presentations

Publications

[Original papers]

N. Fujita, Y. Kazama, N. Yamagishi, K. Watanabe, S. Ando, H. Tsuji, S. Kawano, N. Yoshikawa, and K. Komatsu, "Development of the VIGS system in the dioecious plant *Silene latifolia*," Int. J. Mol. Sci. **20**, 1031 (2019).

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K. Ishii, Y. Kazama, T. Hirano, T. Takeshita, S. Kawano, and T. Abe (poster), "Development of a pipeline for whole-genome mutational analysis and its application on heavy-ion mutagenesis," Rice Functional Genomics Workshop in XXVII Plant & Animal Genome Conference, San Diego, USA, January 12–16, 2019.

T. Abe (invited), H. Ichida, Y. Hayashi, Y. Shirakawa, K. Ishii, and R. Morita, "Ion-beam radiation mutagenesis and plant mutation breeding," 14th Conference of Society for the Advancement of the Breeding Research in Asia and Oceania, Gwangju, Korea, July 2–5, 2019.

[Domestic conferences/workshops]

風間裕介 (招待講演), "Study of plant sex chromosome by using heavy-ion induced mutants," 第 1 回 重・クラスターイオンビーム利用による微生物由来高生産性エネルギー, 環境シンポジウム, 筑波大学, つくば, 2019 年 1 月 29 日.

上田純平, 風間裕介, 阿部知子, 村井耕二 (口頭発表), 「一粒系コムギ DV92 系統における花成遅延変異体 late-heading 2～5 (l h2～5) の同定」, 日本育種学会 第 135 回講演会, 千葉大学, 千葉市, 2019 年 3 月 16–17 日.

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風間祐介（招待講演), 「福井県立大学におけるイオン育種の展望—園芸植物の染色体再編研究」, 福井イオンビーム育種研究会, 若狭湾エネルギー研究センター, 敦賀, 2019 年 12 月 13 日.

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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Hiromitsu HABA

Team Leaders

Hiromitsu HABA
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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 unique radioisotopes (RIs) at RIKEN RI Beam Factory (RIBF) and applies them in the research fields of physics, chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences. 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, and IRMS. 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 30-MeV proton, 24-MeV deuteron, and 50-MeV alpha beams from the AVF cyclotron, we presently produce about 100 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, ^{197}Au, and ^{232}Th irradiated with a 135-MeV nucl.$^{-1}$ ^{14}N beam from the RIKEN Ring Cyclotron. These multitracers are also supplied to universities and institutes as collaborative researches.

In 2019, we developed production technologies of radioisotopes such as ^{24}Na, ^{42,43}K, ^{44m}Sc, ^{48}Cr, ^{111}Ag, ^{186}Re, ^{211}At, ^{224}Ra, ^{212}Pb, and ^{225}Ac which were strongly demanded but lack supply sources in Japan. We also investigated the excitation functions for the ^{nat}V(p,x), ^{nat}Cr(p,x), ^{nat}La(p,x), ^{169}Tm(p,x), ^{nat}Ta(p,x), ^{45}Sc(d,x), ^{nat}Tl(d,x), ^{nat}Ca(α,x), ^{nat}Ni(α,x), ^{nat}Sb(α,x),^{nat}Nd(α,x), ^{nat}Gd(α,x), and ^{nat}Dy(α,x) reactions to quantitatively produce useful RIs. We used radiotracers of ^{42,43}K, ^{44m}Sc, ^{111}Ag, ^{186}Re, ^{211}At, ^{224}Ra, ^{212}Pb, and ^{225}Ac for application studies in chemistry, ^{24}Na, ^{42,43}K, ^{44m}Sc, ^{67}Cu, ^{186}Re, ^{211}At, and ^{225}Ac in nuclear medicine. We also produced ^{65}Zn, ^{67}Cu, and ^{88}Y for our scientific researches on a regular schedule and supplied the surpluses through Japan Radioisotope Association to the general public. In 2019, we accepted 2 orders of ^{65}Zn with a total activity of 6.7 MBq, 1 order of ^{67}Cu with 5 MBq, and 2 orders of ^{88}Y with 2 MBq. We also distributed ^{44m}Sc (2 MBq × 3), ^{88}Zr (1 MBq × 1 and 2 MBq × 1), ^{95}Nb (1 MBq × 2 and 2 MBq × 1), ^{124}Sb (2 MBq × 1), ^{141}Ce (9 kBq × 1 and 13 kBq × 1), ^{175}Hf (1 MBq × 1 and 2 MBq × 1), and ^{211}At (5 MBq × 4, 50 MBq × 6, 100 MBq × 11, and 120 MBq × 1) 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 2019, 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) which was developed by the research group of Osaka University. The distribution coefficients of ^{262}Db on the anion-exchange resin in the mixed HF/HNO_3

system were also measured with the Automated Rapid Chemistry Apparatus (ARCA) of Japan Atomic Energy Agency. We 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. In 2019, we developed a cryogenic RF-carpet gas cell, which will be placed on the focal plane of GARIS and connected to a gas chromatographic apparatus, for the future gas-phase chemistry of the short-lived SHEs (<3 s).

(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 2019, 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. We established a sampling technique for pigment without any damages on the artifacts or wall paintings, using a S-free adhesive tape. Then, we applied the technique to the analyses of the pigment from Roman ruins in Badalona, Spain. We also applied the technique to the analyses of the red-color substances on the artifacts such as Kyoden remains (Izumo-city, Shimane prefecture), Renpeijou-ato (Zentuji-city, Kagawa prefecture) and so on. We also investigated the transmutation of the long-lived ^{107}Pd to the stable Pd isotopes by the deuteron-induced nuclear reaction.

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

In 2019, 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

[Original papers]

M. Aikawa, M. Saito, Y. Komori, H. Haba, S. Takács, F. Ditrói, and Z. Szűcs, "Activation cross sections of alpha-particle induced nuclear reactions on natural palladium," Nucl. Instrum. Methods Phys. Res. B, **449**, 99–104 (2019).

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S. Takács, M. Aikawa, M. Saito, T. Murata, N. Ukon, Y. Komori, and H. Haba, "Activation cross sections of alpha particle-induced reactions on natural hafnium up to 50 MeV", Nucl. Instrum. Methods Phys. Res. B **459**, 50–58 (2019).

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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 a 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 July 2019, the ninth IN-PAC met and approved two fee-based proposals from new users. In January 2019, IN-PAC held a mail review and approved one fee-based proposal from a continuously using private company. In January and February 2019, four fee-based beam times were performed with Kr-84 (70 MeV/nucleon) and Ar-40 (95 MeV/nucleon) beams at the E5A beamline. The client used the beam to simulate single-event effects of space-use semi-conductors 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 beam quality. 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. We tested radiochromic films as a new method of two-dimensional dose distribution measurement. We have irradiated two types of radiochromic films using C, Ar, and Fe ions and measured the change of optical density as a function of the dose. We conclude that radiochromic films can be useful to measure the dose distribution of heavy-ion irradiations with a spatial resolution of about 1 mm.

(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), Sr-85 (65 days) and Cu-67 (2.58 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 2019, we delivered no Cd-109, two shipments of Zn-65 with a total activity of 6.7 MBq, two of Y-88 with a total activity of 2 MBq, and one of Cu-67 with an activity of 5 MBq. The final recipients of the RIs were two universities, one research institute and one medical research center.

(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 2019, 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

Presentations

[Domestic conferences/workshops]

吉田敦 (口頭発表), 「加速器施設で発生するイオンビームの非生物系産業利用」, 福井イオンビーム育種研究会, 福井県若狭湾エネルギー研究センター, 敦賀, 2019 年 12 月 13 日.

吉田敦 (口頭発表), 「宇宙時代到来～半導体でも重イオン照射～」, 理研シンポジウム「重イオンビーム育種技術の実用化 20 年」, 和光, 2020 年 1 月 23 日.

Subnuclear System Research Division
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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) Theory of the Anomalous Magnetic Moment of the Electron

The anomalous magnetic moment of the electron ae measured in a Penning trap occupies a unique position among high precision measurements of physical constants in the sense that it can be compared directly with the theoretical calculation based on the renormalized quantum electrodynamics (QED) to high orders of perturbation expansion in the fine structure constant α, with an effective parameter α/π. Both numerical and analytic evaluations of ae up to $(\alpha/\pi)^4$ were firmly established. The coefficient of $(\alpha/\pi)^5$ has been obtained recently by an extensive numerical integration. The contributions of hadronic and weak interactions have also been estimated. The sum of all these terms leads to a_e(theory) = 1 159 652 181.606 (11)(12)(229) $\times 10^{-12}$, where the first two uncertainties are from the tenth-order QED term and the hadronic term, respectively. The third and largest uncertainty comes from the current best value of the fine-structure constant derived from the cesium recoil measurement: α^{-1} (Cs) = 137.035 999 046 (27). The discrepancy between a_e(theory) and a_e((experiment)) is 2.4σ. Assuming that the standard model is valid so that a_e(theory) = a_e(experiment) holds, we obtained α^{-1} (a_e) = 137.035 999 1496 (13)(14)(330), which is nearly as accurate as α^{-1} (Cs). The uncertainties are from the tenth-order QED term, hadronic term, and the best measurement of a_e, in this order.

(1-2) Optimized perturbation theory and its relation to anti-Stokes lines

We discussed fundamental properties of the fastest apparent convergence (FAC) condition which is used as a variational criterion in optimized perturbation theory (OPT). We examine an integral representation of the FAC condition and a distribution of the zeros of the integral in a complex artificial parameter space on the basis of theory of Lefschetz thimbles. We find that the zeros accumulate on a certain line segment known as an anti-Stokes line in the limit $K \to \infty$, where K is a truncation order of a perturbation series. This phenomenon gives an underlying mechanism that physical quantities calculated by OPT can be insensitive to the choice of the artificial parameter.

(1-3) Perturbative static quark potential in Maximal Abelian gauge

One of the most interesting features of QCD is its peculiar behavior at low energies, where it displays confinement. Among the many explanations proposed for this phenomenon, one of the more interesting approaches utilizes its similarity to the behavior of a magnetic field in a type II superconductor. The magnetic field cannot penetrate the superconductor except for narrow flux tubes, much like the chromoelectric field extends only between confined particles, and if there existed elementary magnetic charges, they would be confined inside a superconductor much like quarks in the vacuum. We calculated the static quark potential for an SU(N) gauge theory in the Maximal Abelian gauge as well as its Abelian projection up to two loops in perturbation theory, and we discussed its renormalization properties.

(1-4) Lorentzian conformal field theories through sine-square deformation

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. We reexamined two-dimensional Lorentzian conformal field theory using the formalism previously developed in a study of sine-square deformation of Euclidean conformal field theory. We construct three types of Virasoro algebra. One of them reproduces the result by Lüscher and Mack, while another type exhibits the divergence in the central charge term. The other leads the continuous spectrum and contains no closed time-like curve in the system.

(2) Theory of spontaneous symmetry breaking

(2-1) Effective Lagrangian for Nambu-Goldstone modes in nonequilibrium open systems

We developed the effective field theory of diffusive Nambu-Goldstone (NG) modes associated with spontaneous internal symmetry breaking taking place in nonequilibrium open systems. The effective Lagrangian describing semi-classical dynamics of the NG modes is derived and matching conditions for low-energy coefficients are also investigated. Due to new terms peculiar to open systems, the associated NG modes show diffusive gapless behaviors in contrast to the propagating NG mode in closed systems. We demonstrate two typical situations relevant to the condensed matter physics and high-energy physics, where diffusive type-A or type-B NG modes appear.

(2-2) Spontaneous symmetry breaking and Nambu-Goldstone modes in open classical and quantum 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. We discussed spontaneous symmetry breaking of open classical and quantum systems. When a continuous symmetry is spontaneously broken in an open system, a gapless excitation mode appears corresponding to the Nambu-Goldstone mode. Unlike isolated systems, the gapless mode is not always a propagation mode, but it is a diffusion one. Using the Ward-Takahashi identity and the effective action formalism, we establish the Nambu-Goldstone theorem in open systems, and derive the low-energy coefficients that determine the dispersion relation of Nambu-Goldstone modes. Using these coefficients, we classify the Nambu-Goldstone modes into four types: type-A propagation, type-A diffusion, type-B propagation, and type-B diffusion modes.

(3) Lattice gauge theory

(3-1) NΩ dibaryon from lattice QCD near the physical point

The nucleon(N)-Omega(Ω) system in the S-wave and spin-2 channel was studied from the (2+1)-flavor lattice QCD with nearly physical quark masses. The time-dependent HAL QCD method is employed to convert the lattice QCD data of the two-baryon correlation function to the baryon-baryon potential and eventually to the scattering observables. The potential, obtained under the assumption that its couplings to the D-wave octet-baryon pairs are small, is found to be attractive in all distances and to produce a quasi-bound state near unitarity. Including the extra Coulomb attraction, the binding energy of becomes 2.5 MeV. Such a spin-2 state could be searched through two-particle correlations in p-p, p-nucleus and nucleus-nucleus collisions.

(3-2) ΛΛ and NΞ interactions from lattice QCD near the physical point

The S-wave ΛΛ and NΞ interactions were studied on the basis of the (2+1)-flavor lattice QCD simulations close to the physical point. Lattice QCD potentials in four different spin-isospin channels are extracted by using the coupled-channel HAL QCD method and are parametrized by analytic functions to calculate the scattering phase shifts. The ΛΛ interaction at low energies shows only a weak attraction, which does not provide a bound or resonant dihyperon. The NΞ interaction in the spin-singlet and isospin-singlet channel is most attractive and lead the NΞ system near unitarity. Relevance to the strangeness = −2 hypernuclei as well as to two-baryon correlations in proton-proton, proton-nucleus and nucleus-nucleus collisions was also discussed.

(3-3) Stress tensor around static quark-anti-quark from Yang-Mills gradient flow

The spatial distribution of the stress tensor around the quark-anti-quark pair in SU(3) lattice gauge theory was studied. The Yang-Mills gradient flow plays a crucial role to make the stress tensor well-defined and derivable from the numerical simulations on the lattice. The resultant stress tensor with a decomposition into local principal axes shows, for the first time, the detailed structure of the flux tube along the longitudinal and transverse directions in a gauge invariant manner. The linear confining behavior of the potential at long distances is derived directly from the integral of the local stress tensor.

(4) QCD under extreme conditions

(4-1) Finite density QCD based on complex Langevin method

The complex Langevin method (CLM) is one of a promising approach to overcome the sign problem. The central idea of this approach is that the stochastic quantization does not require the probabilistic interpretation of the Boltzmann weight e^{-S} even when the action takes complex values. Although the equivalence between CLM and the familiar path integral quantization is quite nontrivial, it is pointed out that the probability distribution of the drift term can judge the correctness of the CLM. This enable us to perform lattice simulation of QCD based on CLM in the finite density region in a self-contained manner. We discussed the applicability of the CLM with four-flavor staggered fermions on a $8^3 \times 16$ lattice with quark mass $m = 0.01$. In particular, we focus on the behavior of the eigenvalue distribution of the fermion mass matrix which is closely related to the appearance of the singular drift problem.

(4-2) Non-equilibrium quantum transport of chiral fluids from kinetic theory

We introduced the quantum-field-theory (QFT) derivation of chiral kinetic theory (CKT) from the Wigner-function approach, which manifests side jumps and non-scalar distribution functions associated with Lorentz covariance and incorporates both background fields and collisions. The formalism is utilized to investigate second-order responses of chiral fluids near local equilibrium. Such non-equilibrium anomalous transport is dissipative and affected by interactions. Contributions from both quantum corrections in anomalous hydrodynamic equations (EOM) of motion and those from the CKT and Wigner functions (WF) are considered in a relaxation-time approximation (RTA). Anomalous charged Hall currents engendered by background electric fields and temperature/chemical-potential gradients are obtained. Furthermore, chiral magnetic/vortical effects (CME/CVE) receive viscous corrections as non-equilibrium modifications stemming from the interplay between side jumps, magnetic-moment coupling, and chiral anomaly.

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

We presented a much improved equation of state for neutron star matter, QHC19, with a smooth crossover from the hadronic regime at lower densities to the quark regime at higher densities. We now use the Togashi *et al*. equation of state, a generalization of the Akmal-Pandharipande-Ravenhall equation of state of uniform nuclear matter, in the entire hadronic regime; the Togashi equation of state consistently describes nonuniform as well as uniform matter, and matter at beta equilibrium without the need for an interpolation between pure neutron and symmetric nuclear matter. We describe the quark matter regime at higher densities with the Nambu-Jona-

Lasinio model, now identifying tight constraints on the phenomenological universal vector repulsion between quarks and the pairing interaction between quarks arising from the requirements of thermodynamic stability and causal propagation of sound. The resultant neutron star properties agree very well with the inferences of the LIGO/Virgo collaboration, from GW170817, of the pressure versus baryon density, neutron star radii, and tidal deformabilities. The maximum neutron star mass allowed by QHC19 is 2.35 MS, consistent with all neutron star mass determinations.

(5) Nuclear and atomic many-body problems

(5-1) Renormalized random-phase approximation

A fully self-consistent renormalized random-phase approximation was constructed based on the self-consistent Hartree-Fock mean field plus exact pairing solutions (EP). This approach exactly conserves the particle number and restores the energy-weighted sum rule, which is violated in the conventional renormalized particle-hole random-phase approximation for a given multipolarity. The numerical calculations are carried out for several light-, medium-, and heavy-mass nuclei such as O22, Ni60, and Zr90 by using the effective MSk3 interaction. To study the pygmy dipole resonance (PDR), the calculations are also performed for the two light and neutron-rich O24,28 isotopes, whose PDRs are known to be dominant. The results obtained show that the inclusion of ground-state correlations beyond the random-phase approximation (RPA) by means of the occupation numbers obtained from the EP affects the RPA solutions within the whole mass range, although this effect decreases with increasing the mass number. At the same time, the antipairing effect is observed via a significant reduction of pairing in neutron-rich nuclei. The enhancement of PDR is found in most neutron-rich nuclei under consideration within our method.

(5-2) Ab initio covariant density functional theory for nuclear structure

Nuclear structure models built from phenomenological mean fields, the effective nucleon-nucleon interactions (or Lagrangians), and the realistic bare nucleon-nucleon interactions were presented. The success of covariant density functional theory (CDFT) to describe nuclear properties and its influence on Brueckner theory within the relativistic framework are focused upon. The challenges and ambiguities of predictions for unstable nuclei without data or for high-density nuclear matter, arising from relativistic density functionals, are discussed. The basic ideas in building an ab initio relativistic density functional for nuclear structure from ab initio calculations with realistic nucleon-nucleon interactions for both nuclear matter and finite nuclei are presented. The current status of fully self-consistent relativistic Brueckner-Hartree-Fock (RBHF) calculations for finite nuclei or neutron drops (ideal systems composed of a finite number of neutrons and confined within an external field) is reviewed. The guidance and perspectives towards an ab initio covariant density functional theory for nuclear structure derived from the RBHF results are provided.

(5-3) QCD-like phase diagram with Efimov trimers and Cooper pairs

We investigated color superfluidity and trimer formation in resonantly interacting SU(3) Fermi gases with a finite interaction range. The finite range is crucial to avoid the Thomas collapse and treat the Efimov effect occurring in this system. Using the Skorniakov-Ter-Martirosian equation with medium effects, we show the effects of the atomic Fermi distribution on the Efimov trimer energy at finite temperature. We show the critical temperature of color superfluidity within the many-body T-matrix approximation. In this way, we can provide a first insight into the phase diagram as a function of the temperature T and the chemical potential μ. This phase diagram consists of trimer, normal, and color-superfluid phases, and is similar to that of quantum chromodynamics at finite density and temperature.

(5-4) Superfluid phase transitions in asymmetric nuclear matter

We investigated superfluid phase transitions of asymmetric nuclear matter at finite temperature (T) and density (ρ) with a low proton fraction ($Y_p \leq 0.2$), which is relevant to the inner crust and outer core of neutron stars. A strong-coupling theory developed for two-component atomic Fermi gases is generalized to the four-component case, and is applied to the system of spin-1/2 neutrons and protons. The phase shifts of neutron-neutron (nn), proton-proton (pp) and neutron-proton (np) interactions up to $k = 2$ fm^{-1} are described by multi-rank separable potentials. We show that the critical temperature T^C_{nn} of the neutron superfluidity at $Y_p = 0$ agrees well with Monte Carlo data at low densities and takes a maximum value $T^C_{nn} = 1.68$ MeV at $\rho/\rho_0 = 0.14$ with $\rho_0 = 0.17$ fm^{-3}. Also, the critical temperature T^C_{nn} of the proton superconductivity for $Y_p \leq 0.2$ is substantially suppressed at low densities due to np-pairing fluctuations, and starts to dominate over T^C_{nn} only above $\rho/\rho_0 = 0.70(0.77)$ for $Y_p = 0.1(0.2)$, and (iii) the deuteron condensation temperature T^C_d is suppressed at $Y_p \leq 0.2$ due to a large mismatch of the two Fermi surfaces.

(5-5) One-dimensional Bose and Fermi gases with contact interactions

One-dimensional spinless Bose and Fermi gases with contact interactions have the close relationship via Girardeau's Bose-Fermi mapping, leading to the correspondences in their energy spectra and thermodynamics. However, correlation functions are in general not identical between these systems. We derive in both systems the universal relations for correlation functions, which hold for any energy eigenstate and any statistical ensemble of the eigenstates. These relations include the large-momentum tails of static structure factors and of momentum distributions as well as energy relations, which connect the sums of kinetic and interaction energies to the momentum distributions. The relations involve two- and three-body contacts, which measure local two- and three-body correlations, respectively. We clarified how the relations for bosons and fermions differ and are connected with each other. In particular, we found that the three-body contact makes no contribution to the bosonic energy relation, but it plays a crucial role in fermionic one.

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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) With use of ΞN interaction based on HAL Lattice QCD, we predict to have a bound state for NN Ξ four-body system which would be the lightest bound Ξ hypernucleus. We also propose how to produce this hypernucleus.
(2) Several compact ssscc-bar pentaquark resonances are predicted quark model, that is, $J^\pi = 1/2^-$ ‘E = 5180 MeV, Γ = 20 MeV), $5/2^-$ (5645 MeV, 30 MeV), $5/2^-$ (5670 MeV, 50 MeV), and $1/2^+$ (5360 MeV, 80 MeV). These are the candidates of compact pentaquark resonance states from the current best quark model, which should be confirmed either by experiments or lattice QCD calculations.
(3) Mixtures of two kinds of fermions, such as spin up and down electrons in materials, are well-known to lead to pairing and superconductivity. In this project, study mixtures of three different kinds of fermions were studied. In these systems, in addition to pairing, a new kind of clustering by three can appear due the Efimov effect. We obtained the phase diagram of these systems and showed that it is similar to that of QCD, where the hadron phase is the analogue of the phase of Efimov clusters of three fermions.

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List of Publications & Presentations

Publications

[Original papers]

J. Lee, Q. Wu, Y. Funaki, and E. Hiyama, “Three-Body structure of Λ^9Be with $\alpha\alpha\Lambda$ cluster model,” Few-Body Syst. **60**, 30 (2019).

R. Lazauskas, E. Hiyama, and J. Carbonell, “Ab initio calculation of ^{5}H resonant states,” Phys. Lett. B **791**, 335 (2019).

J. Lee, N. Yamanaka, and E. Hiyama, “Effect of the Pauli exclusion principle in the electric dipole moment of ^{9}Be with $|\Delta S| = 1$ interactions,” Phys. Rev. C **99**, 055503 (2019).

E. Hiyama, R. Lazauskas, F. M. Marques, and J. Carbonell, “Modeling ^{19}B as a ^{17}B-n-n three-body system in the unitary limit,” Phys. Rev. C **100**, 011603(R) (2019).

T. -W. Wu, M. -Z. Liu, L. -S. Geng, E. Hiyama, and M. P. Valderrama, “DK, DDK and DDDK molecules-understanding the nature of the D^*_{s0} (2317),” Phys. Rev. D **100**, 034209 (2019).

E. Hiyama, K. Sasaki, T. Miyamaoto, T. Doi, T. Hatsuda, Y. Yamamoto, and T. Rijken, “Possible lightes Ξ hypernuceus with Modern ΞN interaction,” Phys. Rev. Lett. **124**, 092501 (2020).

Y. Shimizu, Y. Yamaguchi, and M. Harada, “Heavy quark spin multiplet structure of Pc(4312), Pc(4440), and Pc(4457),” arXiv:1904.00587 [hep-ph] (2019).

Y. Yamaguchi, H. G.- Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, and M. Takizawa, “Pc pentaquarks with chiral tensor and quark dynamics,” Phys. Rev. D **101**, 091502 (2020).

Y. Yamaguchi and N. Yamanaka, “Large electric dipole moment of charged leptons in the standard model,” arXiv:2003.08195 [hep-ph] (2020).

Q. Meng, E. Hiyama, K. U. Can, P. Gubler, M. Oka, A. Hosaka, and H. Zong, “Compact ssscc pentaquark states predicted by a quark model,” Phys. Lett. B **798**, 135028 (2019).

P. Froelich, T. Yamashita, Y. Kino, S. Jonsell, E. Hiyama, and K. Piszczatowski, “Four-body treatment of the antihydrogen-positronium system: binding, structure, resonant states and collisions,” Hyperfine Interact. **240**, 46 (2019).

[Review articles]

Y. Yamaguchi, A. Hosaka, S. Takeuchi, and M. Takizawa, “Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners,” J. Phys. G **47**, 053001 (2020).

[Proceedings]

Y. Yamaguchi, “pi J/psi-DDbar* potential described by the quark exchange diagram,” EPJ Web Conf. **204**, 01007 (2019).

Y. Yamaguchi, “Short range interaction in pi J/psi-DDbar* channel,” Int. J. Mod. Phys. Conf. Ser. **49**, 1960005 (2019).

Y. Yamaguchi, “Short range pi J/psi -DDbar* potential described by the quark exchange diagram,” Springer Proc. Phys. **238**, 629 (2020).

Presentations

[International conferences/workshops]

E. Hiyama (invited), “Five-body structure of sssc_c,” The 1st CENuM Workshop for Hadron Physics, Incheon, Korea, June 17–18, 2019.

E. Hiyama (invited), “Structure of light Ξhypernuclei with modern ΞN interaction,” International workshop on “Nuclear structure at the crossroads” (INT 19-2a), Seattle, U.S.A., July 1–August 2, 2019.

E. Hiyama (invited), “Five-body structure of sssc_c,” International Workshop on Perspectives in Hadron Physics, Quy Nhon, Vietnam, September 22–28, 2019.

P. Naidon (Invited), "A bubble of polarons," 2nd workshop "Clusters in quantum systems: from atoms to nuclei and hadrons," Fukuoka, Japan, January 27–31, 2020.

Y. Yamaguchi (oral), "Role of the tensor force in the heavy hadronic molecules," The 18th International Conference on Hadron Spectroscopy and Structure (HADRON2019), Guilin, China, August 16–21, 2019.

Y. Yamaguchi (oral), "Tensor force in heavy hadronic molecules," Workshop on Chiral and heavy quark symmetries in quark-hadron physics, Osaka, Japan, August 25, 2019.

Y. Yamaguchi (oral), "Hadronic molecules of heavy hadrons with tensor force," The 24th European conference on few-body problems in physics (EFB24), Guirford, UK, September 2–6, 2019.

Y. Yamaguchi (oral), "Heavy hadronic molecules: pion exchange and coupling to multiquark states," Workshop on "Physics of heavy-quark and exotic hadrons," Tokai, Ibaraki, Japan, January 27–29, 2020.

Y. Yamaguchi (oral/poster), "Tensor force in the heavy hadronic molecules," REIMEI Workshop on Universal Features of Quantum Flows with Spin, Orbital and Tensor Correlations, Tokai, Ibaraki, Japan, February 17–19, 2020.

K. U. Can (oral), "Structure of the charmed baryons through an electromagnetic perspective," 15th Rencontres du Vietnam Perspectives in Hadron Physics, ICISE, Quy Nhon, Vietnam, September 22–28, 2019.

T. Yamashita, Y. Kino, E. Hiyama, S. Jonsell, and P. Froelich (poster), "Inelastic resonant scattering of positronium by (anti)hydrogen atom," XX International Workshop on Low-Energy Positron and Positronium Physics & XXI International Symposium on Electron-Molecule Collisions and Swarms, Belgrade, Serbia, July 18–20, 2019.

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Y. Yamaguchi, "Heavy hadronic molecules: pion exchange and coupling to compact states," Tokyo Institute of Technology, Tokyo, December 13, 2019.

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肥山詠美子, 科学技術分野の文部科学大臣表彰 科学技術賞（研究部門）「量子少数多体系の厳密計算理論の確立とその応用研究」, 2019 年 4 月 17 日.

Press releases

肥山詠美子室長, 土井琢身専任研究員, 数理創造プログラムの初田哲男プログラムディレクターらの国際共同研究グループ, 新たなハイパー原子核「グザイ・テトラバリオン」—グザイ粒子の振る舞いを精密計算で解き明かす—, 2020 年 3 月 5 日.

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) also directed by H. En'yo carries our core team at BNL for those exciting researches using the PHENIX detector and its upgraded sPHENIX detector in preparation. 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 showed 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 and preparing for the electron-ion collider (EIC). 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 publication of the complementary charged pion double spin asymmetries at the same collision energy. 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. These results will be included in future global fits of all the existing experimental data in the world and will improve the sensitivity of quark and gluon spin contributions to the total spin of the nucleon. Additionally, the first double spin asymmetry results for direct photons and jets are being prepared by PHENIX. Both are in principle cleaner probes since no fragmentation functions are involved. The direct photon probe also restricts the initial, hard interaction to be predominantly between a quark and a gluon thus further increasing the sensitivity to the gluon spin.

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. 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 now been published. When moving to more central rapidities, the left-right asymmetries are known to be very small for neutral pions. Since then they have been confirmed to be small also for eta mesons and, for the first time, also for direct photons. The direct photon asymmetries are again very important here as they are only sensitive to the transverse spin effects in the initial state and not the fragmentation. Both results are being prepared for publication.

In June of 2017, an electro-magnetic calorimeter was installed 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 results have been accepted for publication in PRL.

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 2020 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 KEK-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 2019, transverse momentum dependent cross sections of pions, kaons and protons were published 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.

As the Electron-Ion Collider is becoming a reality, many of us are participating in the various community efforts to define the physics goals of the EIC and how they inform on the choices of collisions energies, luminosities and detector components. While the accelerator efforts are naturally led by the two main Nuclear physics laboratories in the US, BNL and JLAB, a large EIC user group of more than 1000 members from all around the world is working on making the EIC a reality. Within this group, we are participating in various functions from the steering committee, the conference and talks committee to various physics or detector related topical groups.

(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 (Phys. 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 $p_{\mathrm{T}} > 4$ GeV/c, but the suppression factor is smaller than that of charm decay electrons for $3 < p_{\mathrm{T}} < 4$ 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 Physical Review D99, 092003 (2019). The centrality dependence of the suppression b→e and c→e from the 2014 Au+Au data is in preparation.

PHENIX published measurements of flow strength in p + Au, d + Au, and ^{3}He+Au (Nature Physics **15**, 214 (2019)). The results provide strong evidence for formation of small droplet of quark gluon plasma in collisions of small systems at RHIC.

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, 1TB 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 BigWaterfall/SailingShip supercomputer systems operated by the Head Office for Information Systems and Cybersecurity. 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 assembled and installed in the spectrometer magnet at J-PARC. Read-out electronics and trigger logic modules are also installed and tested. We have been a member of the CERN-RD51 collaboration to acquire the read-out technology for GEM. The MoU for RD51 was 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 was completed finally in early 2020 to perform this experiment. We performed the 1st half of commissioning run (Run0a) in June 2020 successfully, and the 2nd half is planned in January 2021.

(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 "EIC". 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 was approved for the Project Decision-2/3 (corresponds to DOE's Critical Decision-2/3) in May 2019. We RIKEN group have been developing the one of the tracking devices of sPHENIX detector, so called intermediate tracker (INTT) since 2015. The INTT provides the best timing resolution among the sPHENIX tracking system, in conjunction with a time projection chamber and a MAPS based vertex detectors. The R&D of INTT detector is almost in the last stage. The prototype detectors demonstrated satisfactory performance in the efficiency and position resolutions as designed in the last two beam tests at the Fermilab Test Beam Facility (FTBF) using 120 GeV proton beam in March 2018 and June 2019. The preparation for the production ladder assembly is ongoing both in Taiwan Silicon Detector Facility (TSiDF) and BNL.

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 EIC. We are preparing test bench to perform R&D for the forward hadron calorimeter.

As the further investigation of the neutral pion production asymmetry discovered in the RHICf experiment, we started preparation for the next phase of the experiment, namely RHICf-II. The target year of physics data taking is 2024 as a part of sPHENIX experiment. The highlight of the upgraded experiment is the larger acceptance of the high position resolution part of the zero-degree calorimeter (ZDC). We found the detector technology developed for the FoCAL upgrade project of the ALICE experiment at LHC well satisfies the RHICf-II performance requirement. We thus resumed the associated membership of the ALICE collaboration and the RHICf-II detectors are to be developed together with the FoCAL collaboration. This new detector technology development is also a part of the R&D program for the essential ZDC detector for EIC.

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List of Publications & Presentations

Publications

[Original papers]

C. Aidala *et al.* (PHENIX Collaboration), "Measurements of $\mu\ \mu$ pairs from open heavy flavor and Drell-Yan in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. D **99**, 072003 (2019).

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Y. Goto, "Asymmetry measurement of very forward neutral particle production in the RHICf experiment," Acta Phys. Polon. B Proc. Suppl. **12**, 837 (2019).

S. Ashikaga *et al.*, (J-PARC E16 Collaboration), "Measurement of vector meson mass in nuclear matter at J-PARC," JPS Conf. Proc. **26**, 024005 (2019).

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

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

Y. Goto (oral), "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 (invite), "Electron-ion collider project," Workshop on Progress on Hadron Structure Functions in 2018, Tsukuba, Japan, November 19, 2018.

Y. Goto (invited), "Forward spin physics at PHENIX and sPHENIX," International Workshop on Forward Physics and Forward Calorimeter Upgrade in ALICE, Tsukuba, Japan, March 7, 2019.

Y. Goto (invited), "RHICf results," Cold QCD Workshop, RHIC & AGS Annual Users' Meeting, Upton, New York, USA, June 4, 2019.

Y. Goto (invited), “Plan for EIC (Electron-Ion Collider),” 14th ANPhA Board meeting and Symposium in Korea, Jeju Island, Korea, June 28, 2019.

Y. Goto (invited), “Overview of future facilities for nucleon spin studies,” 11th Circum-Pan-Pacific Symposium on High Energy Spin Physics (Pacific Spin 2019), Miyazaki, Japan, August 30, 2019.

Y. Goto (invited), “Physics and detector requirements at zero degree of EIC,” Workshop on Forward Physics and QCD at the LHC, the future Electron Ion Collider and Cosmic Ray Physics, Guanajuato, Mexico, November 19, 2019.

S. Yokkaichi (invited), “Measurement of the spectral change of vector mesons in nuclei at the high-momentum beam line in J-PARC HEF,” J-PARC Symposium 2019, Tsukuba, Japan, September 23–26, 2019.

S. Ashikaga, “Measurement of vector meson mass in nuclear matter at J-PARC,” The 8th International Conference on Quarks and Nuclear Physics (QNP2018), Tsukuba, Japan, November 13–17, 2018.

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Subnuclear System Research Division
Meson Science Laboratory

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 $\Lambda(1405)$ that could be $K-p$ bound state. By these experiments, we are studying the $\bar{K}N$ interaction, and clarify the nature of kaon in nuclei. At Spring-8 and at GSI, we are planning to study omega and η' 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 $\bar{K}N$, the $\bar{K}$ 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 completed to observe the "K^-pp" bound state by the in-flight ^{3}He(K^-, n) reaction, which allows us the formation 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 40 MeV. The momentum transfer q naturally prefers lower momentum for the bound state formation, but the observed event concentration extended having the form-factor parameter ~400 MeV/c. Based on the PWIA calculation, the data indicated that the "K^-pp" system could be as small as ~0.6 fm. It is astonishingly compact in contrast to the mean nucleon distance ~1.8 fm.

This observed signal shows that ***a meson ($\bar{q}q$) 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 $\bar{K}N$ interaction at zero energy from the atomic state level shift and width of kaon, we have performed an X-ray spectroscopy of atomic $3d \rightarrow 2p$ 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 $2p$-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 $2p \rightarrow 1$ s 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.

(1-4) $^3{}_\Lambda$H lifetime puzzle and our approach

Three recent heavy ion experiments (HypHI, STAR, and ALICE) announced surprisingly short lifetime for $^3{}_\Lambda$H hyper-nucleus's *Mesonic Weak Decay* (MWD), which seems to be inconsistent with the fact that the $^3{}_\Lambda$H is a very loosely bound system. It is very interesting to study this with a different experimental approach. We proposed a direct measurement of $^3{}_\Lambda$H MWD lifetime with ~20% resolution at J-PARC hadron facility by using K^- meson beam at 1 GeV/c. As for the feasibility test, we also measure $^4{}_\Lambda$H lifetime.

A Cylindrical Detector System (CDS) used in J-PARC E15/E31 experiment is employed to capture the delayed π^- as a weak decay product from $^{3,4}{}_\Lambda$H; a calorimeter is installed in the very forward region to tag fast π^0 meson emission at ~0 degree, which ensures that the Λ hyperon production with small recoil momentum. By this selection, we can improve the ratio between $^{3,4}{}_\Lambda$H and quasi-free Λ and Σ background. A test beam for feasibility study with ^{4}He target has been conditionally approved by J-PARC PAC. We will conduct the experiment and to present the data in short.

(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) Deformed nodal superconducting gap state and asymmetric spin-fluctuation mediated Cooper pair in the quasi two-dimensional organic superconductor Λ-$[BETS]_2GaCl_4$
(2) Multi magnetic transitions in the Ru-based pyrochlore systems, $R_2Ru_2O_7$.
(3) Magnetic properties of the nano-cluster gold in the border of macro- and micro- scale.
(4) Novel magnetic and superconducting properties of nano-size La-based high-T_C superconducting curates.
(5) Determination of muon positions estimated from density functional theory (DFT) and dipole-field calculations.
(6) Chemical muonic states in DNA molecules.

(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.

Ultra-cold muon beam has been produced by laser ionization of muoniums in vacuum (bound system of μ^+ and electron). 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. However, in order to increase the intensity by one more order, we need a larger size crystal. So far we have inhomogeneity problem but we are trying 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. 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. In this fiscal year, we carried out measurement on muonic proton in low pressure hydrogen gas.

Members

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Part-time Worker

Mayumi YOSHIMURA (Administrative Part-time Worker II)

Assistants

Yoko FUJITA
Kumiko TAKAHASHI
Mitsue YAMAMOTO

List of Publications & Presentations

Publications

[Original papers]

M. Clemenza, *et al.*, "Muonic atom X-ray spectroscopy for non-destructive analysis of archaological samples," Journal of Radioanalytical and Nuclear Chemistry **322**, 1357–1363 (2019).

B. V. Hampshire, K. Butcher, K. Ishida, G. Green, D. Paul, and A. Hillier, "Using negative muons as a probe for depth profiling silver Roman coinage," Heritage **2**, 400–407 (2019).

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M. A. Baqiya, T. Adachi, A. Takahashi, T. Konno, T. Ohgi, I. Watanabe, and Y. Koike, "Muon-spin relaxation study of the spin correlations in the overdoped regime of electron-doped high-T_C cuprate superconductors," Phys. Rev. B 100, 064514/1-5 (2019).

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K. M. Suzuki, S. Asano, H. Okabe, A. Koda, R. Kadono, I. Watanabe, and M. Fujita, "Successive magnetic ordering sequence observed from muon spin rotation in T'-structured R_2CuO_4 (R = Nd, Eu)," Phys. Rev. B (in press).

H. Yamauchi, D. P. Sari, I. Watanabe, Y. Yasui, L. -J. Chang, K. Kondo, T. U. Ito, M. Ishikado, M. Hagihara, M. D. Frontzek, S. Chi, J. A. Fernandez-Baca, J. S. Lord, A. Berlie, A. Kotani, S. Mori, and S. Shamoto, "High-temperature short-range order in Mn_3RhSi," Commun. Mater. (in press).

K. Oinuma, N. Okano, H. Tsunakawa, S. Michimura, T. Kobayashi, H. Taniguchi, K. Satoh, J. Angel, I. Watanabe, Y. Ishii, H. Okamoto, and T. Itou, "Spin structure at zero magnetic field and field-induced spin reorientation transitions in a layered organic canted antiferromagnet bordered on a superconducting phase," Phys. Rev. B (in press).

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[Review articles]

H. Ohnishi, F. Sakuma, and T. Takahashi, "Hadron physics at J-PARC," Prog. Part. Nucl. Phys., (in press)

[Books]

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Presentations

[International conferences/workshops]

F. Sakuma (invited), "K^-pp bound system at J-PARC," The 15th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon (MENU-2019), Cohon University Center, Carnegie Mellon University, Pittsburgh Pennsylvania, June 2–7, 2019.

K. Itahashi (invited), "Mesons in nuclei: review and perspectives," 3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics, Krakow, June 23–28, 2019.

K. Itahashi (oral), "Precision spectroscopy of pionic atoms at RIBF," The 27th International Nuclear Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019.

T. Yamaga (oral), "Result of KbarNN search via exclusive measurements of (K^-, n) reaction at J-PARC," The 27th International Nuclear Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019.

S. Okada (oral), "Kaonic atom X-ray spectroscopy with superconducting detector," The 27th International Nuclear Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019.

T. Hashimoto (oral), "Towards the X-ray measurement of kaonic deuterium at J-PARC," The 27th International Nuclear Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019.

K. Ishida, "Status of the $g-2$ and EDM experiment at J-PARC," FCCP2019, Anacapri, Italy, August 2019.

K. Ishida, "Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen utilizing muon spin repolarization with laser: Principle and Method," Proton Radius 2019, Veli Losinji, Croatia, September 2019.

S. Kanda, "Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen utilizing muon spin repolarization with laser: Preparation Status," Proton Radius 2019, Veli Losinji, Croatia, September 2019.

K. Ishida, "Status of the $g-2$ and EDM experiment at J-PARC," Proton Radius 2019, Veli Losinji, Croatia, September 2019.

M. Iwasaki (invited), "Kaonic nuclear bound state "K^-pp" observation and possible future plan," The 3rd J-PARC symposium (J-PARC2019), Tsukuba, September 23–26, 2019.

K. Ishida *et al.*, "Laser spectroscopy of the 1*s* hyperfine splitting energy of muonic hydrogen for the determination of proton Zemach radius," The 3rd J-PARC symposium (J-PARC2019), Tsukuba, Japan, September 23–26, 2019.

M. Iwasaki (invited), "A novel and peculiar quantum system—*K*-meson and two protons bound state," STRANEX: Recent progress and perspectives in STRANge EXotic atoms studies and related topics ECT*, Trento, October 21–25, 2019.

F. Sakuma (invited), "$\Lambda(1405)pn$ Final State in the $K^- + {}^3$He reaction," STRANEX: Recent progress and perspectives in STRANge EXotic atoms studies and related topics ECT*, Trento, October 21–25, 2019.

[Domestic conferences/workshops]

岩崎雅彦（招待講演），「*K* 中間子 と 2 つの陽子が束縛した奇妙な量子多体系」, 日本物理学会秋季大会, 山形大学, 山形, 2009 年 9 月 17–20 日.

O. Zhadyra（口頭発表），「The physics E31 experiment to search the $\Lambda(1405)$ via the $d(K^-, \pi\Sigma)$ reaction at J-PARC K1.8BR」, 日本物理学会秋季大会, 山形大学, 山形, 2009 年 9 月 17–20 日.

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関屋涼平,「GSI における WASA 検出器を用いたハイパー核分光実験および η' 中間子原子核探索実験のためのプラスチックシンチレータバレルの開発（II)」, 日本物理学会秋季大会, 山形大学, 山形, 2009 年 9 月 17–20 日.

石田勝彦,「英国理研 RAL ミュオン施設とミュオン利用分析」, 第 2 回文理融合シンポジウム 量子ビームで歴史を探る—加速器が紡ぐ文理融合の地平—, 大阪, 2019 年 12 月.

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[Seminars]

RIKEN Symposium, "International Workshop of Topological Quantum Materials," Tainan, Taiwan, January 10–12, 2019.

RIKEN Symposium, "The 5th International Symposium in Current Progress in Mathematics and Sciences," Depok, Indonesia, July 9–10, 2019.

Awards

S. Winarsih, RIKEN Summer School 2019, Poster Prize (in Physics).

S. Winarsih, RIKEN Summer School 2019, Poster Prize (Best Presentation).

S. Winarsih, RIKEN Exchange Meeting 2019, Poster Prize (Student Section), 理研栄峰賞 板橋健太 2020 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/sPHENIX 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. The Deputy Director of RBRC is D. Morrison (BNL). 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

Deputy Director
David P. MORRISON

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

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 developed the theory of bulk viscosity's behavior near the critical point and investigated universality-driven analytic structure of QCD crossover (V. Skokov).

Y. Kikuchi (in collaboration with K. Kashiwa and A. Tomiya) have developed a novel approach to the phase transitions using the neural network. In collaboration with R. Kobayashi, K. Shiozaki, and S. Ryu), Y. Kikuchi has proven a new theorem with higher-form symmetry and applied it to the quantum dimer models.

(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, D. Kharzeev and V. Skokov in their papers 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 small x gluon distributions are directly related to the entanglement entropy. D. Kharzeev, in collaboration with T. Ullrich and Z. Tu, investigated the role of entanglement in explaining the LHC data on hadron multiplicity distributions, and proposed a program to study entanglement at the EIC.

Y. Hatta has investigated the photoproduction of J/Ψ charmonium near the threshold and its link to the problem of the origin of the proton's mass. He has found that this process can be used to extract the proton mass distribution. Y. Hatta has also developed the theory of spin dependence of Pomeron and Odderon in elastic scattering, and proposed a mechanism for single spin asymmetry observed at RHIC. He has also made important contributions to developing the science program at the EIC.

Y. Mehtar-Tani has developed a theory of jet propagation through a dense QCD matter that properly takes into account the multiple scattering effects. He has also evaluated higher order QCD corrections to jet quenching, and proposed a dynamical grooming algorithm for QCD jets.

C. Shen has advanced the applications of hydrodynamics to the description of heavy ion collisions, and built a quantitative model for the Beam Energy Scan at RHIC. In collaboration with Kharzeev and others, he has implemented the effects of magnetic field on the hydrodynamical evolution.

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 and his students have proposed a new chiral magnetic photocurrent that has been observed experimentally. Kharzeev in collaboration with Q. Li have developed a concept of a new type of "chiral qubit" based on Dirac and Weyl semimetals.

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.

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List of Publications & Presentations

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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 $1 < p_T < 3$ 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 $3 < p_T < 4$ 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 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.

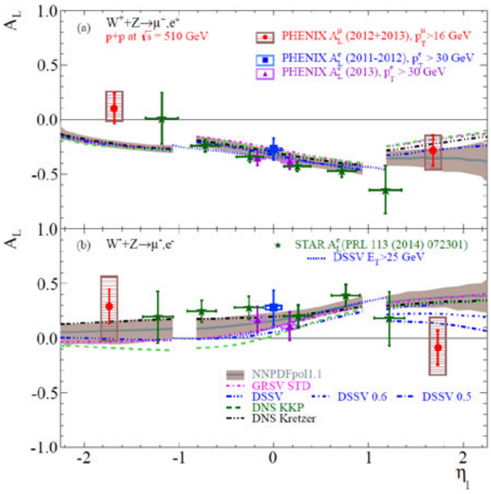

Fig. 1. Single spin asymmetry A_L of electrons from W and Z decays. The A_L is sensitive to the polarization of anti-quarks in the proton. The curves and the shaded region show theoretical calculations based on various polarized parton distribution (PDF) sets. The mid-rapidity points were published in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

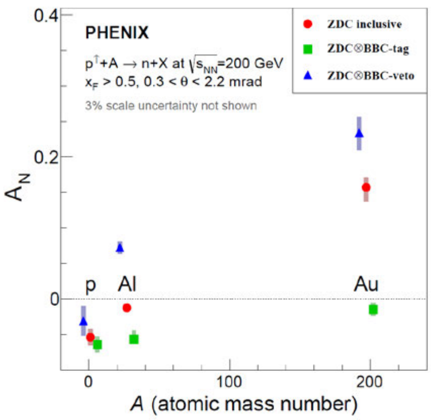

Fig. 2. Single spin asymmetry A_N of very forward neutron in $p + p$, p + Al, and p + Au collision. Published in Phys. Rev. Lett. 120, 022001 (2018).

(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 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

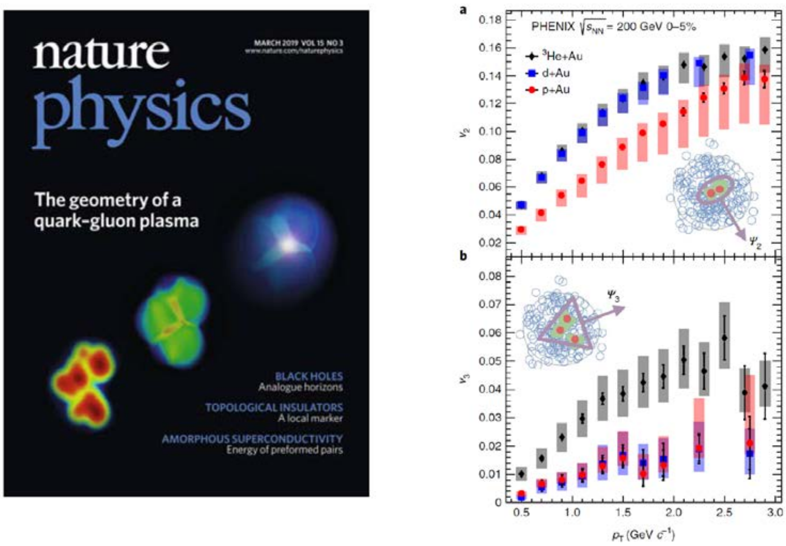

Fig. 3. Left: Cover of Nature Physics March 2019 issue featuring the PEHNIX article reporting strong evidence of small QGP droplent formation. Right: Data of elliptic and triangular flow measured in p+Au, d+Au and ^{3}He+Au collisions.

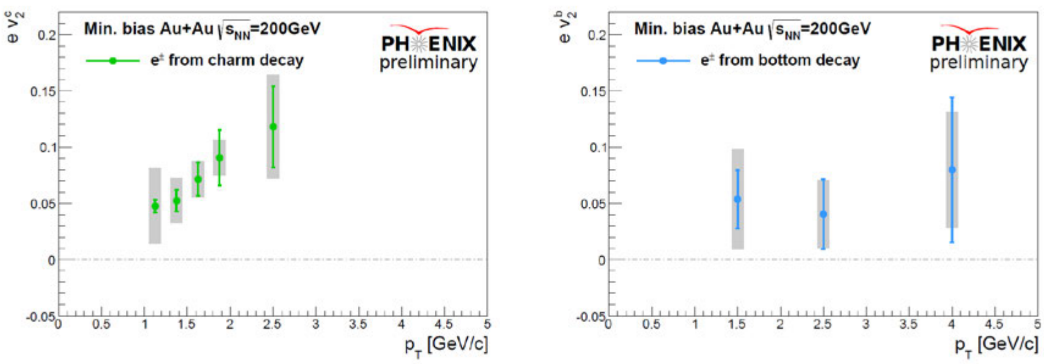

Fig. 4. Preliminary results of the elliptic flow strength v_2 of single electrons from charm and bottom decays.

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.

(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 ($3 < p_T < 4$ 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. The results of bottom/charm ratios in $p + p$ collisions at 200 GeV from the 2015 run was published (Phys. Rev. D99 092003 (2019)). A paper reporting measurements of the nuclear suppression factor R_{AA} of charm and bottom in Au+Au collisions from the 2014 data is in preparation.

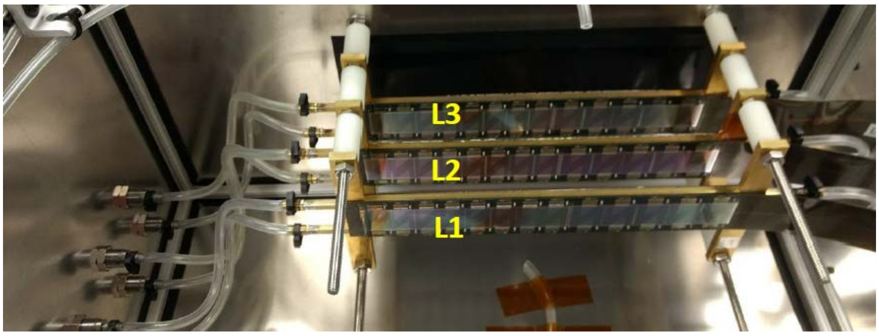

Fig. 5. Three ladder telescope made from INTT silicon tracker prototype. The prototype detector was tested in a beam test at FNAL in February 2018.

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.

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List of Publications & Presentations

Publications

[Original papers]

C. Aidala *et al*., “Creation of quark-gluon plasma droplets with three distinct geometries,” Nature Physics **15**, 214 (2019).

A. Adare *et al*., “Beam energy and centrality dependence of direct-photon emission from ultrarelativistic heavy-ion collisions,” Phys. Rev. Lett. **123**, 022301 (2019).

C. Aidala *et al*., “Nuclear dependence of the transverse single-spin asymmetry in the production of charged hadrons at forward rapidity in polarized p+p, p+Al, and p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV,” Phys. Rev. Lett. **123**, 122001 (2019).

A. Adare *et al*., “Multiparticle azimuthal correlations for extracting event-by-event elliptic and triangular flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV,” Phys. Rev. C **99**, 024903 (2019).

C. Aidala *et al*., “Nonpertuarbative transverse momentum broadening in dihedron angular correlations in $\sqrt{s_{NN}}$ = 200 GeV proton-nucleus collisions,” Phys. Rev. C **99** 044912 (2019).

A. Adare *et al*., “Measurement of two-particle correlations with respect to second- and third- order event planes in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV,” Phys. Rev. C **99**, 5,054903 (2019).

C. Aidla *et al*., “Measurements of $\mu\mu$ pairs from open heavy flavor and Drell-Yan in p+p collisions at $\sqrt{s}$ = 200 GeV,” Phys. Rev. D **99**, 072003 (2019).

C. Aidla *et al*., "Measurement of charm and bottom production from semileptonic hadron decays in p+p collisons at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. D **99**, 092003 (2019).

Presentations

[International conferences/workshops]

T. Hachiya (invited), "PHENIX heavy flavor highlights," 8th International conference on new frontiers in physics (ICNFP 2019), Crete, Greece, August 21–29, 2019.

M. Connors (invited), "PHENIX jighlights," 28th International conference on ultrarelativistic nucleus-nucleus collisions (Quark Matter 2019), Wuhan, China, November 4–9, 2019.

T. Todoroki (oral), "Quark flavor dependence of particle flow in nucleus-nucleus collisions measured by PHENIX," 28th International conference on ultrarelativistic nucleus-nucleus collisions (Quark Matter 2019), Wuhan, China, November 4–9, 2019.

Awards

Megan Connors, CAREER award from the National Science Foundation.

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 sPHENIX and future Electron Ion Collider (EIC), Hyper Kamiokande, DUNE, or the origin of the current matter rich universe (rather than anti-matter). Towards finite density QCD, they also explore Quantum Computing to overcome the sign problem.

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 CKM theory for kaons and B mesons that include the new calculation of b-baryon decay, $\Lambda_b \to p$; 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 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.

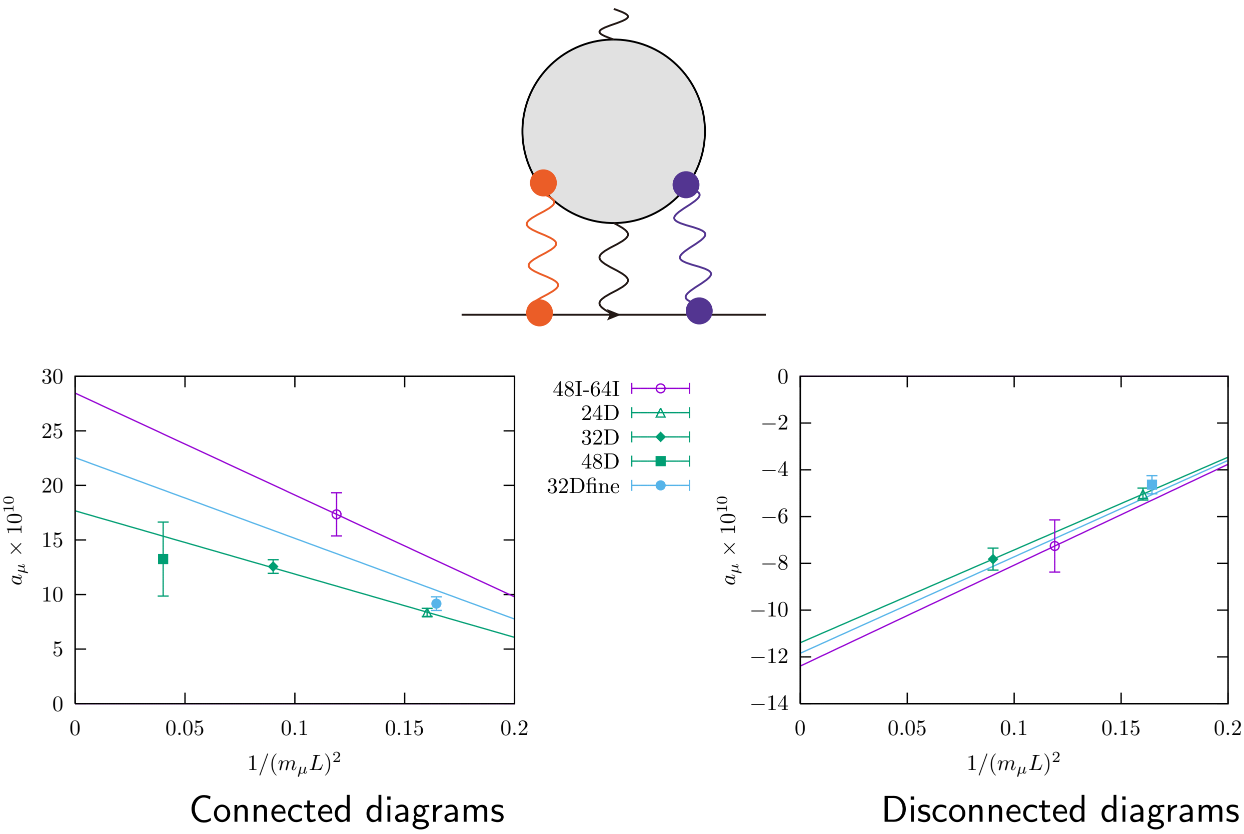

Fig. 1. The bottom plots are Hadronic Light-by-Light (HLbL) contributions to muon anomalous magnetic moment shown at top diagram.

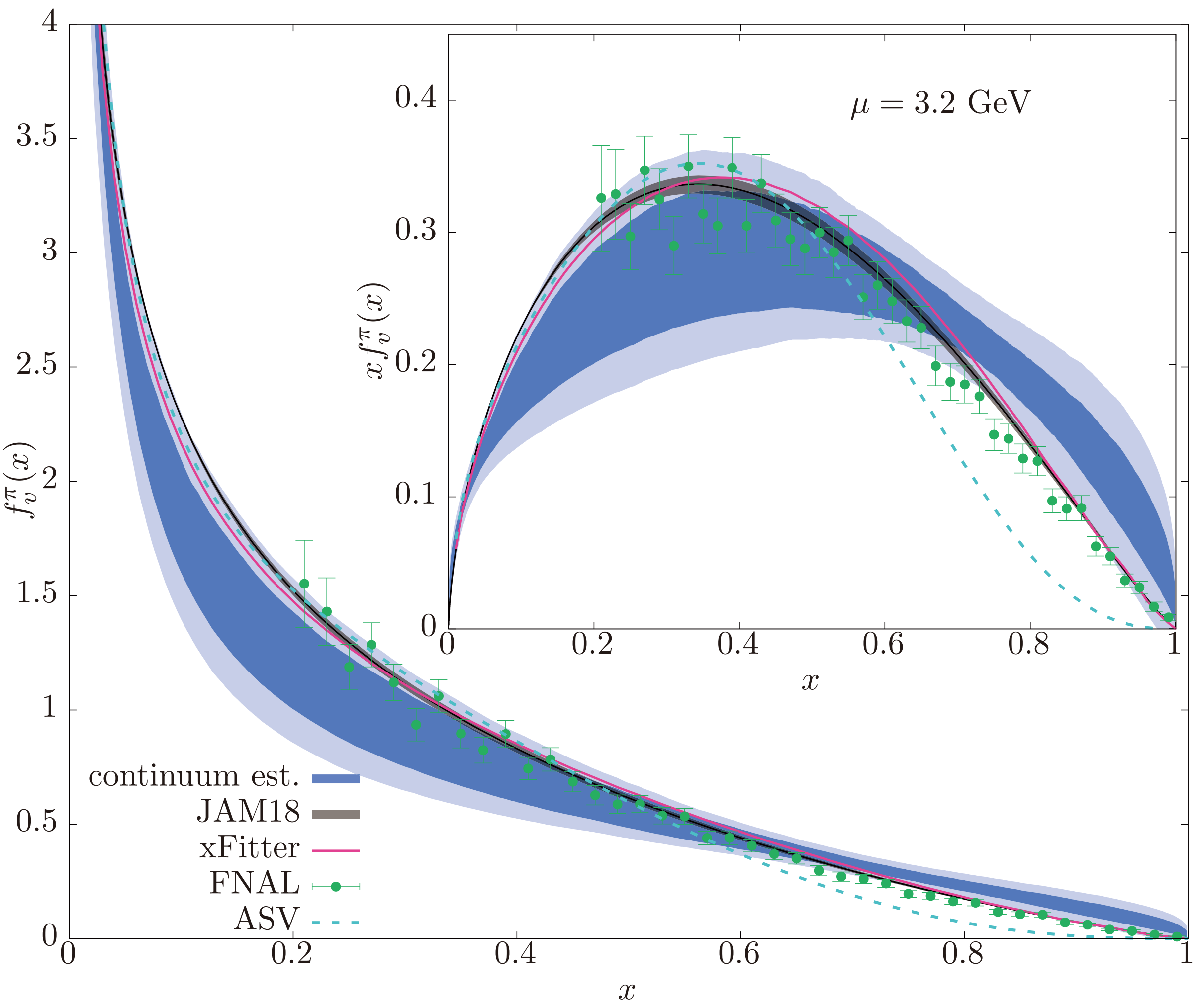

Fig. 2. Parton Distribution of pion as function of momentum fraction of valence quark, x, at factorization scale 3.2 GeV compred to phenomenological and experimental determinations. From arXiv:2007.06590

Members

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Christopher KELLY (Columbia Univ.)

List of Publications & Presentations

Publications

[Original papers]

C. Y. Seng, X. Feng, M. Gorchtein, and L. C. Jin, "Joint lattice QCD–dispersion theory analysis confirms the quark-mixing top-row unitarity deficit," Phys. Rev. D **101**, 111301 (2020). doi:10.1103/PhysRevD.101.111301 [arXiv:2003.11264 [hep-ph]].

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Presentations

[International conference/workshops]

L. Jink (invited), "QED corrections to hadron masses," χ QCD collaboration meeting at University of Kentucky, December 13, 2019.

L. Jin (invited), "Status of Muon g − 2," Brookhaven Forum 2019: Particle Physics and Cosmology in the 2020's, September 26, 2019.

L. Jin (invited), "Hadronic Light-by-Light RBC," Hadronic contributions to (g − 2) μ , INT Workshop INT-19-74W, September 11, 2019.

L. Jin (invited, plenary) "QED_∞ in muon g − 2, hadron spectroscopy, and beyond," 37th international conference on lattice field theory, June 20, 2019.

A. Tomiya (invited), "Applications of machine learning to computational physics," A.I. for nuclear physics (invited), Jefferson Laboratory, Virginia, USA, November 3, 2020.

A. Tomiya, "Chiral condensate in Schwinger model by quantum computer," International Workshop on "Theoretical Particle Physics 2019," Tokyo, Japan, November 4, 2019.

A. Tomiya, "Phase structure of three flavor QCD in external magnetic fields," XQCD 2019, Tokyo, Japan, June 2019.

A. Tomiya, "Phase structure of three flavor QCD in external magnetic fields," Lattice 2019, Wuhan, China, June 2019.

[Domestic Conferences/Workshops]

A. Tomiya, "Phase structure of three flavor QCD in external magnetic fields," JPS meeting, Kyushu University, March 2019.

A. Tomiya, "QCD phase transition under external magnetic field with improved staggered fermions," JPS meeting, Tokyo University of Science, March 2018.

[Seminars]

A. Tomiya, "Lattice gauge theory with quantum computers," (Virtual) RIKEN Center for Computational Science, Japan, June 3, 2020.

A. Tomiya, "Lattice gauge theory with quantum computers," (Virtual) Osaka university, Japan, May 12, 2020.

A. Tomiya, "An introduction to deep learning (lecture)," Jamstec (Japan Agency for Marine-Earth Science and Technology), Japan, January 13, 2019.

A. Tomiya, "An introduction to lattice gauge theories (lecture)," Math club, Tokyo, Japan, December 28, 2019.

A. Tomiya, "An introduction to deep learning (lecture)," Kochi Technological university, Kochi, Japan, December 13, 2019.

A. Tomiya, "An introduction to Machine learning and science (lecture)," Kochi Technological university, Kochi, Japan, December 13, 2019.

A. Tomiya, "An introduction to lattice gauge theories (lecture)," Jilin U, China, November 18, 2019.

A. Tomiya, "An introduction to deep learning (lecture)," Waseda U (hpc-phys working group), Japan, November 7, 2019.

A. Tomiya, "Phase transition in three flavor QCD with background magnetic field," Jilin U, China, September 24, 2019.

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A. Tomiya, "Applications of machine learning to computational physics," Brookhaven National Laboratory, NY, US, May 30, 2019.

A. Tomiya, "Towards reduction of autocorrelation in HMC by machine learning," Riken CCS, Kobe, Japan, March 29, 2019.

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Awards

L. Jin and K. G. Wilson, "For his outstanding contributions to the calculation of the hadronic light-by-light scattering component of the anomalous magnetic moment of the muon," Award for Excellence in Lattice Field Theory, 2019.

L. Jin, "Lattice Calculation of the QED Correction to Meson Leptonic Decay," U.S. Department of Energy (DOE), Early Career Research Program, Proposal 0000253629.

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Press Releases

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May 5, 2020, RIKEN, Brookhaven National Laboratory, Columbia University, Universities of Connecticut, Nagoya, Regensburg, "Four Years of Calculations Lead to New Insights into Muon Anomaly"

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—with 2020 being the 30th years of continuous agreements between RIKEN and RAL. The Facility enables muon science throughout Japan and other field—it continues to attract proposals from a wide variety of Japanese universities and institutions (with over 80 groups having now used the facility), and including industrial users such at Toyota, and has been instrumental in establishing scientific links with other Asian universities.

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 aSR 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 2017 to 2020, following subjects of material sciences are most important achievements at the RIKEN-RAL muon facility:

(1) Deformed nodal superconducting gap state and asymmetric spin-fluctuation mediated Cooper pair in the quasi two-dimensional organic superconductor λ-[BETS]$_2$GaCl$_4$
(2) Multi magnetic transitions in the Ru-based pyrochlore systems, $R_2Ru_2O_7$.
(3) Magnetic properties of the nano-cluster gold in the border of macro- and micro- scale.
(4) Novel magnetic and superconducting properties of nano-size La-based high-T_C superconducting cuprates.
(5) Determination of muon positions estimated from density functional theory (DFT) and dipole-field calculations.
(6) Chemical muonic states in DNA molecules.

Result-1) We developed a novel method to determine deformed superconducting-gap structure with the density functional theory calculations. It was concluded that the two-dimensional organic superconductor λ-[BETS]$_2$GaCl$_4$ has a deformed nodal gap which has the steeper width rather than that of the d-wave state. 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) and 4) The nano-size effect show a new scheme of electronic properties of metallic element. We confirmed that the nano-gold cluster can have free electronic moment on one nano-cluster. The same nano-size effect was examined on the La-based high-T_C superconducting oxide changing the electronic state from insulating to superconducting. We confirmed the reduction in the magnetic interaction and the disappearance of the superconducting state leading the increase in the ferromagnetic interaction within the wide-range of the hole concentration. Result-5) 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.

We have been continuing to develop muon-science 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 are creating new collaborations with new teams in different countries and also continuing collaborations in μSR experiments on strongly correlated systems with researchers from Taiwan, Indonesia, China, Thailand and Malaysia 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), miniature boats from Sardinia, reliefs on Baptist church gate, 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. The study was extended to see the difference by isotopes of silver and lead, which may give hint on the source of the material.

(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. In addition, the ultra-cold muon is very important as the source of 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. We are working hard to improve the crystal homogeneity including the option of using slightly different material.

We also succeeded in developing an efficient muonium generator, laser ablated silica aerogel, which emits more muoniums into vacuum even at room temperature. Study has been done at TRIUMF utilizing positron tracking method of muon decay position. We demonstrated in 2013 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. From the analysis, we found the emission has large positive correlation with the laser ablated area rather than with any other parameters. We also confirmed the muon polarization in vacuum. An alternative detection method for muonium emission 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. The study was further applied the measurement of the temperature dependence.

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 2S-2P transition of 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. 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. Another key is the lifetime of the upper hyperfine state of the muonic hydrogen that will contribute the polarization. We successfully observed the clear muon spin precession of muonic deuterium atom in 2018 for the first time in the world. The measurement with muonic protium was carried out 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 was passed to ISIS, a refurbishment programme of the facility has started, a user programme for Japanese scientists continued under the partnership between RIKEN and ISIS. 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.

Members

Director
Philip KING

Research Scientist
Isao WATANABE (Senior Research Scientist)

Contract Researcher
Katsuhiko ISHIDA

List of Publications & Presentations

Publications

[Original papers]

M. Abe *et al*. (J-PARC E34 collaboration), "A new approach for measuring the muon's anomalous magnetic moment and electric dipole moment," Prog. Theor. Exp. Phys. **2019**, 053C02 (2019).

M. Clemenza *et al*., "Muonic atom X-ray spectroscopy for non-destructive analysis of archaological samples," Journal of Radioanalytical and Nuclear Chemistry **322**, 1357–1363 (2019).

B. V. Hampshire, K. Butcher, K. Ishida, G. Green, D. Paul, and A. Hillier, "Using negative muons as a probe for depth profiling silver Roman coinage," Heritage **2**, 400–407 2019.

S. Asano, K. M. Suzuki, K. Kudo, I. Watanabe, A. Koda, R. Kadono, T. Noji, Y. Koike, T. Taniguchi, S. Kitagawa, K. Ishida, and M. Fujita, J. Phys. Soc. Jpn. **88**, 084709-1–6 (2019).

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M. A. Baqiya, T. Adachi, A. Takahashi, T. Konno, T. Ohgi, I. Watanabe, and Y. Koike, "Muon-spin relaxation study of the spin correlations in the overdoped regime of electron-doped high-TC cuprate superconductors," Phys. Rev. B **100**, 064514-1–5 (2019).

S. Wenner, C. Marioara, K. Nishimura, K. Matsuda, S. Lee, T. Namiki, I. Watanabe, T. Matsuzaki, and R. Holmestad, "Muon spin relaxation study of solute-vacancy interactions during natural aging of Al-Mg-Si-Cu alloys," Metallurgical and Materials Transactions A **50**, 3446–3451 (2019).

Presentations

[International conferences/workshops]

K. Ishida (oral), "Status of the g-2 and EDM experiment at J-PARC," FCCP2019, Anacapri, Italy, August 29–31, 2019.

K. Ishida (oral), "Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen utilizing muon spin repolarization with laser: Principle and Method," Proton Radius 2019, Veli Losinji, Croatia, September 15–20, 2019.

S. Kanda (oral), "Measurement of the proton Zemach radius from the hyperfine splitting in muonic hydrogen utilizing muon spin repolarization with laser: Preparation Status," Proton Radius 2019, Veli Losinji, Croatia, September 15–20, 2019.

K. Ishida (oral), "Status of the g-2 and EDM experiment at J-PARC," Proton Radius 2019, Veli Losinji, Croatia, September 15–20, 2019.

K. Ishida (oral), “Laser spectroscopy of the 1 s hyperfine splitting energy of muonic hydrogen for the determination of proton Zemach radius,” The 3rd J-PARC symposium (J-PARC2019), Tsukuba, Japan, September 23–26, 2019.

I. Watanabe (oral), The 1st International MIPAnet Conference on Science and Mathematics (IMC-SciMath 2019), Parapat, Indonesia, October 9–11, 2019.

I. Watanabe (oral), 4th Padjadjaran International Physics Symposium (PIPS2019), Bandung, Indonesia, November 13–14, 2019.

I. Watanabe (oral), International Conference on Magnetism and Its Application (IICMIA2019), Solo, Indonesia, November 20–21, 2019.

[Domestic conferences/workshops]

石田勝彦（招待講演),「英国理研 RAL ミュオン施設とミュオン利用分析」, 第 2 回文理融合シンポジウム 量子ビームで歴史を探る—加速器が紡ぐ文理融合の地平—, 大阪大学中之島センター, 大阪, 2019 年 12 月 25 日–26 日.

石田勝彦（口頭発表),「理研 RAL の現状と展望」, 第 10 回「muon 科学と加速器研究」研究会, 理化学研究所, 和光, 2020 年 1 月 8 日–9 日.

[Seminars]

RIKEN Symposium, “International workshop of topological quantum materials,” Tainan, Taiwan, January 10–2, 2019.

RIKEN Symposium, “The 5th international symposium in current progress in mathematics and sciences,” Depok, Indonesia, July 9–10, 2019.

Awards

S. Winarsih, RIKEN Summer School 2019, Poster Prize（in Physics）

S. Winarsih, RIKEN Summer School 2019, Poster Prize（Best Presentation）

S. Winarsih, RIKEN Exchange Meeting 2019, Poster Prize（Student Section）

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 interlock system for which is the part of the radiation control system developed for the RILAC upgrade was installed and started to operate. Access management system for the RILAC building, which was installed previous year, was improved to control

Minor improvements of the radiation safety systems were also done. The old UPS for radiation management system of Nishina building was replaced. Halogen sensitive filter for the exhaust system of Nishina building was newly installed.

Members

Director

Kanenobu TANAKA

Research/Technical Scientists

Rieko HIGURASHI (Technical Scientist)
Hisao SAKAMOTO (Technical Scientist)

Expert Technician

Atsuko AKASHIO

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Student Trainees

Shougo IZUMITANI (Kyushu Univ.)
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Part-time Workers

Kimie IGARASHI (Administrative Part-time Worker I)
Satomi IIZUKA (Administrative Part-time Worker II)
Yukiko SHIODA (Administrative Part-time Worker II)
Naoko USUDATE (Administrative Part-time Worker II)

Temporary Staffing

Ryuji SUZUKI

Assistant

Tomomi OKAYASU

List of Publications & Presentations

Publications

[Proceedings]

田中鐘信,「大規模加速器施設における, 事故時の円滑なジョョ湯方伝達と避難の取り組み」, 日本放射線安全管理学会誌 **18**, 2 (2019).

向井弘樹, 田中鐘信, 上蓑義朋,「RIBF 加速器施設の冷却水に関する放射線管理」, Isotope News **762**, 4 (2019).

Presentations

[International conferences/workshops]

K. Tanaka (oral), "Recent trouble and measures in unsealed radioisotope handling at RIBF," International Technical Safety Forum 2019, Lund, Sweden, May 13–17, 2019.

K. Tanaka (invited), "Radiation evaluation in RIBF," Tsukuba, Japan, September 23–26, 2019.

K. Sugihara(poster), "Measurement of neutron energy spectra of 345 MeV/u ^{238}U Incidence on a Cu Target," 2019 Symposium on Nuclear Data, Kasuga, Japan, November 28–30, 2019.

S. Izumitani(poster), "Production via the ^{7}Li(p ,n) ^{7}Be reaction with 2.49 MeV proton injection," 2019 Symposium on Nuclear Data, Kasuga, Japan, November 28–30, 2019.

[Domestic conference/workshops]

田中鐘信 (招待講演),「RIBF のインターロックと運用」, 第 7 回加速器施設安全シンポジウム, 東海村, 2020 年 1 月 23–24 日.

Awards

[Excellent poster award]

S. Izumitani, "Production via the ^{7}Li(p, n) ^{7}Be reaction with 2.49 MeV proton injection," 2019 Symposium on Nuclear Data, Kasuga, Japan, November 28–30, 2019.

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

Director

Hideki UENO

Research Consultants

Ikuko HAMAMOTO (The Lund Univ.)
Munetake ICHIMURA (Univ. of Tokyo)

Assistants

Yu NAYA
Tomomi OKAYASU
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

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

Technical Staff I
Narumasa MIYAUCHI

List of Publications & Presentations

Outreach activities

Special Exhibition of the International Year of the Periodic Table 2019（国際周期表年特別展 2019「理化学研究所のニホニウム模型をつくろう」), Niihama (Ehime Prefectural Science Museum), January 18–19, 2020.

RIKEN Osaka Campus Open Day 2019, Suita, November 23, 2019.

Science Agora 2019 (an open forum organized by the Japan Science and Technology Agency), Tokyo (The National Museum of Emerging Science and Innovation), November 15–17, 2019.

Office of the Center Director

Summary of Research Activity

This office is in place from JFY2018 to support the center director in subjects which the promotion office is not able to cover. It also works as a home laboratory for research administrators and assistants with an indefinite term contract. This year's most important activity of the office was to support the International Symposium on Superheavy Elements (SHE2019) held at Hakone, Japan from 1st to 5th of December 2019. The Chair parsons K. Morita and H. Haba run the symposium and were supported largely by this office; research administrator Narumasa MIYAUCHI and assistants Noriko ASAKAWA and Noriko KIYAMA. Miyachi also contributed largely to the International Year of Periodic table (IYPT2019), in the preparation of the travelling exhibitions and the preparation of the session "Creation of superheavy elements" in the IYPT2019 Closing Ceremony. His handmade video of "The Landscape of Nihonium Avenue" was greatly appreciated by the audience. Below is a list of activity of Nishina Center Director's Office, in public or semi-public events.

2019.03.01	NuPECC at Warsaw	Nishina Center is the associate member of (NuPECC: Nuclear Physics European Collaboration Committee, an Expert Committee of the European Science Foundation). The status report of Nishina Center was presented at their regular meeting at Warsaw, Poland. The minutes are available in http://www.nupecc.org/misc/min94.pdf
2019.03.11	RBRC SRC	Nishina Director participated in Scientific Review Committee of RIKEN-BNL Research Center.
2019.03.17	JPS meeting at Ito Campus, Kyushu University	As recommended by Nishina Center, Japan Physics Society organized a special joint session for IYPT2019 at the Ito Campus of Kyushu University with the Chemical Society of Japan at Kobe-Okamoto Campus of Konan University. K. Morita gave a plenary talk.
2019.04.17	Nishina Center, New-commers' Orientation	In the orientation for new commers in Nishina Center, introductory talk of "Researcher's Must Have" was given by Nishina Director.
2019.05.19	Completion Ceremony for Nihonium Avenue	Wako City held the Completion Ceremony of Nihonium Avenue in the RIKEN Wako Campus. The Mayer Matsumoto invited the donors and students to the Ceremony. The Nishina Director gave the presentation of "Welcome to the birthplace of 113th element, nihonium (in Japanese)". Many of audience also attended the challenge exam for chemical elements, held together with the ceremony.
2019.05.29	ORNL visit	Nishina Director visited Oak Ridge National Laboratory to participate in the collaboration meeting for superheavy element search.
2019.06.11	Sakura Science High School Visit	Sakura Science High School, a government-driven virtual school for foreign exchange Students, visited RIKEN. Nishina Director gave a presentation of "Welcome to the birthplace of 113th element, nihonium".
2019.06.24	NCAC	Nishina Center Advisory Committee was held. Nishina Director and the Center activities were reviewed for three days.
2019.06.28	ML-PAC	Nishina Director gave an introductory talk for ML-PAC (Program Advisory Committee for Materials and Life Science).
2019.07.10	IN-PAC	Nishina Director gave an introductory talk for In-PAC(Program Advisory Committee for Industrial usage), which was held in a closed session.
2019.07.27	Mendeleev 150	4th International Conference on the Periodic Table (Mendeleev 150) was held at ITMO University in Saint Petersburg, Russian Federation (see https://mendeleev150.ifmo.ru/). Nishina Director gave a lecture titled "History of Nihonium" on behalf of Kosuke Morita. The talk was published in https://doi.org/10.1515/pac-2019-0810
2019.08.01	SCK-CEN visit	Nishina Director visited CNK-CEN which is the Belgian nuclear research centre, to seek for possible collaboration in MYRRHA(Multi-purpose hYbrid Research Reactor for High-tech Application).
2019.08.02	IUPAP-WG9	Nishina Director participated in the annual general meeting for IUPAP-WG9 (Working Group 9) held at University of Notre Dame in London, UK. Agenda is available at https://iupap.triumf.ca/icnp/meetings.html.
2019.08.21	NICT Visit	A delegation from NICT (National Institute of Information and Communication Technology) visited Nishina Center. Nishina Director made an introduction to them with a story of the first cyclotron made by Nishina was made on the Paulsen's arc converted which was developed for radio communication.
2019.08.26	TAN19	Tan19(6th International Conference on the Chemistry and Physics of the Transactinide Elements) was held in Wilhelmshaven, Germany. Nishina Director was invited to give a lecture "Element Genesis over 13.8 Billion Universal Years" in a session dedicated to the International Year of Periodic Table: https://www-win.gsi.de/tan19/symposium.html.
2019.09.07	IYPT2019 Special Exhibition in Kyoto	Nishina Director gave a public lecture in the Special Exhibition in Kyoto for the International Year of Periodic Table, titled "13.8 billion years of element genesis, from Big-Bang to nihonium (in Japanese)".
2019.10.03	J. Soffer's Memorial	Nishina Director participated in a memorial symposium for J. Soffer, who was a leading theorist of perturbative QCD and the father of the RHIC spin project, at BNL, NY, USA.
2019.10.23	RAC	Nishina director gave a presentation in RIKEN Advisory Council.
2019.11.00	Chemistry and Chemical Industry	Nishina Director contributed a report of Mendeleev150 Symposium to the special contents for IYPT2019 in Chemistry and Chemical Industry, 940, Vol72-11, 2019.

2019.11.25	Event Myrrha	Nishina Director participated in Event MYRRHA (introduction of MYRRHA project to Japanese communities) held at Belgian Embassy at Tokyo, Japan
2019.12.05	IYPT2019 Closing Ceremony	Nishina director was a port of the organizing committee for the closing ceremony of IYPT2019, held in Tokyo, Japan. He produced and chaired a session named "Creation of superheavy elements" attended by many of actual discoverers. https://iypt.jp
2019.12.01	SHE2019	Director's office fully supported the international Symposium on Superheavy Elements (SHE2019) held at Hakone, Japan from 1st to 5th of December 2019. The Chair parsons are K. Morita and H. Haba. https://she2019.riken.jp
2019.12.16	NP-PAC	Nishina Director gave an introductory talk for NP-PAC (Program Advisory Committee for Nuclear Physics).
2020.01.24	ML-PAC	Nishina Director gave an introductory talk for ML-PAC (Program Advisory Committee for Materials and Life Science).
2020.01.00	Nuclear Physics News	Nishina Director reported "Superheavy Elements at the Closing Ceremony of IYPT" to Nuclear Physics News, Vol. 30, No. 1, 2020.
2020.01.27	Strategic review of Helmholtz Association	Nishina Director visited Helmholtz Association in Berlin, Germany, to review of the scientific field "MATTER" which includes GSI, DESY and other large-scale laboratories

Members

Director

Hideto EN'YO

Research Administrator

Narumasa MIYAUCHI (concurrently appointed to Outreach Team)

Assistants

Noriko ASAKAWA
Noriko KIYAMA
Yu NAYA (concurrently appointed to RIBF User Liaison Team)
Karen SAKUMA (concurrently appointed to Accelerator Group)
Asako TAKAHASHI (concurrently appointed to Spin Isospin Laboratory)
Mitsue YAMAMOTO (concurrently appointed to Meson Science Laboratory)
Izumi YOSHIDA (concurrently appointed to Nuclear Spectroscopy Laboratory)

List of Publications & Presentations

Publications

[Proceedings]

Hideto En'yo (invited), "History of nihonium," Proceedings of Mendeleev 150, Pure and Applied Chemistry, **91**, 1941 (2019).

Presentations

[International conferences/workshops]

Hideto En'yo (invited), "History of nihonium," 4th International Conference on the Periodic Table (Mendeleev 150), ITMO University in Saint Petersburg, Russian Federation, July 26–28, (2019).

Hideto En'yo (invited), "Element genesis over 13.8 billion Universal years," Special Symposium for International Year of Periodic Table in the 6th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN19), Wilhelmshaven, Germany, August 25–30, 2019.

Outreach activities

Hideto En'yo, "Welcome to the birthplace of 113th element, nihonium," a lecture given to the Sakura Science High School, RIKEN-Wako, June 11, 2019.

Hideto En'yo *et al*. (invited), "Creation of superheavy elements," The Closing Ceremony of IYPT2019, Tokyo, Japan, December 5, 2019.

Hideto En'yo, "Superheavy Elements at the Closing Ceremony of IYPT" contributed to Nuclear Physics News **30**, 39 2020.

延與秀人, 「ようこそ, 113 番元素ニホニウムの生誕地, 理研仁科センターへ」, ニホニウム通り完成記念式典（和光市主催）, 理研和光キャンパス, 和光, 2019 年 5 月 19 日.

延與秀人, 「元素創成の 138 億年: ビッグバンからニホニウムに至るまで」, 国際周期表年 2019 特別展, 京都大学, 京都, 2019 年 9 月 7 日.

Partner Institutions

The Nishina Center started research collaboration with universities and research institutes in 2008 under the “Research Partnership” agreement. This collaboration framework 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 (CNS), the University of Tokyo; 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” agreement.

The CNS and the Nishina Center signed the partnership agreement in 2008. Until then, the 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 the 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 the CNS and KEK.

The activities of the 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. A new project for fundamental symmetry using heavy RIs has been starting to install new experimental devices in the RIBF. We promote collaboration programs at RIBF as well as RHIC-PHENIX and ALICE-LHC with scientists in the world, and host international meetings and conferences. We also provide educational opportunities to young scientists in the heavy-ion science through the graduate course as a member of the department of physics in the University of Tokyo and through hosting the international summer school.

2. Major Research Subjects

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

3. Summary of Research Activity

(1) Accelerator Physics

One of the major tasks of the accelerator group is the AVF upgrade project that included development of ion sources. In 2019, the operating time of the HyperECR was 2326 hours, which is 76% of the total operating time of the AVF cyclotron. The beam extraction system of the HyperECR is under development realize a high intensity and low emittance beam. For the pepper-pot emittance monitor used for the analysis of the beam injection transport system, we optimized the exposure time and gain of digital camera for a variety of thicknesses of fluorescent agent and was able to keep homogenized measurements despite of thickness. For the beam transport analysis of the beamline to CRIB, E7B, and EDM experiment from AVF cyclotron, we started developing 4D emittance monitor because the transverse components of beam are coupled and it is expected to measure high intensity beam in a few seconds.

(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}Be$(n,\alpha)/(n,p)$ astrophysical reactions were studied with the Trojan Horse method, and the rate of ^{7}Be(n,p_1), the (n,p) reaction with ^{7}Li excitation, is evaluated at the BBN temperature for the first time. ^{7}Be(d,p) measurement with a ^{7}Be-implanted target was carried out in 2018, in collaboration with RCNP, Osaka Univ. and JAEA. ^{8}Li(α,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}Li(α,n), a new experiment with γ-ray measurement was performed at CRIB in September 2018. To confirm the exotic linear-chain cluster structure in ^{14}C nucleus indicated in the previous ^{10}Be + α 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 October 2018. A measurement on ^{25}Al + p resonant scattering was performed at CRIB in February 2019, to study the resonances relevant for the astrophysical ^{22}Mg(α,p) reaction in X-ray bursters.

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. As the first experiment of the INSPIRATION project, a measurement of the proton-halo ^{8}B+^{120}Sn system at energies around the Coulomb barrier was carried out in April 2019, under the collaboration of Japan and China. This was to study the reaction mechanism, including the break-up, of the system involving a weakly-bound nucleus, 8B. On the interest of nuclear clustering in the ^{14}O nucleus, a measurement of ^{10}C+α elastic scattering was performed, under the collaboration of Belgium (ULB), Kyoto Univ., Osaka Univ., CNS, and other groups. We identified several peaks in the energy spectrum, which may show the existence of cluster states. Studies on big-bang nucleosynthesis (BBN) are currently under way. To give a solution to the cosmological ^{7}Li abundance problem, ^{7}Be$(n,\alpha)/(n,p)$ astrophysical reactions were measured with the Trojan Horse method, and the first reliable evaluation of the rate of ^{7}Be$(n,p1)$, the (n,p) reaction with ^{7}Li excitation, at the BBN temperature, was made during 2019. To produce

RI beams at CRIB with higher intensity, a project to improve the heat capacity of the cryogenic gas target was initiated in 2019. We tested several materials for the sealing foils and the flanges, and a thermal monitoring with a thermography was introduced.

(3) Nuclear structure of exotic nuclei

The NUSPEQ (NUclear SPectroscopy for Extreme Quantum system) group studies exotic structures in high-isospin and/or high-spin states in nuclei. The CNS GRAPE (Gamma-Ray detector Array with Position and Energy sensitivity) is a major apparatus for high-resolution in-beam gamma-ray spectroscopy. Missing mass spectroscopy using the SHARAQ is used for another approach on exotic nuclei. The group plays a major role in the OEDO/SHARAQ project described below. In 2019, analysis of a new measurement of the ^{4}He(^{8}He, ^{8}Be)4n reaction for better statistics and better accuracy has been proceeding.

(4) Quark Physics

Main goal of the quark physics group is to understand the properties of hot and dense nuclear matter created by colliding heavy nuclei at relativistic energies. The group has been involved in the PHENIX experiment at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, and the ALICE experiment at Large Hadron Collider (LHC) at CERN. As for ALICE, the group has involved in the data analyses, which include the measurement of low-mass lepton pairs in Pb-Pb 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 been involved in the ALICE-TPC upgrade using a Gas Electron Multiplier (GEM). Installation of GEM chambers in the TPC and commissioning of the TPC were carried out in 2019. The group has started working on the online space-charge distortion correction of the TPC by utilizing the GPUs and Machine learning technique.

(5) Nuclear Theory

The nuclear theory group participated in a project, "Priority Issue 9 to be tackled by using the Post-K Computer" and promotes computational nuclear physics utilizing supercomputers. We developed shell-model codes for the conventional Lanczos method and the Monte Carlo shell model for massively parallel computation. In FY2019, we performed the Monte Carlo shell model calculations of the Sm isotopes and revealed that the excited states of ^{154}Sm and ^{166}Er whose structures were considered to be β/γ vibration can be interpreted in view of shape coexistence.

(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. In 2019, we developed a surface ionizer for production of a high intensity Fr ion beam. Using the surface ionizer, the 1st Fr production experiment was also conducted in 2019. At present, the development of a magneto-optical trap and an atomic interferometer are in progress.

Members

Director

Susumu SHIMOURA

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List of Publications & Presentations

Publications

[Original papers]

K. Nakano, Y. Watanabe, S. Kawase, H. Wang, H. Otsu, H. Sakurai, S. Takeuchi, Y. Togano, N. Nakamura, M. Maeda, D. S. Ahn, M. Aikawa, S. Araki, S. Chen, N. Chiga, P. Doornenbal, N. Fukuda, T. Ichihara, T. Isobe, S. Kawakami, T. Kin, Y. Kondo, S. Koyama, T. Kubo, S. Kubono, M. Uesaka, A. Makinaga, M. Matsushita, T. Matsuzaki, S. Michimasa, S. Momiyama, S. Nagamine, M. Niikura, T. Ozaki, A. Saito, T. Saito, Y. Shiga, M. Shikata, Y. Shimizu, S. Shimoura, T. Sumikama, P. A. Söderström, H. Suzuki, H. Takeda, R. Taniuchi, J. Tsubota, Y. Watanabe, K. Wimmer, T. Yamamoto, and K. Yoshida, "Isotope production in proton-, deuteron-, and carbon-induced reactions on ^{93}Nb at 113 MeV/nucleon," Phys. Rev. C **100**, 044605 (2019).

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Presentations

[International conferences/workshops]

N. Imai (Oral), "Single particle structure coupled to the second 0+ state in 32Mg," High resolution gamma ray spectroscopy at RIBF, T. U. Darmstadt, Germany, April 10–12, 2019.

N. Imai (Invited), "Controlling the motions of two kinds of fermions in a nucleus, a new energy degraded RI beam line OEDO," Frontier Session of KPS meeting, Deajon, Korea, April 24–26, 2019.

N. Imai (Oral), "Evaluation of the neutron capture reaction on ^{79}Se via a surrogate reaction of d(^{79}Se, p) reaction at OEDO," The 15th International Symposium on Origin of Matter and Evolution of Galaxies, Kyoto, July 2–5, 2019.

S. Michimasa (Oral), "Closed-shell nature in neutrons of ^{54}Ca," International Nuclear Physics Conference 2019 (INPC2019), Scottish Event Campus, Glasgow, UK, July 29–August 2, 2019.

M. Dozono (Oral), "Proton-induced reactions on ^{107}Pd at around 30 MeV/nucleon: First result using slowed-down RI beams at OEDO," International Nuclear Physics Conference 2019 (INPC2019), Scottish Event Campus, Glasgow, UK, July 29–August 2, 2019.

J. Hwang (Oral), "Performance of the OEDO beamline," International Nuclear Physics Conference 2019 (INPC2019), Scottish Event Campus, Glasgow, UK, July 29–August 2, 2019.

N. Kitamura (Oral), "Structure of ^{30}Mg studied by in-beam gamma-ray spectroscopy via neutron knockout reactions," International Nuclear Physics Conference 2019 (INPC2019), Scottish Event Campus, Glasgow, UK, July 29–August 2, 2019.

N. Kitamura (Oral), "High-resolution spectroscopy of $^{95–98}$Kr," 8th SUNFLOWER Workshop / HiCARI Workshop, Osaka University, Osaka, Japan, August 26–28, 2019.

S. Michimasa (Invited), "OEDO status report and development," OEDO collaboration meeting 2019, Nishina, Saitama, Japan, September 2, 2019.

N. Imai (Invited), "Status report of ImPACT17-02-02," OEDO collaboration meeting 2019, Nishina, Saitama, Japan, September 2, 2019.

M. Dozono (Invited), "Status report of ImPACT17-02-01," OEDO collaboration meeting 2019, Nishina, Saitama, Japan, September 2, 2019.

J. Hwang (Invited), "Study of octupole deformation at OEDO," OEDO collaboration meeting 2019, Nishina, Saitama, Japan, September 2, 2019.

N. Imai (Invited), "Proposal of he surrogate reaction of ^{130}Sn(n, γ)," OEDO collaboration meeting 2019, Nishina, Saitama, Japan, September 2, 2019.

S. Shimoura (Invited), "OEDO project—Slowing-down beam line in RIKEN RIBF," XXIII International School on Nuclear Physics and Application (Varna2019), Varna, Bulgaria, September 23–27, 2019.
S. Michimasa (Invited), "Present status of the OEDO-SHARAQ system," Expert Meeting on Next-Generation Fragment Separators 2019, GSI, Germany, September 30–October 2, 2019.

S. Shimoura (Invited), "Slowing-down beam line in RIKEN RIBF—OEDO," 14th Asia-Pacific Physics Conference (APPC2019), Kuching, Malaysia, November 17–22, 2019.

S. Michimasa (Oral), "Experimental study of neutron shell gap in Calcium-54," 14th Asia-Pacific Physics Conference (APPC2019), Kuching, Malaysia, November 17–22, 2019.

S. Ota (Oral), "Research of isoscalar giant monopole resonances using gaseous activetarget," 14th Asia-Pacific Physics Conference (APPC2019), Kuching, Malaysia, November 17–22, 2019.

N. Imai (Invited), "Shape coexistence of atomic nuclei," Frontier Session of KPS meeting, KDJ Center, Gwangju, Korea, December 23–25, 2019.

M. Dozono (Invited), "Nuclear astrophysics studies with OEDO," JSPS/NRF/NSFC A3 Foresight Program "Nuclear Physics in the 21st Century" Joint Kickoff Meeting, Kobe, Hyogo, Japan, December 6–7, 2019.

S. Ota (invited), "K_τ from ISGMR measurements on and around ^{132}Sn," Gordon Research Conference, Nuclear Chemistry, "Exploring simple structure patterns and the dynamics of nuclei," New London, NH, US, June 16–21, 2019.

S. Ota (oral), "Giant resonances in Tin-region nuclei studied using gaseous active target," Vth Topical Workshop on Modern Aspects in Nuclear Structure, Bormio, Italy, February 04–09, 2020.

H. Yamaguchi (invited), "Studying astrophysical reactions and nuclear clusters with low-energy RI beams," 2019 KPS Spring Meeting, Pioneering session: Low energy nuclear science for astrophysics, Daejeon, Korea, April 25, 2019.

H. Yamaguchi (invited), "Experiments on astrophysical reactions with low-energy unstable nuclei beams at CRIB," The 27th International Nuclear Physics Conference (INPC 2019), Glasgow, U.K., July 29–August 2, 2019.

H. Yamaguchi (invited), "Nuclear astrophysics with low-energy RI beams," Nuclear Physics School for Young Scientists (NUSYS-2019), Lanzhou, China, August 12–17, 2019.

H. Shimizu (poster), "Isomeric ^{26}Al beam production with CRIB," NUclear physics School for Young Scientists (NUSYS-2019), Lanzhou, China, August 12–17, 2019.

H. Yamaguchi (oral), "Activities at the low-energy RI beam separator CRIB," RIBF Users Meeting 2019, Wako, Saitama, Japan, September 3–4, 2019.

H. Yamaguchi (invited), "Nuclear astrophysics projects at CNS, the University of Tokyo," International workshop on Origin of Elements and Cosmic Evolution: From Big-Bang to Supernovae and Mergers (OECE), Beijing, China, November 27–29, 2019.

H. Yamaguchi (oral), "Active target for the TTIK method," Workshop on RI-beam Spectroscopy by Innovative Gaseous Active Targets, Osaka, Japan, December 19–20, 2019.

S. Hayakawa (invited), "Experimental study on the ^{7}Be$(n,p)^7$Li and the ^{7}Be$(n,\alpha)^4$He reactions for cosmological lithium problem," The 15th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG15), Kyoto, Japan, July 2–5, 2019.

H. Shimizu (poster), "Study on ^{26m}Al(p,γ) reaction at the SNe temperature," The 15th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG15), Kyoto, Japan, July 2–5, 2019

T. Gunji for the ALICE Collaboration (oral), "Recent results in relativistic heavy-ion collisions with the ALICE experiment at the CERN-LHC," 14th Asia-Pacific Physics Conference (APPC 2019), Kuching, Sarawak, Malaysia, November 17–22, 2019.

D. Sekihata for the ALICE Collaboration (Oral), "Light neutral mesons production at the LHC measured by ALICE," PHOTON 2019 International Conference on the Structure and the Interactions of the Photon, INFN-LNF, Frascati, Italy, 3–7 June 2019.

D. Sekihata for the ALICE Collaboration (Poster), "Study of dielectron production in Pb-Pb collisions at $sqrt(s_{NN})$ = 5.02 TeV with ALICE," Quark Matter 2019 - the XXVIIIth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Wuhan, China, November 3–9, 2019.

Y. Sekiguchi for the ALICE collaboration (Oral), "Measurement of long-range two- and multi-particle correlations by ALICE," the XXVIIIth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Wuhan, China, November 3–9, 2019.

Y. Sakemi(invited), "Fundamental physics with cold radioactive atoms," 14th ASIA-PACIFIC PHYSICS CONFERENCE(APPC14), Kuching, Malaysia, November 20, 2019.

Y. Sakemi(invited), "Fundamental physics with laser cooled atoms," 36th Mazurian Lakes Conference on Physics (Probing fundamental laws of nature with exotic nuclei and atoms), Poland, Piaski, September-2, 2019.

Y. Kotaka (Poster), "Development of the calculation method of injection beam trajectory of RIKEN AVF Cyclotron with 4D emittance measured by the developed pepper-pot emittance monitor," 8th International Beam Instrumentation Conference, Malmö, Sweden, September 8–12, 2019.

N. Shimizu (invited), "Configuration-interaction shell-model calculations for nuclear structure physics," 11th Symposium on Discovery, Fusion, Creation of New Knowledge by Multidisciplinary Computational Sciences, Tsukuba International Congress Center, Tsukuba, Ibaraki, Japan, October 15, 2019.

N. Shimizu (invited), "Level densities of pf-shell nuclei by large-scale shell-model calculations," 7th Workshop on Nuclear Level Density and Gamma Strength, Oslo University, Oslo, Norway, May 28, 2019.

T. Abe (oral), "Alpha-cluster structure of light nuclei from no-core Monte Carlo shell model," RIBF Users Meeting, RIKEN RIBF, Saitama, Japan, September 3, 2019.

T. Abe (oral), "Alpha-cluster structure from an ab-initio point of view," RCNP Workshop on RI-beam Spectroscopy by Innovative Gaseous Active Targets, RCNP, Osaka University, Osaka, Japan, October 20, 2019.

T. Abe (oral), "Intrinsic structure of light nuclei from no-core Monte Carlo shell model," Pioneer Symposia on Various Manifestations of Nuclear Structure, KPS Fall Meeting 2019, Gwangju, Korea, October 20, 2019.

K. Yanase (oral), "CP violation in atomic nuclei and Atomic EDM," International workshop for graduate students and young physicists on nuclear physics, Peking, University, Beijing, China, November 22–25, 2019.

K. Yanase (oral), "Atomic EDM and CP violation in atomic nuclei," Nucleon electric dipole moments and spin structure in 2020, KEK, Tokai, Japan, January 11, 2020.

T. Abe (poster), "Alpha-cluster structure from the ab-initio Monte Carlo shell model," International Symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2020), Ryoutiku Bettei, Oita, Japan, January 23, 2020.

J. Menéndez (invited), "Neutrinoless double-beta decay: novel insights on nuclear matrix elements," International Nuclear Physics Conference (INPC), Glasgow (United Kingdom), July 2019.

J. Menéndez (invited), "Double-beta decay calculations: new tests and opportunities," the INT Program "Nuclear Structure at the Crossroads," Seattle (USA), July 2019

J. Menéndez (invited), "Nuclear physics and double-beta decay," "Massive Neutrinos," the Wilhelm und Else Heraeus-Seminar Bad Honnef (Germany), July 2019.

J. Menéndez (invited), "Relating double-beta decay to nuclear properties at hand," the workshop "Neutrino Nuclear Responses for Double Beta Decays and Astro Neutrinos (NNR19)," Osaka (Japan), May 2019.

J. Menéndez (invited), "Beta decay in the nuclear shell model: capabilities, limitations, uncertainties," ECT*Workshop "Precise beta decay calculations for searches for new physics," Trento (Italy)

Y. Tsunoda (poster), "Shapes of Sm isotopes studied by Monte Carlo shell model calculations," 11th Symposium on Discovery, Fusion, Creation of New Knowledge by Multidisciplinary Computational Sciences, Tsukuba International Congress Center, Tsukuba, Ibaraki, Japan, October 15, 2019.

[Domestic conferences/workshops]

N. Imai (Oral), 「r-process 核の中性子捕獲反応実験について」, 基研研究会 "原子核物理で紡ぐ r-process" 京都, 2019 年 5 月 22 日–24 日.

N. Imai (Oral), 「逆運動学 ^{79}Se(d, p) 反応による中性子捕獲反応断面積の評価」, 日本物理学会秋季大会, 山形大学, 山形, 2019 年 9 月 17 日–20 日.

K. Kawata (Oral), 「入射核破砕反応による ^{52}Fe 周辺核の高スピンアイソマーの生成」, 日本物理学会秋季大会, 山形大学, 山形, 2019 年 9 月 17 日–20 日.

R. Tsunoda (Oral), 「スズ同位体の励起状態と組んだアイソバリックアナログ共鳴状態」, 日本物理学会秋季大会, 山形大学, 山形, 2019 年 9 月 17 日–20 日.

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角田佑介（招待講演), 「モンテカルロ殻模型によるベータ崩壊の研究」, 原子核物理でつむぐ r プロセス, 京都大学基礎物理学研究

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[Seminars]

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森永晴彦先生を偲ぶ会, 記念講演会「２１世紀の物理学—宇宙・生命・サブアトム」, 学士会館, 千代田, 2019 年 6 月 2 日.

Awards

N. Kitamura, CNSSS18 Young scientist award, ANPhA/AAPPS-DNP award for young scientist for the presentation “characterization of a tritium target for two-neutron transfer reaction at TRIUMF.”

Others

[External review]

External evaluation of CNS, Hongo Campus and CNS Building, January 30–31, 2020.

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 for high precision mass measurements of superheavy nuclides, and additional MRTOF-MS setups have been 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

The Wako Nuclear Science Center (WNSC) provides low-energy short-lived radioactive ion beams to users from universities using the KEK isotope separator system (KISS). In FY2019, four experimental programs were carried out at KISS. In terms technical developments at KISS, an in-jet laser spectroscopy setup for high-precision laser spectroscopy and a multi-reflection time-of-flight mass spectrograph (MRTOF-MS) have been installed and tested online and applied to some physics cases. One was the hyperfine structure spectroscopy of ^{194}Os and ^{196}Os isotopes to determine their isotope shifts. Their half-lives (6 years and 35.9 minutes, respectively) are too long to reasonably determine the resonance wavelengths through decay measurement. However, the mass spectrograph allows us to use the ion counting method to identify the resonance by discriminating ions of specific isotope from an isobaric mixture in the time-of-flight spectrum. Another was $\beta - \gamma$ spectroscopy of $^{192\mathrm{m}}$Os, $^{192\mathrm{g},\,192\mathrm{m}}$Re isotopes of nuclear astrophysical interest. In this experiment, the KISS beam was shared between the decay station and the MRTOF-MS. During the decay curve measurement at the decay station, the beam was transferred to the MRTOF-MS to determine the masses and the branching ratios of the isomeric states and the ground states. The same scheme was also used for the $\beta - \gamma$ spectroscopy studies of $^{186\mathrm{g},\,186\mathrm{m},\,187\mathrm{g},\,197}$Ta isotopes.

For the interface between the KISS beams and the MRTOF-MS, a gas cell cooler-buncher (GCCB) plays an essential role. Singly-charged 20 keV ion beams from KISS enter the 30 cm-long gas cell through a 2-mm diameter aperture and are thermalized in 1 mbar He gas. The thermal ions are extracted by an RF-carpet and transported to a triplet RF quadrupole ion trap before injection into the MRTOF-MS. We discovered two important phenomena in the GCCB. One is that singly-charged ions are largely converted to doubly charged ions, which provides a significant gain in the mass resolving power. The other is molecular contaminants in the KISS beams are totally destroyed in the thermalization process. This feature can be a savior for all low-energy RI-beam facilities which have always suffered from these molecular contaminations.

In addition to the KISS MRTOF, two more MRTOF setups are presently operated by WNSC in collaboration with RIKEN SLOWRI team, one each at the GARIS-II and the BigRIPS facilities of RIKEN RIBF. These will be used for comprehensive mass measurements of short-lived nuclides including superheavy elements ($Z > 103$). In FY 2019, the first direct mass measurement of superheavy nuclide (^{257}Db, $Z = 105$) has been performed. This setup will be used for precision mass measurements of neutron-rich moscovium and nihonium isotopes for reliable determination of the atomic numbers as well as the mass numbers. The mass spectrograph at BigRIPS (ZD-MRTOF) is being installed at the end of the BigRIPS+ZeroDegree spectrometer and has already shown a highest mass resolving power of 570,000 with 9 ms flight time for $^{39}K^{+}$ ions in offline studies. First online commissioning experiment was scheduled using parasitic beams of in-beam γ experiments in the end of FY2019, however, it was cancelled due to spread of novel coronavirus disease.

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List of Publications & Presentations

Publications

[Original papers]

T. Niwase, M. Wada, P. Schury, H. Haba, S. Ishizawa, Y. Ito, D. Kaji, S. Kimura, H. Miyatake, K. Morimoto, K. Morita, B. M. Rosenbusch, H. Wollnik, T. Shanley, and Y. Benari, "Development of an "α-TOF" detector for correlated measurement of atomic masses and decay properties," Nucl. Instrum. Methods Phys. Res. A **953**, 163198 (2020).

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[International conferences/workshops]

M. Wada (invited), "Towards precise mass measurements of Nh and Mc isotopes," 4th International Symposium on Superheavy Elements (SHE2019), Hakone, Japan, December 1–5, 2019.

M. Wada (invited), "SHE-Mass-II setup for direct mass measurement of hot-fusion superheavy nuclides," 6th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN2019), Wilhelmshaven, Germany, August 25–31, 2019.

M. Wada (invited), "Antiprotonic atoms with short-lived nuclei," ECT* Antiproton-nucleus interactions and related phenomena, Trento, Italy, June 17–23, 2019.

M. Wada (invited), "Towards comprehensive mass measurements with MRTOF mass spectrographs at RIKEN RIBF," 2019 The Korean Physical Society Spring Meeting, Daejeon, Korea, April 24–26, 2019.

M. Wada (invited), "Symbiotic mass measurement with ZD-MRTOF," High Resolution Gamma-Ray Spectroscopy at the RIBF, Darmstadt, Germany, April 10–12, 2019.

H. Miyatake (invited), "KISS Project," 14th Asia-Pacific Physics Conference, Borneo, Indonesia, November 17–22, 2019.

H. Miyatake (invited), "Recent progress of researches with KISS and MRTOF," China-Japan Collaboration Workshop on "Nuclear mass and life for unraveling mysteries of *r*-process," ITP/CAS, Beijing, China, October 9–13, 2019.

H. Miyatake (invited), "Recent progress of researches with KISS and MRTOF," The 15th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG15), Kyoto, Japan, July 2–5, 2019.

Y. Watanabe (invited), "RI production at low energies "Production of N = 126 nuclei and beyond using multinucleon transfer reactions," JSPS/NRF/NSFC A3 Foresight Program—Nuclear Physics in the 21st Century," Nuclear Structure & Nuclear Reaction Joint Kickoff Meeting, Kobe, Japan, December 6–7, 2019.

Y. Watanabe (invited), "Recent experimental results of KEK Isotope Separation System (KISS)," 1-day workshop at GSI on new approaches to MNT reaction studies, Darmstadt, Germany, October 23, 2019.

Y. Watanabe (invited), "Recent experimental results of KEK Isotope Separation System (KISS)," The 13th International Conference on Stopping and Manipulation of Ions and related topics (SMI-2019), Montreal, Canada, July 16–19, 2019.

Y. Watanabe (invited), "Experimental studies of neutron-rich nuclei around N = 126 at KEK isotope separation system," The IV International Conference on Nuclear Structure and Dynamics (NSD2019), Venice, Italy, May 13–17, 2019.

Y. Watanabe (invited), "Production of N = 126 nuclei and beyond using multinucleon transfer reactions," Physics between lead and uranium: in preparation of new experimental campaigns at ISOLDE, Leuven, Belgium, April 16–18, 2019.

Y. Hirayama (invited), "Study of nuclear structure in the vicinity of nuclear structure in the vicinity of N = 126 at KISS," Vth Topical Workshop on Modern Aspects in Nuclear Structure, Bormio, Italy, February 4–9, 2020.

Y. Hirayama (poster), "Nuclear spectroscopy of r-process nuclei in the vicinity of N = 126 by using KISS," 27th International Nuclear

Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019.

Y. Hirayama (invited), "Nuclear spectroscopy of r-process nuclei in the vicinity of N = 126 at KISS," Physics between lead and uranium: in preparation of new experimental campaigns at ISOLDE, Leuven, Belgium, April 16–18, 2019. Hirayama P. Schury (invited), "Nuclear physics by multi-reflection time-of-flight mass spectroscopy at WNSC," 27th International Nuclear Physics Conference (INPC 2019), Glasgow, UK, July 29–August 2, 2019.

P. Schury (invited), "Present status and future plans for slow and stopped beams in RIKEN," The 13th International Conference on Stopping and Manipulation of Ions and related topics (SMI-2019), Montreal, Canada, July 16–19, 2019.

M. Rosenbusch (oral), "Dynamic ejection-field correction for MRTOF mass spectrometry of SHE using arbitrary mass references from reliable sources," 4th International Symposium on Superheavy Elements (SHE2019), Hakone, Japan, December 1–5, 2019.

T. Niwase (poster), "Development and first results from a novel "α-TOF" detector used with a multi-reflection time-of-flight mass spectrograph," 6th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN2019), Wilhelmshaven, Germany, August 25–31, 2019.

T. Niwase (oral), "Correlation measurement of precision mass and decay properties of nuclei via MRTOF-MS with α-ToF detector," 4th International Symposium on Superheavy Elements (SHE2019), Hakone, Japan, December 1–5, 2019.

[Domestic conferences/workshops]

宮武宇也（口頭発表），「KISS での核分光研究」, 短寿命 RI を用いた核分光と核物性研究 VI, 京都大学複合原子力科学研究所, 大阪府熊取, 2020 年 1 月 16–17 日.

宮武宇也（招待講演），「第 7 周期元素科学: 超重元素の物理と化学」, 日本物理学会 2019 年秋季大会, 山形大学, 山形, 2019 年 9 年 17–25 日.

宮武宇也（招待講演），「第 3 ピークと終焉領域に対する実験的アプローチ」, 原子核でつむぐ r プロセス, 京都大学基礎物理学研究所, 京都, 2019 年 5 月 22–24 日.

渡邉裕（招待講演），「Present status of KISS」, RIKEN, RIBF Users Meeting2019, 理化学研究所, 和光, 2019 年 9 月 3–4 日.

渡邉裕（招待講演），「Nuclear researches relevant to r-process with KISS and MRTOF」, 宇宙における物質進化—原子核・原子・分子—第 1 回シンポジウム, 理化学研究所, 和光, 2019 年 8 月 1–2 日.

平山賀一（口頭発表），「KISS でのガスジェット内レーザー共鳴イオン化核分光」, 日本物理学会 2019 年秋季大会, 山形大学, 山形, 2019 年 9 年 17–25 日.

P. Schury（口頭発表），「Current status and ongoing strategy for MRTOF-MS at WNSC」, SSRI-PNS Collaboration Meeting 2019, 理化学研究所, 和光, 2019 年 9 月 4 日.

庭瀬暁隆（口頭発表），「Correlation measurement mass and decay properties of short-lived α-decay nuclei via MRTOF with α-TOF detector (MRTOF+α-TOF を用いた短寿命 α 崩壊核種の質量-崩壊特性測定)」, 日本物理学会第 75 回年次大会, 名古屋大学, 名古屋, 2020 年 3 年 16–19 日.

庭瀬暁隆（口頭発表），「Correlation measurement of precision mass and decay properties of 207Ra with MRTOF+α-TOF」. 日本放射化学会第 63 回討論会 (2020), いわき産業創造館, いわき, 2019 年 9 月 24–26 日.

庭瀬暁隆（口頭発表），「Correlation measurement of precision mass and decay properties of 207Ra with MRTOF-MS」, 日本物理学会 2019 年秋季大会, 山形大学, 山形, 2019 年 9 年 17–25 日.

Events (April 2019 — March 2020)

RNC

Apr. 20	Wako Open Campus
May. 24	The 25th RBRC Management Steering Committee (MSC)
Jun.24–26	The 5th Nishina Center Advisory Council (NCAC)
Jun. 28	The 18th Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)
Jul. 10	The 8th Industrial Program Advisory Committee (In-PAC)
Jul.31–Aug.9	Nishina School
Dec.16–18	The 20th Program Advisory Committee for Nuclear Physics Experiments at RI Beam Factory (NP-PAC)
Jan.24	The 19th Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)

CNS

Aug. 21–27	18th CNS International Summer School CNSSS19 https://indico2.cns.s.u-tokyo.ac.jp/event/65/

Press Releases (April 2019−March 2020)

RNC

May. 2	^{78}Ni revealed as a doubly magic stronghold against nuclear deformation	R. Taniuchi, P. Doornenbal, H. Sakurai, Radioactive Isotope Physics Laboratory
Jun. 15	Transverse momentum dependent production cross sections of charged pions, kaons and protons produced in inclusive e^+e^- annihilation at $\sqrt{s}$ = 10.58 GeV	R. Seidl, Radiation Laboratory
Jun. 26	Gamma-ray Glow preceding Downward Terrestrial Gamma-ray Flash	Y. Wada, High Energy Astrophysics Laboratory
Jul. 5	Enhancement of element production by incomplete fusion reaction with weakly bound nucleus deuteron	W. He, H. Otsu, Fast RI Data Team, H. Sakurai, Nuclear Transmutation Data Research Group
Aug. 9	Proposal of a 1-ampere-class deuteron single-cell linac for nuclear transmutation	H. Okuno, High-Power Target R&D Team, H. Sakurai, Nuclear Transmutation Data Research Group
Sep. 12	X-ray pumping of the ^{229}Th nuclear clock isomer	H. Haba, RI Application Research Group
Oct. 18	Quasifree neutron knockout from ^{54}Ca corroborates arising $N = 34$ neutron magic number	P. Doornenbal, H. Sakurai, Radioactive Isotope Physics Laboratory
Nov. 19	Location of the neutron dripline at fluorine and neon	D.S. Ahn, N. Fukuda, N. Inabe, BigRIPS Team, T. Kubo, Research Instruments Group
Nov. 26	A method of collecting trace amounts of vermilion from artifacts for source estimation by sulfur isotope (δ^{34}S) analysis: use of sulfur-free adhesive tape to minimize damage to the artifact body during sampling	K. Takahashi, Y. Motizuki, Astro-Glaciology Research Group
Nov. 26	Underlying structure of collective bands and self-organization in quantum systems	T. Otsuka, Nuclear Spectroscopy Laboratory
Nov. 29	Energy of the ^{229}Th nuclear clock isomer determined by absolute γ-ray energy difference	H. Haba, RI Application Research Group
Mar. 5	Possible lightest Ξ hypernucleus with modern ΞN interactions	E. Hiyama, Strangeness Nuclear Physics Laboratory, T. Doi, Quantum Hadron Physics Laboratory
Mar. 13	Swelling of doubly magic ^{48}Ca core in Ca isotopes beyond $N = 28$	M. Tanaka, Nuclear Spectroscopy Laboratory, M. Takechi, M. Fukuda, H. Sakurai, Radioactive Isotope Physics Laboratory
Mar. 17	g-Factor of the ^{99}Zr (7/2$^+$) isomer: monopole evolution in shape coexisting region	Y. Ichikawa, J.-M. Daugas, H. Ueno, Nuclear Spectroscopy Laboratory