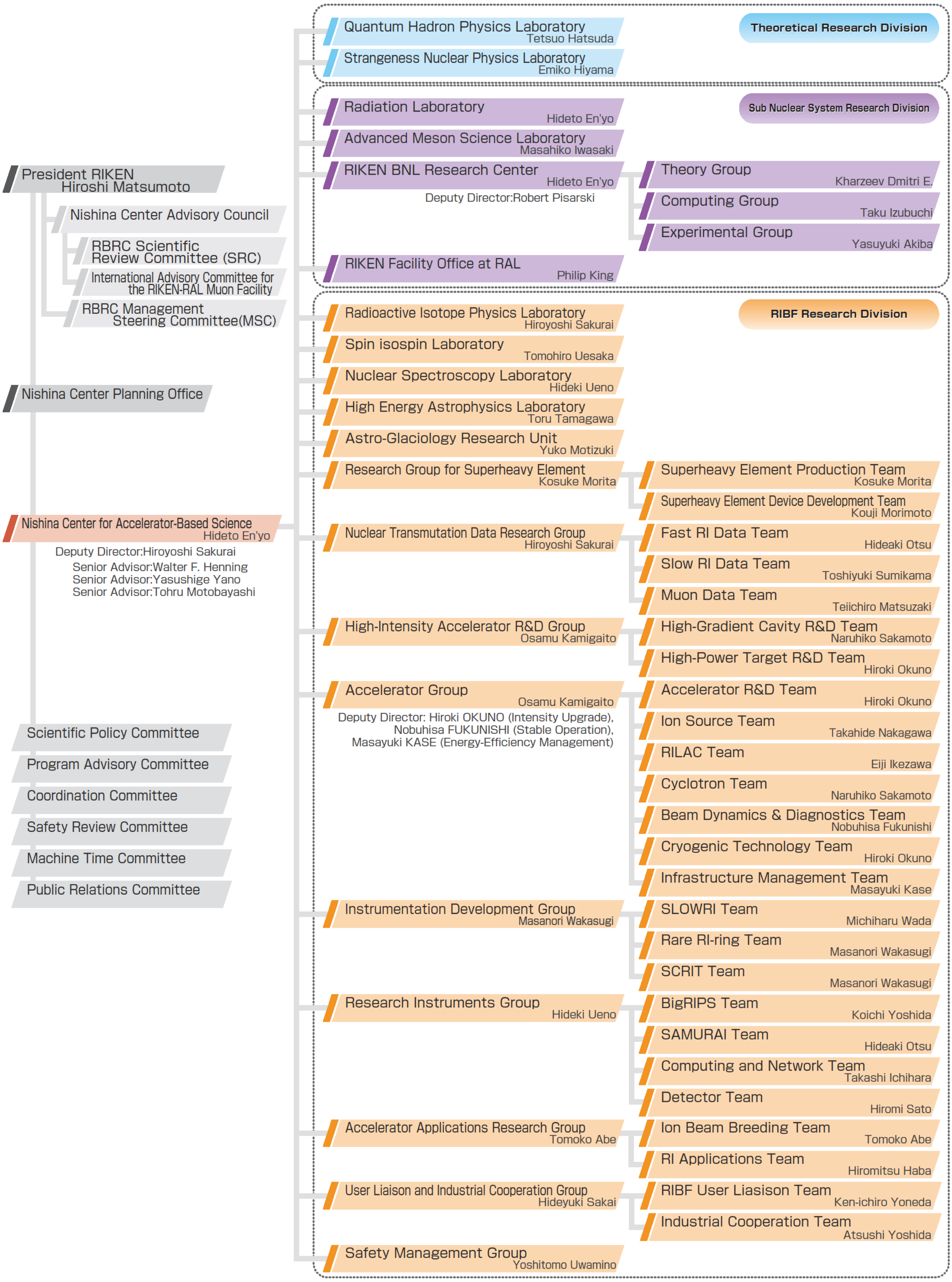
1. Organization

1.1 Organization Chartas of March 31, 2018 (End of FY2017)



1.2 Topics in FY2017

In fiscal year 2017, RNC discovered 73 new isotopes. The total number of new isotopes discovered at the RIBF from 2010 will reach about 194 in the near future.

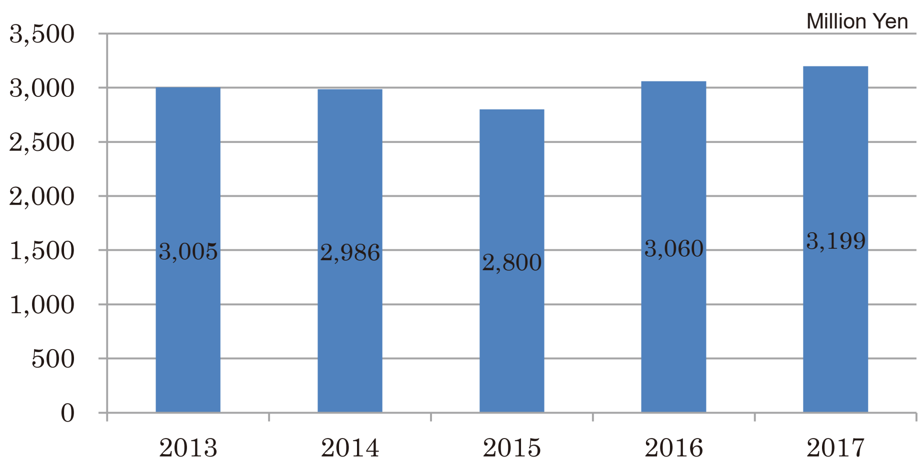
With regard to Superheavy Element Research, RNC succeeded in creating copernicium using GARIS-II which is suitable for hot fusion. It was RNC's first step on the road to search for more new superheavy elements such as element 119.

Having developed new technology to produce a large amount of At-211, RNC has distributed radioisotopes of At-211 to several universities and institutes engaged in radionuclide therapy research.

Year	Date	Topics in Management
2017	Apr. 1	Newly appointed: Director of the RIKEN BNL Research Center: Hideto En'yo
	Aug. 4	Review of the Safety Management Group
	Oct. 30	Review of the Accelerator Applications Research Group
	Nov. 2	Review of the Instrumentation Development Group, the Research Instruments Group and the User Liaison and Industrial Cooperation Group

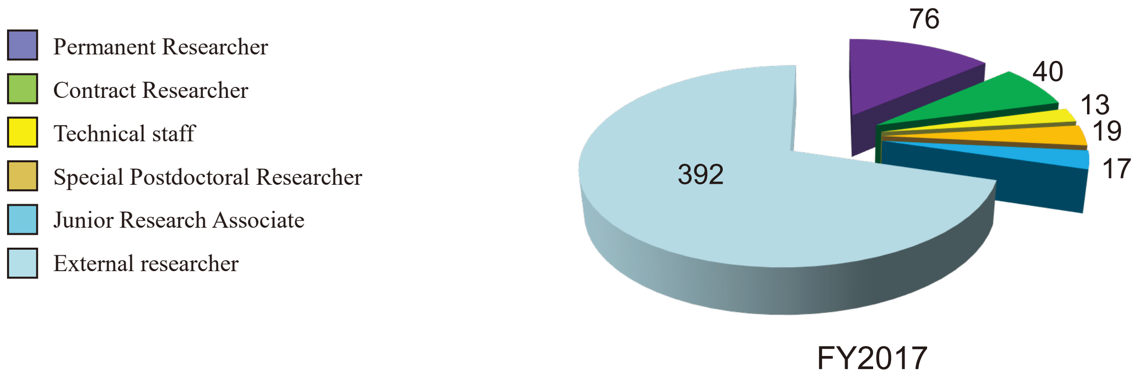
2. Finances

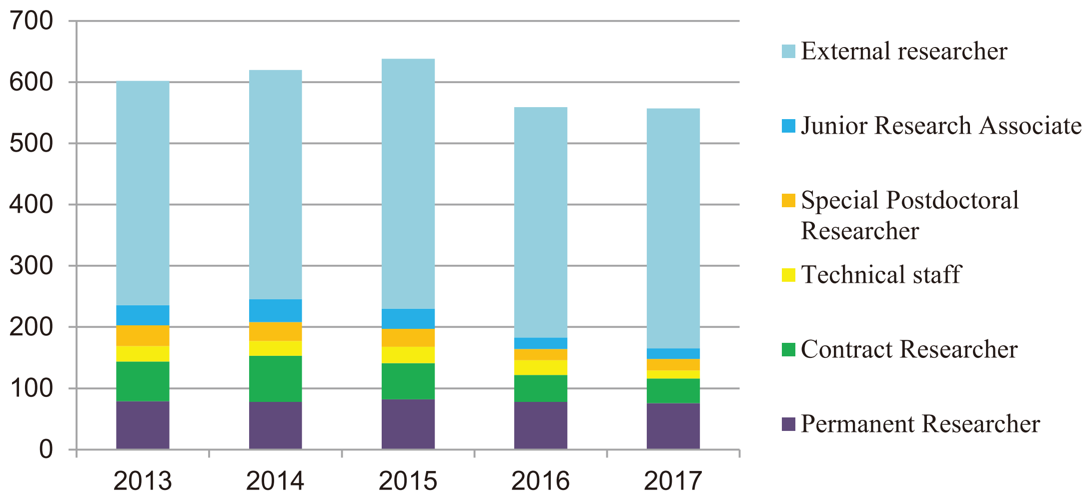
A transition of the RNC budget for the past five years is shown in following graph.



3. Staffing

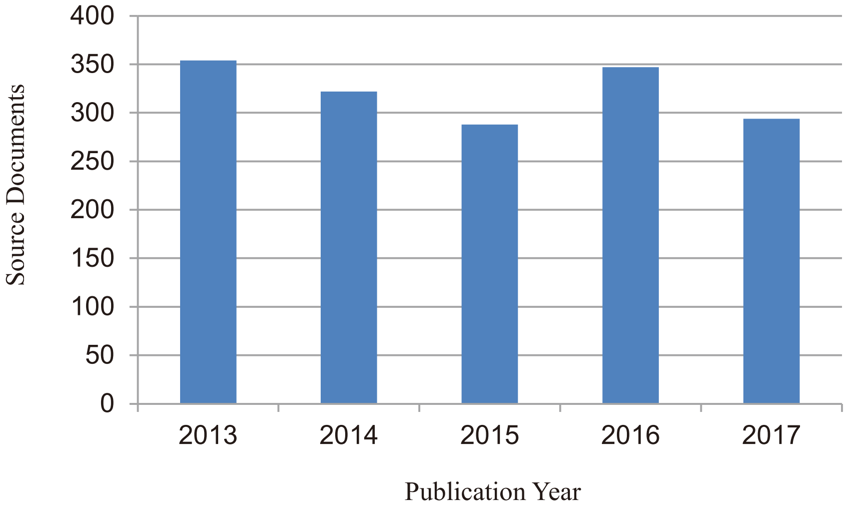
At the start of FY 2017, there were 165 personnel affiliated with RNC and 392 researchers visiting RNC for research purpose. The following graphs show a breakdown of personnel into six categories as of April 1, 2017, and a transition of the number of each category.





4. Research publication

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



Citation analysis for the past five years

As of April, 2018

Indicators \ Year	2013	2014	2015	2016	2017
Total number of papers	354	322	288	347	294
Total number of citations	5250	4503	2866	2329	797
Number of papers in top 10%	58	69	56	51	39
Percentage of papers in top 10%	16.4	21.4	19.4	14.7	13.4
Number of papers in top 1%	7	6	3	3	9
Percentage of papers in top 1%	1.98	1.86	1.04	0.86	3.09

5. Management

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

- 8 Laboratories
- 1 Research unit
- 9 Groups with 25 Teams
- 2 overseas research centers with 3 Groups

as of the latter half of FY2017. There are also three '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 Nishina Center Planning Office under the auspices of President of RIKEN is responsible for administrative matters of RNC. The management of RNC is supported by the following committees:

- Scientific Policy Committee
- Program Advisory 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:

- Scientific Policy Committee
- 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, 2018)

Hideto EN'YO	Director RNC, Chief Scientist, Director of Radiation Laboratory
Hiroyoshi SAKURAI	Deputy Director (RIBF Research), RNC, Chief Scientist, Radioactive Isotope Physics Laboratory, Group Director, Nuclear Transmutation Data Research Group
Walter F. HENNING	Senior Advisor
Yasushige YANO	Senior Advisor
Tohru MOTOBAYASHI	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, 2018)

Hideto EN'YO	Director, RNC, Chief Scientist, Radiation Laboratory
Hiroyoshi SAKURAI	Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory, Group Director, Nuclear Transmutation Data Research Group
Walter F. HENNING	Senior Advisor, RNC
Yasushige YANO	Senior Advisor, RNC
Tohru MOTOBAYASHI	Senior Advisor, RNC
Tetsuo HATSUDA	Chief Scientist, Quantum Hadron Physics Laboratory
Masahiko IWASAKI	Chief Scientist, Advanced Meson Science Laboratory
Tomohiro UESAKA	Chief Scientist, Spin isospin Laboratory
Hideki UENO	Chief Scientist, Nuclear Spectroscopy Laboratory, Group Director, Research Instruments Group
Toru TAMAGAWA	Chief Scientist, High Energy Astrophysics Laboratory
Emiko HIYAMA	Chief Scientist, Strangeness Nuclear Physics Laboratory
Kosuke MORITA	Group Director, Research Group for Superheavy Element, Team Leader, Superheavy Element Production Team
Osamu KAMIGAITO	Group Director, Accelerator Group, Group Director, High-Intensity Accelerator R&D Group
Hideyuki SAKAI	Group Director, User Liaison and Industrial Cooperation Group
Hiroki OKUNO	Deputy Group Director, Accelerator Group, Team Leader, Accelerator R&D Team, Team Leader, Cryogenic Technology Team, Team Leader, High-Power Target R&D Team
Nobuhisa FUKUNISHI	Deputy Group Director, Accelerator Group, Team Leader, Beam Dynamics & Diagnostics Team
Masayuki KASE	Deputy Group Director, Accelerator Group, Team Leader, Infrastructure Management Team
Tomoko ABE	Group Director, Accelerator Applications Research Group, Team Leader, Ion Beam Breeding Team
Yoshitomo UWAMINO	Group Director, Safety Management Group
Masanori WAKASUGI	Group Director, Instrumentation Development Group, Team Leader, Rare RI-ring Team, Team Leader, SCRIT Team
Yuko MOTIZUKI	Research Unit Leader, Astro-Glaciology Research Unit
Eiji IKEZAWA	Team Leader, RILAC Team
Takashi ICHIHARA	Vice Chief Scientist, Radioactive Isotope Physics Laboratory, Team Leader, Computing and Network Team
Hideaki OTSU	Team Leader, SAMURAI Team, Team Leader, Fast RI Data Team
Naruhiko SAKAMOTO	Team Leader, Cyclotron Team, Team Leader, High-Gradient Cavity R&D Team
Hiromi SATO	Team Leader, Detector Team
Toshiyuki SUMIKAMA	Team Leader, Slow RI Data Team
Takahide NAKAGAWA	Team Leader, Ion Source Team
Hiromitsu HABA	Team Leader, RI Applications Team
Teiichiro MATSUZAKI	Team Leader, Muon Data Team
Koji MORIMOTO	Team Leader, Superheavy Element Device Development Team
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Koichi YOSHIDA	Team Leader, BigRIPS Team
Ken-ichiro YONEDA	Team Leader, RIBF User Liaison Team
Michiharu WADA	Team Leader, SLOWRI Team
Yasuyuki AKIBA	Vice Chief Scientist, Radiation Laboratory, Group Leader, Experimental Group, RIKEN BNL Research Center
Katsuhiko ISHIDA	Vice Chief Scientist, Advanced Meson Science Laboratory
Tsukasa TADA	Vice Chief Scientist, Quantum Hadron Physics Laboratory
Kanenobu TANAKA	Deputy Group Director, Safety Management Group
Yasushi WATANABE	Deputy Team Leader, RIBF User Liaison Team
Noriko SHIOMITSU	Director, Nishina Center Planning Office

Nishina Center Planning Office

The Nishina Center Planning Office is responsible for the following issues:

- Planning and coordination of RNC's research program and system
- Planning and management of RNC's use of budget
- Public relations activities

Members (as of March 31, 2018)

Noriko SHIOMITSU	Director, Nishina Center Planning Office
Kazunori MABUCHI	Manager, Nishina Center Planning Office, Administration Manager, RBRC, Administration Manager, RIKEN Facility Office at RAL
Keiko IWANO	Deputy Manager, Nishina Center Planning Office
Hiroshi ITO	Deputy Manager, Nishina Center Planning Office, Deputy Administration Manager, RBRC

Yukari ONISHI	Chief, Nishina Center Planning Office
Kumiko SUGITA	Chief, Nishina Center Planning Office
Yuko OKADA	Task-Specific Employee
Aiko KAWAMURA	Task-Specific Employee
Miyoko NAITO	Task-Specific Employee
Rie KUWANA	Temporary Staff

Scientific Policy Committee

The Scientific Policy Committee deliberates on the following issues:

- Research measures and policies of RNC
- Administration of research facilities under RNC's management

The Committee members are selected among professionals within and outside RNC. The members were not chosen nor the Committee held in FY2017.

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 18th NP-PAC was held on December 7−9, 2017 at RIBF.

Members (as of March 31, 2018)

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

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

The 15th ML-PAC was held on January 11−12, 2018 at RIBF.

Members (as of March 31, 2018)

Adrian HILLIER (Chair)	ISIS, RAL(UK)
Toshiyuki AZUMA	RIKEN
Ryosuke KADONO	Institute of Materials Structure Science(KEK)
Atsushi KAWAMOTO	Hokkaido University
Norimichi KOJIMA	Toyota RIKEN
Kenya KUBO	ICU
Philippe MENDELS	Universite Paris-SUD(France)
Atsushi SHINOHARA	Osaka University
Shukri SULAIMAN	Universiti Sains Malaysia (Malaysia)
Hiroyuki YAMASE	NIMS
Shigeo YOSHIDA	Thera-Projects
Xu-Guang ZHENG	Saga University

Industrial Program Advisory Committee (In-PAC)

The 7th In-PAC was held on January 19, 2018 at RNC.

Members (as of March 31, 2018)

Akihiro IWASE (Chair)	Osaka Prefecture University
Toshiyuki AZUMA	RIKEN
Kenya KUBO	International Christian University
Hitoshi NAKAGAWA	National Agriclture and Food Research Organization.
Nobuhiko NISHIDA	Toyota Physical and Chemical Research Institute
Yasushi AOKI	Sumitomo Heavy Industries, Ltd

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, 2018)

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 Applications Team
Shinichiro MICHIMASA	Assistant Prof., Center for Nuclear Study, University of Tokyo
Hidetoshi YAMAGUCHI	Lecturer, Center for Nuclear Study, University of Tokyo
Yutaka WATANABE	Associate Professor, High Energy Accelerataor Reserch Organization, KEK
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Koichi YOSHIDA	Team Leader, BigRIPS Team
Naoki FUKUDA	Nishina Center Research Scientist, BigRIPS Team
Naruhiko SAKAMOTO	Team Leader, Cyclotron Team
Daisuke SUZUKI	Research Scientist, Radioactive Isotope Physics Laboratory
Juzo ZENIHIRO	Research Scientist, Spin Isospin Laboratory
Yuichi ICHIKAWA	Research Scientist, Nuclear Spectroscopy Laboratory

Ex officio members

Yoshitomo UWAMINO	Group Director, Safety Management Group
Kanenobu TANAKA	Deputy Group Director, Management Group
Hisao SAKAMOTO	Nishina Center Technical Scientist, Safety Management Group

Hot-Lab Safety Review Committee

Members (as of March 31, 2017)

Masako IZUMI (Chair)	Senior Research Scientist, Ion Beam Breeding Team
Yoshitomo UWAMINO	Group Director, Safety Management Group
Hisao SAKAMOTO	Nishina Center Technical Scientist, Safety Management Group
Hiroki MUKAI	Assigned Employee, Safety Management Group
Kanenobu TANAKA	Deputy Group Director, Safety Management Group
Hiromitsu HABA	Team Leader, RI Applications 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 him.

Members (as of March 31, 2018)

Hideyuki SAKAI (Chair)	Group Director, User Liaison and Industrial Cooperation Group
Tomoko ABE	Group Director, Accelerator Applications Research Group
Nobuhisa FUKUNISHI	Deputy Group Director for Stable and Efficient Operation, Accelerator Group
Osamu KAMIGAITO	Group Director, Accelerator Group
Masayuki KASE	Deputy Group Director for Energy -Effciency Management, Accelerator Group
Kouji MORIMOTO	Team Leader, Superheavy Element Research Device Development Team
Hiroki OKUNO	Deputy Group Director for Intensity Upgrade, Accelerator Group

Hiroyoshi SAKURAI	Chief Scientist, Radioactive Isotope Physics Laboratory
Hideki UENO	Chief Scientist, Nuclear Spectroscopy Laboratory, Group Director, Research Instruments Group
Tomohiro UESAKA	Chief Scientist, Spin Isospin Laboratory
Yoshitomo UWAMINO	Group Director, Safety Management Group
Masanori WAKASUGI	Group Director, Instrumentation Development Group
Koichi YOSHIDA	Team Leader, BigRIPS Team
Ken-ichiro YONEDA	Team Leader, RIBF User Liasion Team

External members

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

Observers

Hideto EN'YO	Director, RNC
Susumu SHIMOURA	Director, Center for Nuclear Study, University of Tokyo
Hiroari MIYATAKE	Director, KEK Wako Nuclear Science Center
Hiromitsu HABA	Team Leader, RI Applications Team
Kosuke MORITA	Group Director, Research Group for Superheavy Element
Tohru MOTOBAYASHI	Senior Advisor, RNC
Hideaki OTSU	Team Leader, SAMURAI Team
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Kanenobu TANAKA	Deputy Group Director, Safety Management Group
Tadaaki ISOBE	Senior Reserch Scientist, Radioactive Isotope Physics Laboratory
Kazunori MABUCHI	Manager, Nishina Center Planning 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, 2018)

Noriko SHIOMITSU (Chair)	Director, Nishina Center Planning Office
Hiroyoshi SAKURAI	Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory
Tetsuo HATSUDA	Chief Scientist, Quantum Hadron Physics Laboratory
Tohru MOTOBAYASHI	Senior Advisor
Walter F. HENNING	Senior Advisor
Yasushige YANO	Senior Advisor
Masahiko IWASAKI	Chief Scientist, Advanced Meson Science Laboratory
Tomohiro UESAKA	Chief Scientist, Spin isospin Laboratory
Hideki UENO	Chief Scientist, Nuclear Spectroscopy Laboratory, Group Director, Research Instruments Group
Toru TAMAGAWA	Chief Scientist, High Energy Astrophysics Laboratory
Emiko HIYAMA	Chief Scientist, Strangeness Nuclear Physics Laboratory
Kosuke MORITA	Group Director, Research Group for Superheavy Element
Osamu KAMIGAITO	Group Director, Accelerator Group
Hideyuki SAKAI	Group Director, User Liaison and Industrial Cooperation 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 23rd MSC was held on June 15, 2017.

Members (as of June 15, 2017)

Yoichiro MATSUMOTO	Executive Director, RIKEN
Shoji NAGAMIYA	Science Advisor, RIKEN
Tetsuo HATSUDA	Progrum Director, RIKEN Interdisciplinary Theoretical and Mathematical Sciences Program
Berndt MUELLER	Associate Laboratory Director for Nuclear and Particle Physics, BNL
Satoshi OZAKI	Senior Scientist Emeritus, BNL
David LISSAUER	Deputy Chair, Physics Department, BNL

6. International Collaboration

Country	Partner Institute	Objects	RNC contact person
Austria	Stefan Meyer Institute for Subatomic Physics	Experimental and theoretical hadron physics, especially in exotic hadronic atoms and meson and baryon nuclear bound states	Masahiko IWASAKI, Chief Scientist, Advanced Meson Science Laboratory
China	China Nuclear Physics Society	Creation of the council for China -Japan research collaboration on nuclear physics	Hiroyoshi SAKURAI, Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory
	Peking University	Nuclear Science	Hiroyoshi SAKURAI, Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory
	Institute of Modern Physics, Chinese Academy of Science	Physics of heavy ions	Hiroyoshi SAKURAI, Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory
	School of Nuclear Science and Technology, Lanzhou University	Framework	Yue MA, Senior Research Scientist, Advanced Meson Science Laboratory
	School of Physics, Nanjing University	Framework	Emiko HIYAMA, Chief Scientist, Strangeness Nuclear Physics Laboratory
	Department of Physics, Faculty of Science, The Univ. of Hong Kong	Experimental and educational research collaboration in the area of experimental nuclear physics	Hiroyoshi SAKURAI, Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory
	School of physics, Nankai University	Framework	Emiko HIYAMA, Chief Scientist, Strangeness Nuclear Physics Laboratory
Finland	University of Jyvaskyla	Basic nuclear physics and related instrumentation	Michiharu WADA, Team Leader, SLOWRI Team
France	National Institute of Nuclear Physics and Particle Physics (IN2P3)	Physics of heavy ions	Tohru MOTOBAYASHI, Senior Advisor, RNC
	CNRS, CEA,GANIL, Université Paris Sud, etc.	Creation of an International Associated Laboratory (LIA) French-Japanese International Associated Laboratory for Nuclear Structure Problems	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	CEA-DSM	The use of MINOS device at RIKEN	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	SIMEM Graduate School, Department of Physics, Caen University	Framework	Tohru MOTOBAYASHI, Senior Advisor, RNC
	Centre National de la Rocherche Scientifique（CSRS） Commissariat A L'Energie Atomique Et Aux Energies Alternatives (CEA)	Research Collaboration in EXPAND（Exploration Across the Neutron Dripline） project	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
Germany	Technische Universität München	Nuclear physics, hadron physics, nuclear astrophysics	Emiko HIYAMA, Chief Scientist, Strangeness Nuclear Physics Laboratory
	GSI	Physics of heavey ions and accelerator	Hiroyoshi SAKURAI, Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory
	Department of Physics, Technische Universität Darmstadt	Framework	Emiko HIYAMA, Chief Scientist, Strangeness Nuclear Physics Laboratory
Hungary	The Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI)	Nuclear physics, Atomic Physics	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
Indonesia	ITB, UNPAD, ITS, UGM, UI	Material science using muons at the RIKEN-RAL muon facility	Masahiko IWASAKI, Chief Scientist, Advanced Meson Science Laboratoy
	Universitas Hasanuddin	Agricultural science and related fields involving heavy-ion beam mutagenesis using Indonesian crops	Tomoko ABE, Group Director, Accelerator Applications Research Group
Italy	Applied Physics Division, National Institute for New Technologies, Energy and Environment (ENEA)	Framework	Tohru MOTOBAYASHI, Senior Advisor, RNC
	European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*)	Theoretical physics	Tetsuo HATSUDA, Chief Scientist, Quantum Hadron Physics Laboratory

Country	Partner Institute	Objects	RNC contact person
Korea	Seoul National University	Nishina School	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
	Department of Physics, Kyungpook National University	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	College of Science, Yonsei University	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	Department of Physics, Korea University	Framework	Hideto EN'YO, Chief Scientist, Radiation Laboratory
	College of Natural Science, Ewha Women's University	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	College of Natural Sciences, INHA Univ.	Framework	Emiko HIYAMA, Chief Scientist, Strangeness Nuclear Physics Laboratory
Malaysia	Universiti Sains Malaysia	Muon Science	Isao WATANABE, Senior Research Scientist, Advanced Meson Science Laboratoy
Poland	the Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences(IFPAN)	Framework	Hiroyoshi SAKURAI, Deputy Director, RNC, Chief Scientist, Radioactive Isotope Pfysicis Laboratory
Romania	"Horia Hulubei" National Institute of Physics and Nuclear Engineering Bucharest-Magurele, Romania	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
Russia	Joint Institute for Nuclear Research (JINR)	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	Russian Research Center "Kurchatov Institute"	Framework	Hiroyoshi SAKURAI, Tomohiro UESAKA, Osamu KAMIGAITO, Masanori WAKASUGI
Switzerland	Paul Scherrer Institute	Improve the performance and reliability of accelerator systems	Osamu KAMIGAITO, Director, Accelerator Group
	CERN	RD-51 R&D programme for micro-pattern gas detectors (MPGD)	Hideto EN'YO, Chief Scientist, Radiation Laboratory
	CERN	Collaboration in the ALICE Experiment as an Associate Member	Hideto EN'YO, Chief Scientist, Radiation Laboratory
UK	The Science and Technology Facilities Council	Muon science using the ISIS Facility at the Rutherford Appleton Laboratory	Philip KING, Director of RIKEN-RAL muon facility
	University of Surrey	Theoretical physics	Tetsuo HATSUDA, Chief Scientist, Quantum Hadron Physics Laboratory
USA	BNL	The Spin Physics Program at the Relativistic Heavy Ion Collider (RHIC)	Hideto EN'YO, Chief Scientist, Radiation Laboratory
	Columbia University	The development of QCDCQ	Taku IZUBUCHI, Group Leader, Computing Group, RBRC
	Michigan State University	Comprehensive The use of TPC (Time Projection Chamber)	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory Hiroyoshi SAKURAI, Deputy Director, RNC Chief Scientist, Radioactive Isotope Physics Laboratory, Tadaaki ISOBE, Senior Research Scientist, Radioactive Isotope Physics Laboratory
Vietnam	Vietnam Atomic Energy Commission	Framework	Tohru MOTOBAYASHI, Senior Advisor, RNC
	Institute of Physics, Vietnam Academy of Science and Technology	Framework	Hiroyoshi SAKURAI, Deputy Director, RNC, Chief Scientist, Radioactive Isotope Physics Laboratory
Europe	European Nuclear Science and Application Research2	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory

7. Awards

Awardee, Laboratory / Team	Award	Organization	Date
The Research Group for Superheavy Element	HAPPY NEWS 2016	The Japan Newspaper Publishers & Editors Association	Apr. 8
The Element 113 Research Group	The 2017 48th Seiun Awards Non-Section category	The Japan Science Fiction Convention	Aug. 26
Yusuke KAZAMA, Contract Researcher at the Ion Breeding Team	BSJ Encouragement Prize	The Botanical Society of Japan(BSJ)	Sep. 9
Naoki KIMURA, Student Trainee at the SLOWRI Team	The Young Scientist Award	The Atomic Collision Society of Japan	Oct. 11
Rachid NOUICER, Visiting Scientist at the Experiment Group of the RIKEN BNL Research Center	APS Fellow	The Atomic Collision Society of Japan	Oct. 12
Kosuke MORITA, Group Director of the Research Group for Superheavy Element	The 76th Western Japan Culture Award	Nishi Nihon Shimbunsha	Nov. 13
Taiki TANAKA, Junior Research Associate at the Superheavy Element Production Team, the members of the Research Group for Superheavy Element	Papers of Editors' Choice	The Physical Society of Japan	Dec. 14
Hiroshi SUZUKI, Visiting Scientist at Quantum Hadron Physics Laboratory	The 2017 Yukawa-Kimura Prize	Yukawa Institute for Theoretical Physics, Kyoto University	Nov. 16
Hiromitsu HABA, Team Leader at the RI Applications Team	The BRAVE Prize and the Cosmo Bio Awar	Cosmo Bio	Mar. 5
Yukari MATSUO, Senior Visiting Scientist at Nuclear Spectroscopy Laboratory	The 8th Promotion and Nurturing of Female Researchers Contribution Award (Kodate Kashiko Award)	The Japan Society of Applied Physics (JSAP)	Mar. 17
Naoki KIMURA, Student Trainee at the SLOWRI Team	The 6th Student Presentation Award	The Physical Society of Japan	Mar. 23
Sohtaro KANDA, Special Postdoctoral Researcher at the Advanced Meson Science Laboratory	The 4th Student Encouragement Award for FY2017	The Society of Muon and Meson Science of Japan	Mar. 23
Sohtaro KANDA, Special Postdoctoral Researcher at the Advanced Meson Science Laboratory	The 12th (2018) Young Scientist Award	The Physical Society of Japan	Mar. 23
Hajime TOGASHI, Special Postdoctoral Researcher at the Strangeness Nuclear Physics Laboratory	The 12th (2018) Young Scientist Award	The Physical Society of Japan	Mar. 23
Gaku MITSUKA, RBRC Researcher at the Experiment Group of the RIKEN BNL Research Center	The 12th (2018) Young Scientist Award	The Physical Society of Japan	Mar. 23

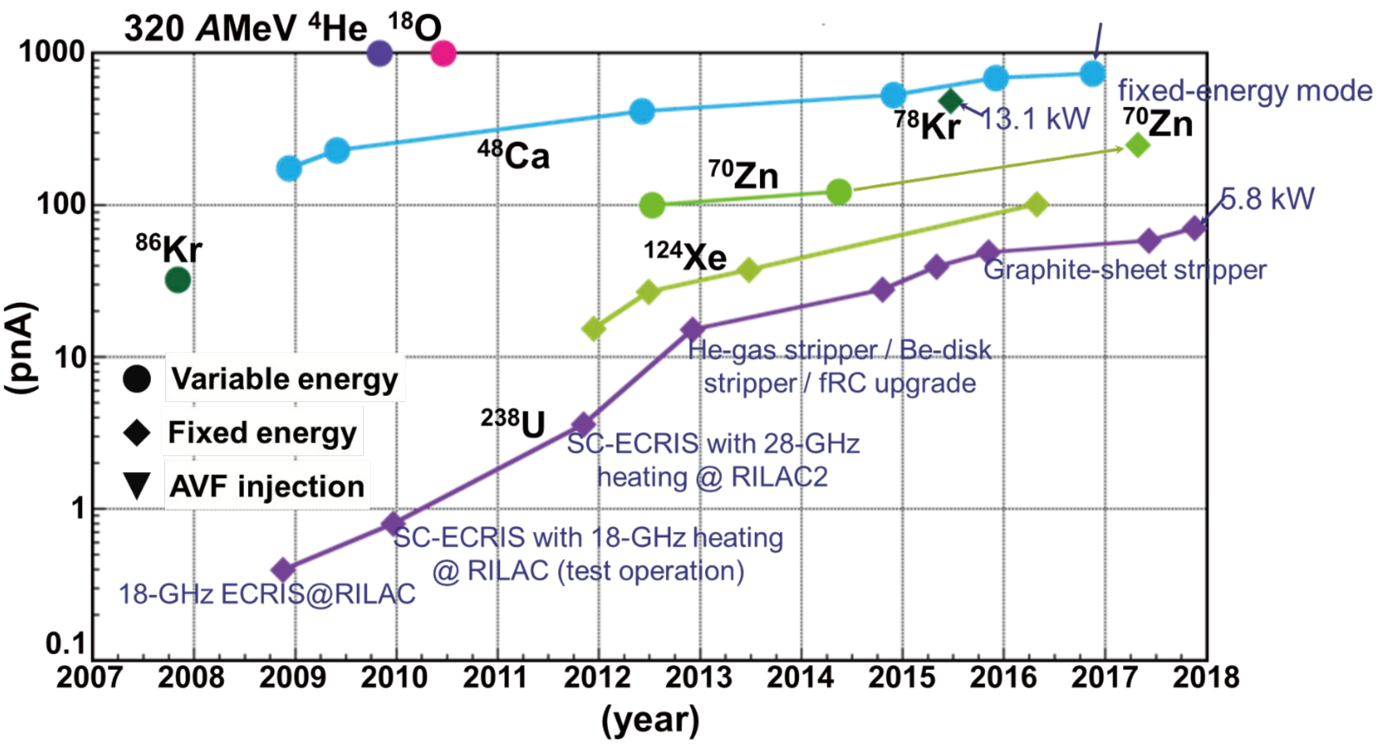
8. Brief overview of the RI Beam Factory

Intensity of Primary Beams

Achieved beam intensities (as of March 2018)

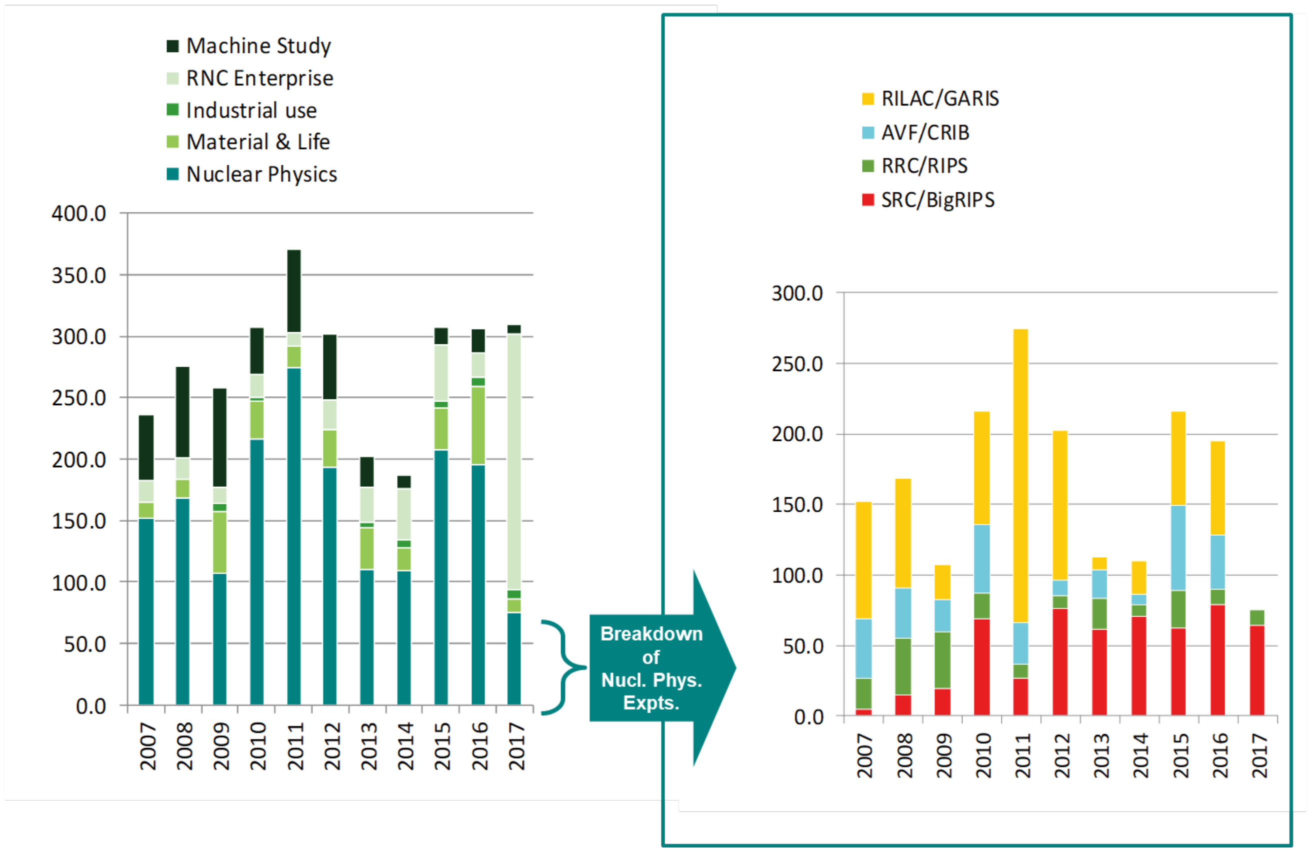
^{238}U	70 pnA (345 MeV/nucleon, Nov. 2017)
^{124}Xe	102 pnA (345 MeV/nucleon, Apr. 2016)
^{86}Kr	30 pnA (345 MeV/nucleon, Nov. 2007)
^{78}Kr	486 pnA (345 MeV/nucleon, May. 2015)
^{70}Zn	250 pnA (345 MeV/nucleon, May 2017)
^{48}Ca	730 pnA (345 MeV/nucleon, Nov. 2016)
^{18}O	1000 pnA (345 MeV/nucleon,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

History of Beam Intensity Upgrade

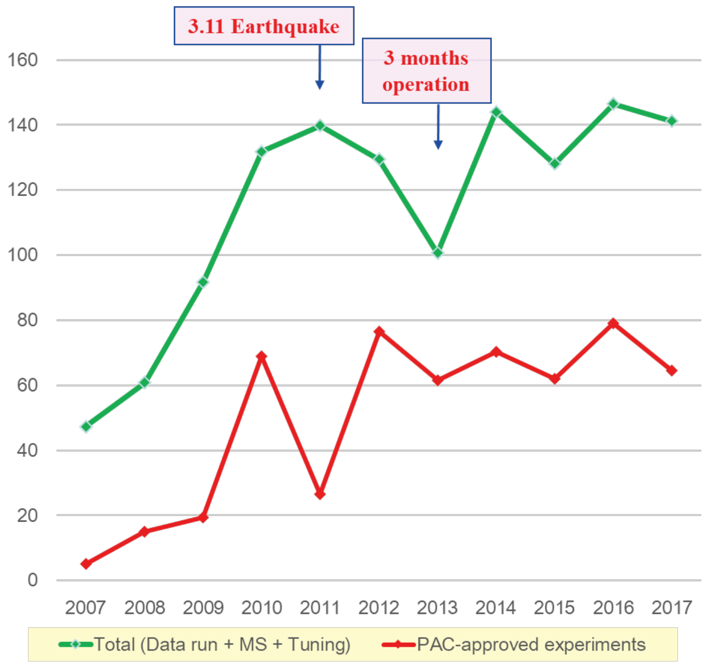


Beam energies are 345 AMeV if it is not explicitly written.

Total beam time for experiments



Total beam time allocated to BigRIPS experiments



Theoretical 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) 10th order QED calculation and the lepton anomalous magnetic moments

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

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

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

(1-3) Functional renormalization group

- BEC-BCS crossover in cold fermionic atoms

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

- Tricritical point of the superconducting transition

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

- Chiral dynamics under strong magnetic field

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

(1-4) Emergent spacetime

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

(2) Theory of spontaneous symmetry breaking

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

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

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

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

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

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

(3) Lattice gauge theory

(3-1) Hadron interactions from lattice QCD

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

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

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

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

(4) QCD under extreme conditions

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

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

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

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

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

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

(5) Nuclear and atomic many-body problems

(5-1) Giant dipole resonance in hot nuclei

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

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

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

(5-3) Efimov Physics in cold atoms

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

(5-4) Supersymmetric Bose-Fermi mixtures

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

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1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

(1) Recently, at RIBF, they observed tetra neutron system to be bound or resonant state. Theoretically, it is requested to study this system theoretically. We performed four-body calculation using NN realistic force and a phenomenological three-body force. We found that we need unrealistically strong three-body force to describe 4n system.
(2) We investigate the effects of the odd-state part of bare ΛΛ interactions on the structure of neutron stars by constructing equations of state (EOSs) for uniform nuclear matter containing Λ and Σ^- hyperons with use of the cluster variational method. The EOS obtained for NS matter becomes stiffer as the odd-state ΛΛ interaction becomes more repulsive, and correspondingly the maximum mass of NSs increases.
(3) We calculate the universal spectrum of trimer and tetramer states in heteronuclear mixture of ultracold atoms with different masses in the vicinity of the heavy-light dimer threshold. We find that trimer and tetramer cross into the heavy-light dimer threshold at the same point and that as the mass ratio M/m decreases, the distance between the thresholds for trimer and tetramer states become smaller.

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List of Publications & Presentations

Publications

[Journal]

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E. Hiyama, "Gaussian Expansion Method and its application to resonant states hadron ohysics," Multiparticle resonances in hadrons, nuclei and ultracold gases, Hirschegg, Austria, January, 2018.

E. Hiyama, "Five-body calculation of heavy pentaquark system," French-Japanese workshop on Hadrons and Nuclear Physics met ultracold atoms, Paris, France, January, 2018.

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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) carries our core team at BNL for those exciting researches using the PHENIX detector. We have observed that the proton spin carried by gluons is finite and indeed sizable. We also identified W bosons in the electron/positron decay channel and in the muon decay channel, with which we are about to conclude how much anti-quarks carry the proton spin. Other than the activities at RHIC we are preparing and starting new experiments at J-PARC and Fermilab to study the nature of hadron. We are also performing technical developments such as novel ion sources, fine-pitch silicon pixel detectors and high-performance trigger electronics.

2. Major Research Subjects

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

3. Summary of Research Activity

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

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

The previously published central neutral pion double spin asymmetries at the highest collision energies at RHIC of 510 GeV have been augmented with the release of charged pion double spin asymmetries in 2017 by PHENIX. 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. The precision of the charged pion asymmetries is slightly limited due to the trigger capabilities in PHENIX but the results are consistent with a dominant, positive gluon contribution to the nucleon spin. With the valence quark spin contribution already reasonably well known, the contributions from sea quarks and orbital angular momenta remain to be understood. PHENIX has collected data to access the sea quark polarizations via leptonic decays of W bosons. Preliminary results have been obtained using all the data taken so far. The central rapidity electron decay channel results have been published while the forward muon decay channel results have been finalized and are submitted for publication.

While orbital angular momentum cannot be directly accessed at RHIC, several transverse spin phenomena have been observed which relate to orbital angular momentum and the three-dimensional structure of the nucleon. These phenomena by themselves have become a major field of research as the dynamics of the strong interaction. During the 2015 RHIC operation, collisions of transversely polarized protons with Au and Al nuclei were provided for the first time. Two rather surprising results have been discovered here. First, the single transverse spin asymmetries for J/ψ particles which are found to be consistent with zero to even higher precisions, show distinctly nonzero asymmetries in proton-Au collisions at the lowest transverse momenta both if detected at slightly forward or backward regions with respect to the polarized beam. The mechanism for such a behavior is not known and the publication will initiate substantial theoretical discussions to resolve this. 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.

In June of 2017, we installed an electro-magnetic calorimeter in the most forward area of the STAR experiment and took polarized proton collision data for neutral particle production (neutron, photon, neutral pion). The cross section measurement will give us new inputs to develop high-energy particle-collision models which are essential to understand air-shower from ultra-high energy cosmic rays. The asymmetry measurement will enable us to understand the hadron collision mechanism based on QCD. 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 2018 to study the sea-quark orbit effect of the polarized proton in the target. For many jet related measurements fragmentation functions are necessary to gain spin and or flavor sensitivity. Those are currently extracted by some of us using the Belle data. In addition to using the fragmentation results with RHIC measurements, they will also provide the basis of several of the key measurements to be performed at the electron-ion collider.

(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 350MeV, far above the expected transition temperature T_c~170MeV, 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. Analysis of heavy quark using the silicon vertex detector is ongoing. The final 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 $p_T > 4$ GeV/*c*, but the suppression factor is smaller than that of charm decay electrons for $3 < p_T < 4$ GeV/*c*. This is the first observation of bottom electron suppression in heavy ion collisions, and the first result that shows the bottom and charm suppression is different. PHENIX recorded approximately 10 times more data of Au+Au collisions in the 2014 run than the 2011 run. We report preliminary results of about 1/4 of the 2014 data in QM2017 conference, confirming the published results with 3 times of statistics. 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.

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. Analysis of heavy quark using the silicon vertex detector is ongoing. The final results of the 2011 run was published in Physical Review C (PRC93, 034904 (2016). This is the first publication from VTX. The result showed that the electrons from bottom quark decay is suppressed for $p_T > 4$ GeV/*c*, but the suppression factor is smaller than that of charm decay electrons for $3 < p_T < 4$ GeV/*c*. This is the first observation of bottom electron suppression in heavy ion collisions, and the first result that shows the bottom and charm suppression is different. PHENIX recorded approximately 10 times more data of Au+Au collisions than the 2011 run in each of the 2014 and 2016 run. PHENIX recorded high statistics $p+p$ and $p+$A data in 2015.

PHENIX concluded its data taking in the 2016 run. We are now working on the data analysis of the high statistics data recorded in 2014 to 2016 runs.

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 disk for data repository (old node: quad-core CPU, 1TB disk, new node: six-core CPU, 2TB 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.

0.9 PB of data for the PHENIX experiment is stored in a hierarchical storage system which is a part of HOKUSAI GreatWave supercomputer system operated by the Advanced Center for Computing and Communication (ACCC). ACCC also provides 10 dedicated PC nodes for CCJ.

(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). We have joined the CERN-RD51 collaboration to acquire the read out technology for GEM. To improve electron-identification performance, lead-glass calorimeters (LG) are used in combination with HBD. The development phase of those detectors is over and we are in the production phase. The parts for six modules of GTR and two modules of HBD are delivered and their assembly processes have started. Read-out electronics and trigger logic modules were also developed and necessary parts are almost delivered. Amongst all the electronics, only the HBD trigger ASIC is still under development. Development of firmware on the trigger logic modules is also on-going.

Due to the budgetary limitation, we aim to install a part of detectors at the beginning of experiment, eight modules of GTR/HBD/LG out of 26 modules in the full installation. The yield of phi mesons and sensitivity to the possible spectral modification with the eight-module configuration under the expected high-rate environment was evaluated by the Geant4 simulation taking into account the expected performance of the detectors and by using a newly-developed GEM-signal simulator. Based on this study, J-PARC PAC gave us a stage-2 approval on Jul. 2017, to the commissioning run (Run 0), which will be performed when the beam line is completed. Although with a significant delay from originally planned March 2016, the construction of the beam line by KEK will be completed in 2019 in order to realize experiments with the stage-2 approval. We are preparing the spectrometer toward the Run 0, which is scheduled on Oct. 2019.

(4) Detector development for PHENIX experiment

The PHENIX experiment proposes substantial detector upgrades to go along the expected accelerator improvements, including the future electron-ion collider “eRHIC”. The present PHENIX detector is repurposed to the sPHENIX (super PHENIX) detector replacing the present magnet with the Babar solenoid magnet at SLAC, and will be covered by the hadronic calorimeter which was absent in present RHIC experiment. The sPHENIX project is now funded by DOE, and RIKEN will participate in the construction of the inner silicon tracker (INTT). The R&D of the INTT has been in progress since 2015 and the 2nd generation prototype successfully demonstrated a designed performance as a result of the beam test executed at Fermilab in March 2018.

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

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[Journal]

(Original Papers) *Subject to Peer Review

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Sub Nuclear System Research Division
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1. Abstract

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

Kaon is the second lightest meson, which has strange quark as a constituent quark. It is expected that if one embed 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 lately attracts strong interest. 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. We have also started next generation kaon experiments (E15 and E31) at J-PARC. In these experiments, we are aiming to determine the $\bar{K}N$ interaction precisely, clarify the nature of kaon in nuclei, and $\Lambda(1405)$ that could be K^-p bound state. At Spring-8 and at GSI, we are also aiming to study omega and eta' nuclei. By these experiments, we aim to be a world-leading scientific research group using these light meta-stable particles.

(1-A) Deeply bound kaonic nuclei

We have performed experimental exploration of theoretically predicted deeply bound kaonic nuclear states, such as the K^-pp bound state. One of the most interesting features of the kaonic nucleus is the strong attraction of the $\bar{K}NN$ interaction. Because of this strong attraction, the kaon in nucleus will attract surrounding nucleons resulting in extremely high-density object, which is several times larger than normal nuclear density. Measurement of the kaon properties at such high energy density will provide precious information on the origin of hadron masses and the chiral symmetry breaking and its partial restoration.

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

The first physics data-taking was carried out in March and May, 2013 with 6×10^9 kaons on ^{3}He target, corresponding to a ~1% of the approved proposal. We successfully obtained semi-inclusive ^{3}He(K^-, n)X missing-mass spectrum, and found a tail structure just below the mass threshold of ($K^- + p + p$) which cannot be explained by well-known processes and backgrounds. We also demonstrated an exclusive analysis by reconstructing ^{3}He(K^-, Λp)n events. To derive more information on the $\bar{K}NN$ interaction by the exclusive measurement, we carried out the second physics data-taking in November-December, 2015 with 43×10^9 kaons on ^{3}He target, in which 7 times more data was accumulated. We have been analyzing the new data set focusing on the ^{3}He(K^-, Λp)n channel, and a significant bump structure below the ($K^- + p + p$) mass threshold has been observed in the Λp invariant-mass spectrum. In addition, we have successfully observed $\Lambda(1405)pn$ final state in $K^- + {}^3$He reactions by reconstructing $\pi^{\pm}\Sigma^{\mp}pn$ events, which is of special importance to understand the production mechanism of the <K^-pp> state via theoretically predicted $\Lambda(1405)p \rightarrow K^-pp$ doorway process. To confirm whether or not the observed structure is the K^-pp bound state, further analysis is currently in progress.

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

Simultaneously with the above experiment (1-A), we have performed an X-ray spectroscopy of atomic $3d \rightarrow 2p$ transition of negatively charged K-mesons captured by helium atoms. However, the energy resolution of the conventional semiconductor spectrometers is insufficient to see the K^--nucleus potential observed by atomic levels at zero energy. This is closely related to the problem on the existence of deeply bound kaonic states in nuclei, well below the atomic levels, and this is one of the biggest problems in strangeness nuclear physics. Aiming to provide a breakthrough from atomic level observation, we will perform high-resolution X-ray spectroscopy of kaonic atoms at a J-PARC hadron beam line using a novel cryogenic X-ray spectrometer: an array of superconducting transition-edge-sensor (TES) micro-calorimeters.

The spectrometer offers unprecedented energy resolution, which is about two orders of magnitude better than that of conventional semiconductor detectors. A spectrometer array of 240 pixels will have an effective area of about 20 mm^2. In 2014, we have performed a proof-of-principle experiment by measuring pionic-atom X rays with a TES array at the πM1 beam line at the Paul Scherrer Institut (PSI), and successfully demonstrated the feasibility of TES-based exotic-atom x-ray spectroscopy in a hadron-beam environment. Based on the results, the kaonic-atom experiment at J-PARC was proposed in 2015 and will be conducted as the physics run in June 2018.

Another important X-ray measurement of kaonic atom would be $2p \rightarrow 1s$ transition of kaonic deuteron. We have measured same transition of kaonic hydrogen, but the width and shift from electro-magnetic (EM) value reflect only isospin average of the $\bar{K}NN$ interaction. We can resolve isospin dependence of the strong interaction by the measurement. We are presently preparing a proposal to J-PARC PAC to measure kaonic deuteron X-ray.

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

We have been working on precision spectroscopy of pionic atoms systematically, that leads to understanding of hidden non-trivial structure of the vacuum and origin of hadron masses. The precision data set stringent constraints on the chiral condensate at nuclear medium. We are presently preparing for the systematic high precision measurement of pionic tin isotopes at RIBF. A pilot experiment was performed in 2010, and showed a very good performance of the system. A main experiment was performed in 2014 and we achieved unprecedented resolution with much reduced systematic errors. A new experiment is being prepared with an improved setup.

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). First experiment was conducted in 2014 in GSI. We accumulated very high quality data in terms of the spectral resolution and the statistics and set constraints in the η'-nucleus interaction. A next generation experiment aims at improving the signal-to-background ratio and is in preparation.

(1-D) Hadron physics at SPring-8/LEPS2

Photo production of meson in nuclei is known to be a powerful tool to investigate property of the hadron in nuclear media. For this study, we started a new experimental project named LEPS2 (Laser Electron Photon at SPring-8 II) in this RIKEN Mid-term. The experimental hutch for LEPS2 at SPring-8 was constructed in March 2011, lead by RIKEN. The Large solenoid spectrometer magnet (2.96 m inner diameter × 2.22 m length) was successfully transported from BNL (US) to SPring-8 and installed into LEPS2 hutch in 2011.

One of the first physics programs is photo-production of η' in nuclei. Especially (γ, p) is most important reaction channel, where we can perform missing mass spectroscopy by detecting forward going proton. One of the big advantages of photo-production reaction is that the initial reaction is expected to be much cleaner than the hadron channel.

Detector construction for the first physics program is in progress. The 4π Electro-Magnetic calorimeter has been constructed and proton counter to detect forward going proton produced via (γ, p) reaction was partially installed in November 2013. Engineering run for the first experiment was performed in December 2013 to confirm performance of our detector system. Detector construction have been completed and 1st physics data taking was starting since 2014. Based on data collected, detail analysis to extract signal of η'-mesic nucleus, photoproduction of η etc are in progress.

(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-A) Condensed matter/materials studies with μSR

Two μSR spectrometer named CHRONUS and ARGUS are working together with ISIS standard data acquisition system, DAEII, with the front-end control system, SECI. Running a pulse-kicker system, we can perform two independent μSR experiments on CHRONUS and ARGUS at the same time, splitting double-pulse to share beam between the two.

Among our scientific activities on μSR studies from year 2017 to 2018, following five subjects of material sciences are most important achievements at the RIKEN-RAL muon facility:

1) Novel superconducting state having partial nodal gaps in the two-dimensional organic superconductor λ-[BETS]$_2$GaCl$_4$.
2) Tiny magnetic moments and spin structures of Ir^{4+}, Nd^{3+} in carrier doped pyrochlore iridates $(Y_{1-x}Ca_x)_2Ir_2O_7$.
3) Magnetism and spin dynamics in superoxides CsO_2, NaO_2 and RbO_2.
4) Magnetic properties of the nano-cluster gold in the border of macro- and micro-scale
5) Effects of the spatial distributions of magnetic moments and muon positions estimated from density functional theory (DFT) and dipole-field calculations.

(2-B) 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-slow muon"), then the capability of μSR study will be drastically improved. The ultra-slow muon beam can stop in thin foil, multi-layered materials and artificial lattices, so one can apply the μSR techniques to surface and interface science. The development of ultra-slow muon beam is also very important as the source of ultra-cold (pencil-like small emittance) muon beam for muon $g-2$ measurement. Therefore, we have been working on R&D study.

We have been working on the "ultra-slow muon" generation by laser ionization of muonium atoms in vacuum (bound system of μ^+ and electron) emitted after stopping "surface muon beam" in a material. In this mid-term, we are developing two key components, namely, high efficiency muonium generator at room temperature and high intensity ionization laser. The study of muonium generator has been done in collaboration with TRIUMF and KEK. 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. In 2017, we further studied in detail which surface structure most contributes to the high yield. We also developed a high power Lyman-α laser based on novel laser crystal Nd:YGAG in collaboration with laser group at RIKEN. We are working on the growth of large laser amplifying crystal to further increase the Lyman-α power. In order to fully apply these new developments to slow muon generation, we installed a new ultra-slow muon source chamber dedicated for silica aerogel in Port-3 with new features such as spin manipulation. We also plan measurement of the muonium emission rate by using μSR method, which should have sensitivity even to the muonium staying very close to the surface where the ionizing laser will be shot.

Concerning the muonic atom, we are planning a new precise measurement of proton radius. A large discrepancy was found recently in the proton charge radius between the new precise value from muonic hydrogen atom at PSI and those from normal hydrogen spectroscopy and e-p scattering. We propose a precise measurement of Zemach radius (with charge and magnetic distributions combined) using the laser spectroscopy of hyperfine splitting energy in the muonic hydrogen atom**.** Preparation of the hydrogen target, mid-infrared laser and muon spin polarization detectors is in progress. This year, we started a measurement of the lifetime of the μp triplet state, for which there has been no measured value but only theoretical calculations. Keeping the triplet state is essential for the measurement of polarization caused by resonant laser excitation.

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List of Publications & Presentations

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Sub Nuclear System Research Division
RIKEN BNL Research Center

1. Abstract

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

2. Major Research Subjects

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

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

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

3. Summary of Research Activity

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

Members

Director
Hideto En'yo (concurrent: Director, Nishina Center for Accelerator-Based Science)

Deputy Director
Robert PISARSKI

Administrative Staff
Kazunori Mabuchi (Administration Manager, Nishina Center Planning Office)
Yasutaka AKAI (Deputy Administration Manager, Nishina Center Planning Office)
Hiroshi ITO (Deputy Administration Manager, Nishina Center Planning Office)
Colleen MICHAEL (Administrative Assistant)
Pamela ESPOSITO (Administrative Assistant)
Maureen McNeill-Shea (Administrative Assistant)

Sub Nuclear System Research Division
RIKEN BNL Research Center
Theory Group

1. Abstract

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

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

2. Major Research Subjects

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

3. Summary of Research Activity

(1) Phase diagram of QCD

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

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

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

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

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

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

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

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

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

(3) Chiral Matter

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

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

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

Members

Group Leader (Lab. Head)
Dmitri KHARZEEV

Deputy Group Leader
Robert PISARSKI

RBRC Researchers
Ho-Ung YEE (RHIC Physics Fellow)
Yuya TANIZAKI (Special Postdoctoral Researcher)
Hiromichi NISHIMURA (Special Postdoctoral Researcher)
Vladimir SKOKOV (Special Postdoctoral Researcher)

Sub Nuclear System Research Division
RIKEN BNL Research Center
Computing Group

1. Abstract

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

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

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

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

2. Major Research Subjects

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

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

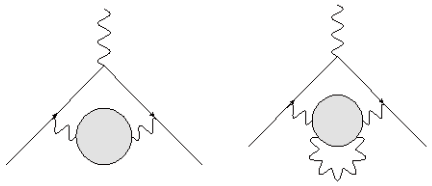
(3) Theoretical and algorithmic development for lattice field theories, QCD machine (co-)design and code optimization.

3. Summary of Research Activity

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

Such computing power enables the group to perform precise calculations using up, down, and strange quark flavors with proper handling of the important symmetry, called chiral symmetry, that quarks have. The group and its collaborators carried out the first calculation for the direct breaking of CP (Charge Parity) symmetry in the hadronic K meson decay ($K \to \pi\pi$) amplitudes, ε'/ε, which provide a new information to CKM paradigm and its beyond. They also provide the hadronic contribution in muon's anomalous magnetic moment $(g-2)_{\mu}$. These calculation for ε'/ε, hadronic light-by-light of $(g-2)$, are long waited calculation in theoretical physics delivered for the first time by the group. The $K \to \pi\pi$ result in terms of ε'/ε currently has a large error, and deviates from experimental results by 2.1 σ. To collect more information to decide whether this deviation is from the unknown new physics or not, the group continues to improve the calculation in various way to reduce their error. Hadronic light-by-light contribution to $(g-2)_{\mu}$ is improved by more than two order of magnitudes compared to our previous results. As of 2018 summer, their calculation provide 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. 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; and QCD thermodynamics in finite temperature/density systems such as those produced in heavy-ion collisions at the Relativistic Heavy Ion Collider.



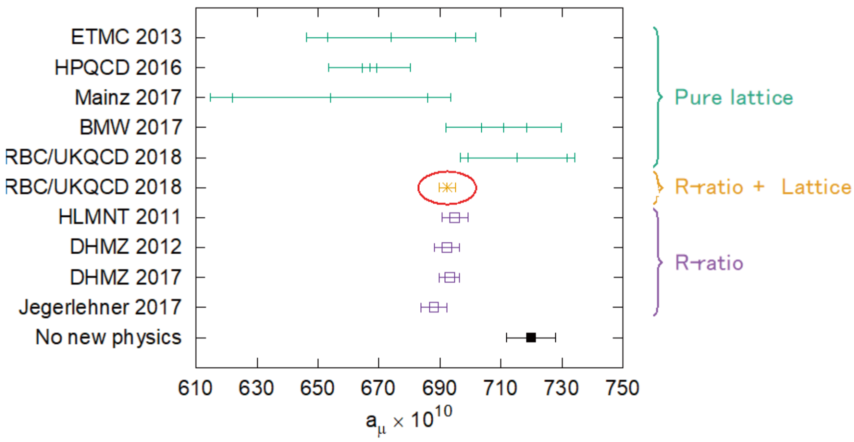


Figure: The botT. plot is the overview of the Hadronic Vacuum Polarization (HVP) to muon anomalous magnetic moment shown at top-left. Our result (RBC/UKQCD 2018) is the first calculation to include QED and the strong isospin breaking (top-right). Our combined method of lattice QCD and R-ratio (circled) validates and improves the precision. From arXiv: 1801.07224.

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

Table: Summery of current physics program and their impacts

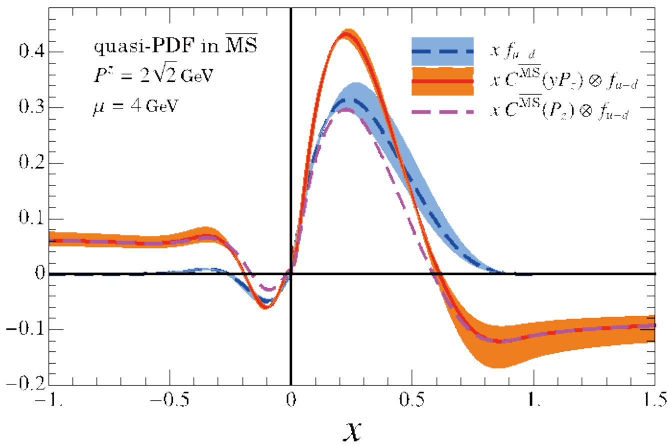


Figure: Parton distribution function (blue) and the corresponding quasi-PDF in MSbar renormalization with the correct Kernel (red) and that from the original formula (purple) from arXiv:1801.03917.

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.

Members

Group Leader (Lab. Head)

T. IZUBUCHI

RBRC Researcher

Y. AOKI (RIKEN BNL Fellow, KEK)
E. NEIL (RHIC Physics Fellow)
S. MEINEL (RHIC Physics Fellow)
S. SYRITSYN (RHIC Physics Fellow)
E. RINALDI (Special Postdoctoral Researcher)
L. Jin (RHIC Physics Fellow)

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T. BLUM (Univ. of Connecticut)
Chulwoo JUNG (BNL)
C. LEHNER (BNL)
Meifeng LIN (BNL)
Robert MAWHINNEY (Columbia Univ.)
Shigemi OHTA (KEK)
Tomomi ISHIKAWA (Shanghai Jiao-Tong Univ.)
H. Oki (Nara Women's Univ.)
Takeshi Yamazaki (Tsukuba Univ.)
Christopher Kelly (Columbia Univ.)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) [* Currently subject to peer review]

T. Blum, P. A. Boyle, V. Gülpers, T. Izubuchi, L. Jin, C. Jung, A. Jüttner, C. Lehner, A. Portelli, and J. T. Tsang, "Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment," arXiv: 1801.07224 (selected as Editors' Suggestion of PRL).*

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[Proceedings]

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

M. Abramczyk, Sinya Aoki, T. Blum, T. Izubuchi, H. Ohki and S. Syritsyn, "Computing nucleon EDM on a lattice," EPJ Web Conf. **175**, 06027 (2018).

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S. Paul, S. Meinel *et al.*, "ππ P-wave resonant scattering from lattice QCD," EPJ Web Conf. **175**, 05022 (2018).

JLQCD Collaboration (K. Suzuki, Y.Aoki *et al.*), "Axial U(1) symmetry at high temperature in 2-flavor lattice QCD," EPJ Web Conf. **175**, 07025 (2018).

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Y. Aoki *et al.*, "Flavor-singlet spectrum in multi-flavor QCD," EPJ Web Conf. **175**, 08023 (2018).

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Oral Presentations

[International Conference etc.]

T. Izubuchi, "Hadronic contributions to muon $g-2$ – LQCD confronting the most precise experiments," invited seminar at Department of Theoretical

Physics (DTP)Tata Institute of Fundamental Research (TIFR), Mumbai, India, April 26, 2018.

T. Izubuchi, “Leading disconnected diagram and other disconnected diagrams,” Invited presentation at Muon $g-2$ Theory Initiative Hadronic Light-by-Light working group workshop, University of Connecticut, Storrs, CT March 12–14, 2018.

T. Izubuchi, “Hadronic contributions to muon $g-2$ and inclusive tau decay,” Invited seminar for Lattice Theory group, DESY, Zeuthen, June 26, 2017.

T. Izubuchi, “Finite volume study for muon $g-2$ light-by-light contribution,” Contribution talk at Lattice 2017, Granada, Spain, 18–24 June, 2017.

T. Izubuchi, “Interplay between R-ratio and Lattice for the muon $g-2$ HVP,” Invited talk at First Workshop of the Muon $g-2$ Theory Initiative, June 4, 2017, Q center, St. Charles, IL, USA.

E. Neil, “Lattice Insights for Composite BSM Models,” High Energy/Cosmology Seminar, University of Wisconsin, Madison, WI. March 2017.

E. Neil, “Lattice study of gauge theory with multiple fermion representations.,” RIKEN Lunch Seminar, Brookhaven National Laboratory, Upton, NY. May 2017.

E. Neil, “Light composite scalars from lattice gauge theory beyond QCD.,” Particle Theory Seminar, Fermi National Accelerator Laboratory, Batavia, IL. September 2017.

E. Neil, “Light composite scalar from $N_f = 8$ lattice gauge theory,” Invited presentation, workshop on Continuum and Lattice Approaches to the Infrared Behavior of Conformal and Quasi-Conformal Gauge Theories, Simons Center for Geometry and Physics, Stony Brook, NY, January 2018.

S. Meinel, “Charm baryon semileptonic decays with lattice QCD,” The 35th International Symposium on Lattice Field Theory, Granada, Spain, June 2017.

S. Meinel, “Weak decays of heavy mesons to multi-hadron final states,” Lattice QCD Workshop, Santa Fe, NM, August 2017.

S. Meinel, “Flavor physics with charm and bottom baryons,” Theory Seminar, Jefferson Lab, Newport News, VA, September 2017.

S. Meinel, “Hints for physics beyond the Standard Model in decays of beauty quarks,” Physics Department Colloquium, Old Dominion University, Norfolk, VA, September 2017.

S. Meinel, “Heavy baryon decay form factors from lattice QCD,” Lattice Meets Continuum Workshop, Siegen, Germany, September 2017.

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

S. Meinel, “Opportunities for lattice QCD in quark and lepton flavor physics,” USQCD All Hands Meeting, Fermilab, Batavia, IL, April 2018.

S. Meinel, “Flavor physics with charm and bottom baryons,” Cosmology Seminar, Arizona State University, Tempe, AZ, May 2018.

S. Meinel, “Form factors for b hadron decays from lattice QCD,” Frontiers in Lattice Quantum Field Theory, Madrid, Spain, May 2018.

Y. Aoki, “Topological susceptibility in $N_f = 2$ QCD at finite temperature,” Lattice 2017, Granada, Spain, June 19, 2017.

Y. Aoki, “Spectral properties and S parameter of $N_f = 8$ QCD,” Brookhaven Forum, BNL, Oct. 11, 2017.

Y. Aoki, “Lattice QCD and hadron structure,” plenary talk at DIS 2018, Kobe Japan, Apr. 16, 2018.

Y. Aoki, “Fate of axial U(1) symmetry at two flavor chiral limit of QCD in finite temperature,” invited talk at XQCD 2018, FIAS, Frankfurt, Germany, May 21, 2018.

L. Jin., “Pion Transition Form Factor (TFF) on Lattice: RBC results,” Second Plenary Workshop of the Muon $g-2$ Theory Initiative, elmholtz-Institut Mainz, Mainz, Germany, June 18, 2018.

L. Jin., “Operator product expansion analysis of Quasi-PDF.” ITP seminar, Peking University, Beijing, China, May 10, 2018.

L. Jin., “HLbL contribution to the muon $g-2$ on the lattice.,” Physics Seminar, University of Kentucky, Lexington, KY, April 12, 2018.

L. Jin., “OPE analysis of quasi-PDFs.” Lattice PDF Workshop, University of Maryland, College Park, MD, April 6, 2018.

L. Jin., “HLbL contribution to the muon g − 2 on the lattice: overall strategy,” Muon $g-2$ Theory Initiative HLbL Working Group Workshop, University of Connecticut, Storrs, CT, March 12, 2018.

L. Jin., “Hadronic light-by-light contribution to muon $g-2$ with lattice QCD and infinite volume, continuum QED,” Theory Seminar, Jefferson Lab, Newport News, VA, January 8, 2018.

L. Jin., “The muon anomalous magnetic moment.” SANTA FE WORKSHOP ON LATTICE QCD, Santa Fe, NM, August 29, 2017.

E. Rinaldi, “Composite dark matter.” Invited Talk at the conference CIPANP18, Palm Springs, CA, USA, June 2018.

E. Rinaldi, “How to test the gauge/gravity duality with lattice simulations.” Invited seminar at New York University, New York, NY, USA, May 2018.

E. Rinaldi, “High-precision tests of the gauge/gravity duality and future applications.” Invited Talk at the workshop LBSM18 “Lattice for Beyond the Standard Model Physics,” University of Colorado, Boulder, CO, USA, April 2018

E. Rinaldi, “What lattice gauge theory can do for dark matter searches?” Invited seminar at Stony Brook University, Stony Brook, NY, USA, February 2018.

E. Rinaldi, “The nucleon axial charge from Lattice QCD” Invited seminar at Lawrence Livermore National Laboratory, Livermore, CA, USA, January 2018.

E. Rinaldi, “Exploring signals of conformality in theories with many flavors: a LatKMI report” Invited talk at the workshop “Continuum and Lattice Approaches to the Infrared Behavior of Conformal and Quasi-Conformal Gauge Theories,” Stony Brook University, Simons Center for Geometry and Physics, Stony Brook, NY, USA, January 2018.

E. Rinaldi, “Dark interactions and supercomputers,” Talk at “Brookhaven forum 2017: in search of new paradigms,” Brookhaven National Laboratory, Upton NY, USA, October 2017.

E. Rinaldi, “Petaflops computing for the search of New Physics” Invited Talk at the inter-institutional meeting ITCPS2017 “Interdisciplinary Theoretical and Computational Physical Sciences,” Tokyo Institute of Technology, Tokyo, Japan, October 2017.

E. Rinaldi, “The nucleon axial coupling from Lattice QCD” Seminar at RIKEN Nishina Center, Wako, Japan, October 2017.

E. Rinaldi, “Lattice Field Theory results on new strong dynamics” Invited Talk at the workshop LFC17 “Old and new strong interactions from LHC to future colliders,” ECT*, Trento, Italy, September 2017.

E. Rinaldi, “Flavor-singlet spectrum in multi-flavor QCD, SU(3) with $N_f = 4$, 8 and 12” Talk at Lattice 2017, Granada, Spain, June 2017.

E. Rinaldi, “How to test the gauge/gravity duality with lattice simulations” Invited seminar at University of Oregon, Eugene, US, May 2017.

E. Rinaldi, “The nucleon axial charge from lattice QCD” Seminar at RIKEN, BNL, Upton, US, May 2017.

E. Rinaldi, “Many-flavor theories on the lattice” Invited talk at the workshop “Lattice for Beyond the Standard Model Physics,” Boston University, Boston, USA, April 2017.

E. Rinaldi, "How to test the gauge/gravity duality with lattice simulations," Invited talk at the workshop "Quantum gravity, string theory and holography," YITP, Kyoto, Japan, April 2017.

E. Rinaldi, "Beyond the Standard Model physics with lattice simulations," Invited seminar at Università di Roma 2, Tor Vergata, Roma, Italy, March 2017.

E. Rinaldi, "What lattice gauge theory can do for Dark Matter searches," Invited seminar at Università di Roma 1, La Sapienza, Roma, Italy, February 2017.

H. Ohki, "Nucleon Electric dipole moments from lattice QCD," The 7th KIAS Workshop on Particle Physics and Cosmopology and The 2nd KEK-NCTS-KIAS Workshop on Particle Physics Phenomenology, KIAS, Soul, Korea, November 10, 2017.

H. Ohki, "|Vus| determination from inclusive strange tau decay and lattice HVP," Lattice 2017, Granada, Spain, June 23, 2017, [Domestic Conference]

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

T. Izubuchi, "Leading disconnected diagram and other disconnected diagrams," Invited presentation at Muon $g-2$ Theory Initiative Hadronic Light-by-Light working group workshop, University of Connecticut, Storrs, CT March 12-14, 2018.

T. Izubuchi, "Hadronic contributions to muon $g-2$ and inclusive tau decay," Invited seminar for Lattice Theory group, DESY, Zeuthen, June 26, 2017.

T. Izubuchi, "Finite volume study for muon $g-2$ light-by-light contribution," Contribution talk at Lattice 2017, Granada, Spain, 18−24 June, 2017.

T. Izubuchi, "Interplay between R-ratio and Lattice for the muon $g-2$ HVP," Invited talk at First Workshop of the Muon $g-2$ Theory Initiative, June 4, 2017, Q center, St. Charles, IL, USA.

Y. Aoki,「QCD の有限温度相転移とトポロジー –サブ課題 A「QCD 相転移」–」, 素粒子・原子核・宇宙「京からポスト京に向けて」シンポジウム, 筑波大学東京キャンパス（東京都）, Feb 17, 2017.

Y. Aoki,「有限温度 2 フレーバーQCD のトポロジカル感受率」, 日本物理学会第 72 回年次大会, 大阪大学, Mar. 18, 2017.

Y. Aoki,「QCD の有限温度相転移とトポロジー –サブ課題 A「QCD 相転移」–」, ポスト「京」重点課題 9 研究報告会(5/31), 筑波大学 CCS, May 31, 2017.

Y. Aoki, "Topology and axial U(1) symmetry at hight temperature in $N_f = 2$ QCD," AICS seminar, Kobe RIKEN AICS, Jan. 15, 2018.

Y. Aoki,「有限温度 2 フレーバーQCD のトポロジカル感受率」, 日本物理学会 2017 年秋期大会, 宇都宮大学, Sep. 12, 2017.

H. Ohki,「New Inclusive Decay Analysis with Lattice QCD," poster presentation at FY 2017 SPDR and FPR Research Report Session, RIKEN, Wako, Japan, January 31, 2018.

H. Ohki, "Nucleon Electric Dipole Moments from Lattice QCD," 10th International Workshop on Fundamental Physics Using Atoms (FPUA), Nagoya University, Nagoya, Japan, January 8, 2018.

H. Ohki,「格子 QCD による核子構造の研究と標準模型を越えた物理 (Lattie QCD study of nucleon EDM and physics beyond the standard model)」, 2017 JPS Autumn meeting, Utsunomiya University, Utsunomiya, Japan, September 14, 2017.

H. Ohki,「核子(chromo)EDM 演算子の格子 QCD 計算 (Lattice calculation of the nucleon chromo-EDM)」, 2017 JPS Annual Meeting, Osaka University, Toyonaka, Japan, March 19, 2017.

Sub Nuclear 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 $W \rightarrow e$ and $W \rightarrow \mu$ decays. The results of $W \rightarrow e$ measurement was published. The final results of $W \rightarrow \mu$ as submitted for publication.

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 $W \rightarrow \mu$ 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.

(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 $W \rightarrow \mu$ decays in the forward direction. With the measurement of $W \rightarrow e$ and $W \rightarrow \mu$, 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 $W \rightarrow e$ channel in combined data of 2011 to 2013 was published. The high statistics results give strong constraints on the polarization of anti-quarks in the proton. The paper on the final results of $W \rightarrow \mu$ was submitted for publication.

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.

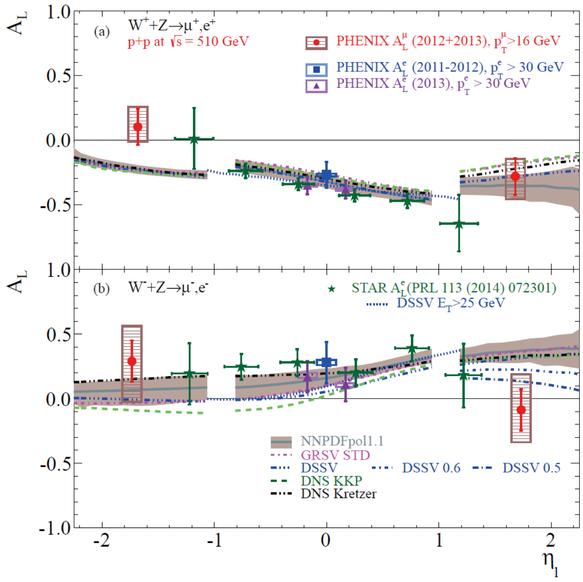

Figure 1. Single spin asymmetry A_L of electrons from W and Z decays. The A_L is sensitive to the polarization of anti-quarks in the proton. The curves and the shaded region show theoretical calculations based on various polarized parton distribution (PDF) sets. The mid-rapidity points are published in Phys. Rev. D **93**, 051103(R) (2016). From arXiv: 1804.04181 (submitted to Physical Review D)

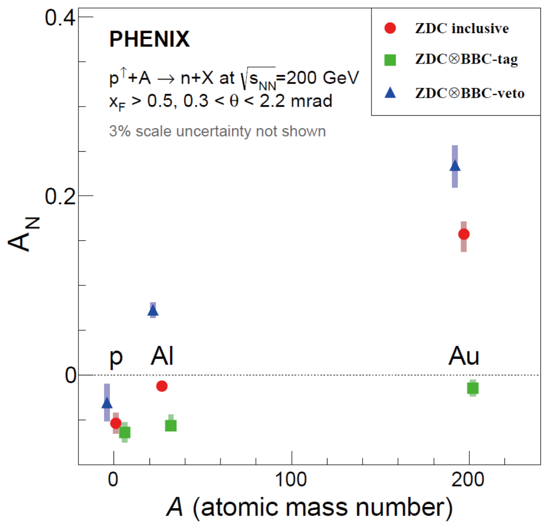

Figure 2. Single spin asymmetry A_N of very forward neutron in $p + p$, p + Al, and p + Au collision. Published in Phys. Rev. Lett. **120**, 022001 (2018).

(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 2500 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.

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

(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.

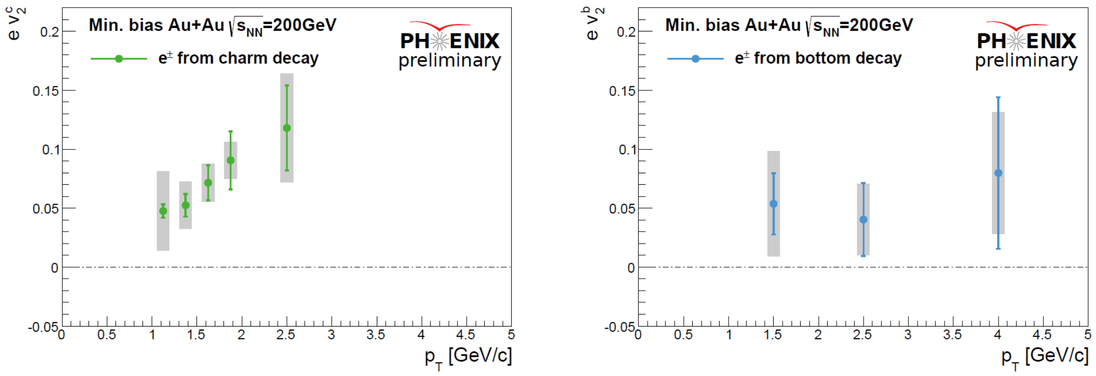

Figure 3. Preliminary results of the elliptic flow strength v_2 of single electrons from charm and bottom decays.

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.

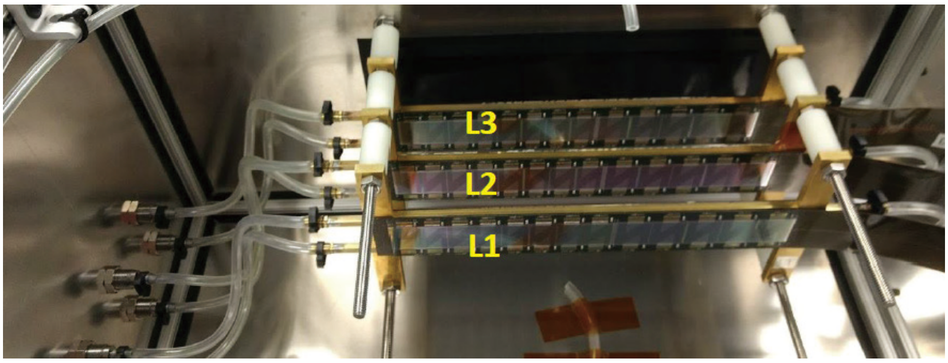

Figure 4. Three ladder telescope made from INTT silicon tracker prototype. The prototype detector was tested in a beam test at FNAL in February 2018.

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List of Publications & Presentations

Publications
[Journal]
(Original Papers)
G. Mitsuka, ”Recently measured large A_N for forward neutron in $p^{\uparrow}A$ collisions at $\sqrt{s_{NN}} = 200$ GeV explained through simulations of ultraperipheral collisions and hadronic interactions,” Phys. Rev. C **95**, 044908 (2017).

Oral Presentations
[International Conference etc.]
T. Hachiya, “Recent results on open and closed heavy flavor from PHENIX at RHIC,” ICHEP2016.
T. Hachiya, “Recent heavy flavor measurements from PHENIX at RHIC,” ISMD2016.
T. Hachiya, “Recent results on heavy flavor production at RHIC-PHENIX,” INPC2016.
G. Mitsuka, ”Disentangling transverse single spin asymmetry for very forward neutrons in polarized *pA* collisions using ultra-peripheral collisions,” 25th International Workshop of Deep Inelastic Scattering (DIS2017).
T. Hachiya, “Nuclear modification factor and flow of charm and bottom quarks in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX Experiment,” (Quark Matter 2018).

[Domestic Conference]
G. Mitsuka, 「RHIC 単スピン非対称測定に対する ultra-peripheral collision の影響」, 日本物理学会 第 72 回年次大会.

Poster Presentations
[International Conference etc.]
G. Mitsuka, “sPHENIX Intermediate silicon tracker INTT,” Quark Matter 2017.

Sub Nuclear System Research Division
RIKEN Facility Office at RAL

1. Abstract
Our core activities are based on the RIKEN-RAL Muon Facility located at the Rutherford Appleton Laboratory (UK), which provides intense pulsed-muon beams. 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 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 on magnetism. We have carried out μSR investigations on frustrated pyrochlore systems, which have a variety of exotic ground states of magnetic spins, so the magnetism study of this system using muons is quite unique.

The ultra-slow muon beam can be stopped in thin foil, multi-layered materials and artificial lattices, which enables us to apply the μSR techniques to surface and interface science. The development of an ultra-slow muon beam is also very important as a source of ultra-cold (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 demonstrated a tremendous increase of the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. We also developed a high power Lyman-alpha laser in collaboration with the Advanced Photonics group at RIKEN. The new laser will ionize muonium atoms 100 times more efficiently for slow muon beam generation.

We are planning a major refurbishment of the muon facility, since the major part of the facility was built around 1994. The plan was discussed in 2017 and the areas and components that need refurbishment were identified. RIKEN and STFC/RAL also agreed on extension of the collaboration for another five years starting 2018. RAL will take over the facility ownershp and will be responsible for its operation and maintenance, while RIKEN will keep access to the facility with access charge to conduct its science program.

2. Major Research Subjects
(1) Materials science by muon-spin-relaxation method
(2) Hyperfine interactions at muon sites studied by the computation science
(3) Nuclear and particle physics studies via muonic atoms and ultra-cold muon beam

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 over a 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 methods (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 research on strong correlated-electron systems, organic molecules and biological samples to study electron structures, superconductivity, magnetism, molecular structures and crystal structures.

In the period from 2017 to 2018, we have obtained excellent results, and the highlights are listed in the following,

1) The superconducting gap state of λ-$[BETS]_2GaCl_4$ has both the *s*- and *d*-wave characters.
2) A static ordering in the Ca-doped pyrochlore iridate; $(Y_{1-x}Ca_x)_2Ir_2O_7$ is strongly suppressed by the carrier doping.
3) A long-range magnetic ordering is observed in alkari-metal superoxides of CsO_2 and RbO_2 but not in NaO_2.
4) Missing of a static ordering is confirmed in both Au25 nano-clusters.
5) The quantum spatial distribution of the muon by the zero-point vibration energy is clarified by density functional theory calculations by using the RIKEN supercomputing system. HOKUSAI.

Result-1) One dimensional organic superconductor, λ-$[BETS]_2GaCl_4$, has a unique Fermi-surface structure with the four-fold nodal points. The estimation of the superconducting gap from computational analysis of μSR experimental data indicates a unique view of the supeconducting gap to be a mixed state of the major *s*-wave component and the minor *d*-wave one. Result-2) Static orderings of Ir magnetic spins are strongly suppressed by the carrier doping. A quantum critical change to the non-magnetic ground state is expected around $x = 0.20$ being accompanied by changes in the transport properties. Result-3) The π electrons which are widely distributed on the O_2 dumbbell in superoxides CsO_2 and RbO_2 are found to form static long-range orderings. The magnetic moment is quantitatively estimated in conjunction with density functional theory calculations and confirmed to shrink to less than a half in the magnetically ordered state. Result-4) Ground states of nano-cluster of Au with 25 atoms are concluded to be still nonmagnetic down to 0.3 K from the magnetic susceptibility, NMR and μSR measurements although those systems have been argued to show some static magnetic states. Result-5) The muon trapped in materials is confirmed to be spatially distributed around the local minimum potential position by the zero-point vibration energy, which is due to the muon’s physics character as a light particle. This quantum spatial distribution is now taken into account for the μSR data analysis with the similar quantum spatial distribution of magnetic moments.

We are developing international collaborations on the muon science with Asian groups in order to organize new μSR experimental research themes and to develop muon-site calculation activities using computational method. We renewed MOU’s with Indonesian and Malaysian universities to enhance collaborative researches on the muon science at the RIKEN-RAL Muon Facility. We formed a new MOU with Universitus Indonesia (UI) as a new partner to work on the muon science and student education. We are developing new collaborations in μSR experiments on strongly correlated systems with researchers from China, Taiwan and Korea including graduate students.

(2) Ultra Slow (low energy) Muon Beam Generation and Applications

A positive muon beam with thermal energy has been produced by laser ionization of muonium atoms (bound system of μ^+ and electron) emitted from 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-slow muon beam in thin foil, multi-layered materials and artificial lattices, we can precisely measure local magnetic field in the materials, and apply the μSR techniques to surface and interface science. Since there has been no appropriate probe to study magnetism at surface and interface, the ultra-slow muon beam will open a new area of these research fields. In addition, the development of ultra-slow muon beam is very important as the source of ultra-cold (pencil-like small emittance) muon beam for muon $g-2$/EDM measurement. It is essential to increase the slow muon beam production efficiency by 100 times for these applications. There are three key techniques in ultra-slow muon generation: production of thermal muonium, high intensity Lyman-alpha laser and the ultra-slow muon beam line.

We have developed a high power Lyman-alpha laser in collaboration with the Advanced Photonics group at RIKEN. This development was funded mostly by the Grant-in-Aid for Scientific Research on Innovative Areas "Frontier in Materials, Life and Particle Science Explored by Ultra Slow Muon Microscope". The new laser system was installed to J-PARC slow muon beam line and is being used for the generation of ultra-slow muons. In this development, we succeeded in synthesizing a novel ceramic-based Nd:YGAG crystal. We already achieved 10 times increase in Lyman-alpha intensity and are waiting the growth of a large crystal to achieve the goal of 100 times increase. This crystal can also be applicable to the flash-lamp based Lyman-alpha laser system of RIKEN-RAL to realize substantial improvement of the laser power at a much reduced cost.

We also aimed to realize drastic improvements on the ultra-slow muon source with much reduced emittance. We have been developing muonium generators to create more muoniums in vacuum even at room temperature. In 2013, we demonstrated at least 10 times increase of the muonium emission efficiency in one of the silica aerogel samples with fine holes fabricated on the surface. The measurement was carried out at TRIUMF in collaboration with J-PARC muon $g-2$/EDM group. In 2017, we carried out systematic study of muonium emission under various target conditions at TRIUMF in collaboration with Canadian collaborators who developped the method of stable production of various laser drill-holes.

We are planning to feed these new techniques to RIKEN-RAL ultra-slow muon beam line to realize further improvement of ultra-slow muon technology. The muonium production target section, which had been designed with hot tungsten, was completely redesigned and rebuilt to use advantages of the new room temperature silica aerogel target, such as no need of thermal shielding and spin control by applying weak magnetic field, etc. In test experiment, we demonstrated a new powerful method of the muon stopping optimization in silica aerogel using muonium spin rotation.

(3) New Proposal for Fundamental Physics

We proposed the measurement of the proton radius by using the hyperfine splitting of the 1S states of muonic hydrogen. Recent measurement of the proton radius using muonic hydrogen at PSI revealed that the proton radius is surprisingly smaller than the radius so far measured using normal hydrogen spectroscopy and *e-p* scattering by more than 5 times their experimental precision. In contrast to the conventional measurement by means of electron, measurement with muonic hydrogen 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. The cause of the discrepancy is not understood yet, thus a new measurement with independent method is much anticipated.

There are two independent experimental proposals to RIKEN-RAL PAC to measure the hyperfine splitting energy of the 1S energy levels by laser excitation from singlet ground state to triplet state. This energy splitting is sensitive to the Zemach radius, which is a convolution of charge and magnetic distributions inside proton. Both commonly search resonant excitation from singlet 1S ($F=0$) to triplet 1S ($F=1$) using high intensity 6.7 μm excitation laser, but different schemes are proposed to detect the resonance. One is to detect muon transfer to the surrounding impurity atom by x-ray (European group), and the other is to detect the muon decay asymmetry recovery along the circularly polarized excitation laser, which selectively excites one of the $F=1$ states and regenerates the muon spin polarization (RIKEN group). RIKEN-RAL PAC accepted both proposals for feasibility studies.

RIKEN laser group made basic design of the laser system, based on their recent success on mid-infared (6 μm) high-power pulse laser system. There is no direct way to produce 6.7 μm lasers, so we started to test the wavelength conversion efficiency of the laser key components. Concerning the target, we need to stop muons in extremely low-density hydrogen target to substantially reduce the polarization quenching effect due to atomic collision. All the muons stopped in the material other than the target can be a background source. Thus, we carried out the measurement of long-life background level, and confirmed that the background dies out quickly before the laser is introduced. We also started the optimizaiton of the muon stopping in low-density gas target.

(4) Other topics

There were many demands for the use of negative muons for the non-destructive elements analysis using muonic x-rays. Especially its good depth sensitivity was clearly demonstrated. The applied objects so far are archaeological coins, sword, ship models, oxygen concentration measurement in levers, movement of Li concentration in batteries, etc. Several papers on this work have already been published both on the technique's development and potential capabilities. Techniques developments such as new data aquisition system, pixel detector for imaging, and 3D imaging with rotating samples are in progress.

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Administration Manager
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List of Publications & Presentations

Publications
[Journal]
(Original Papers) *Subject to Peer Review

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A. Taufiq *et al.*, “Studies on nanostructure and magnetic behaviors of Mn-doped black iron oxide magnetic fluids synthesized from iron sand,” Nano **12**, 1750110-1-11 (2017).*

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S. Bae *et al*., “First muon acceleration using a radio frequency accelerator,” accepted publication in Phys. Rev. Accel. Beams (2018).*

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K. Ishida, “MuP HFS measurement with spin polarization,” FAMU meeting, Trieste, May 2017.

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K. Ishida for J-PARC muon $g-2$/EDM collaboration, “Muon $g-2$/EDM experiment at J-PARC,” The 19th international workshop on neutrinos from accelerators (NUFACT2017), Uppsala, Sweden, September 2017.

S. Kanda, “Precision laser spectroscopy of the ground state hyperfine splitting in muonic hydrogen,” The 19th international workshop on neutrinos from accelerators (NUFACT2017), Uppsala, Sweden, September. 2017.

K. Ishida, “Nuclear physics experiments using muons,” CSNS Seminar, Dongguan, China, December 2017.

S. Kanda, “Precision laser spectroscopy of the ground-state hyperfine splitting in muonic hydrogen atom,” FPUA2018, Nagoya, January 2018.

K. Ishida, “Proton radius measurement from studies in muonic hydrogen,” International Symposium on Nucleon Structure, Yamagata, March 2018.

[Domestic Conference]

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RIBF Research Division
Radioactive Isotope Physics Laboratory

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

(1) In-beam gamma spectroscopy

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

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

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

To further strengthen the in-beam gamma spectroscopy at RIBF, we have proposed a new setup of MINOS + DALI2 to search for the 1st excited states in even-even neutron-rich nuclei with $Z \sim 20$ to 40. The program was submitted to the PAC 2013 as a new category "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 two campaigns were organized in 2014 and 2015 to study very neutron-rich isotopes. In 2017, the third campaign was organized at the SAMURAI spectrometer, and bunch of structure data was obtained for very exotic nuclei at $Z \sim 20$.

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

(2) Decay spectroscopy

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

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

The success of the first decay-spectroscopy campaign stimulated to form a new large-scale collaboration "EURICA," where a twelve Euroball cluster array is coupled with the silicon-strip detectors to enhance gamma efficiency by a factor of 10. A construction proposal of "EURICA" was approved in the PAC 2011, and the commissioning was successfully organized in spring 2012. Since then, physics runs have been conducted for programs approved to survey nuclei of interest as many as possible, such as Ni-78, Pd-128, Sn-100. So far, 44 papers including 12 PRL's and 10 PLB's were published. One of the highlights is discovery of a seniority isomer in Pd-128, of which cascade gamma decay gives the energy of 1st excited state and robustness of $N = 82$ magic number, and the other is a half-life measurement for 110 neutron-rich nuclei across the $N = 82$ shell gap, which shows implications for the mechanism and universality of the r-process path. The EURICA collaboration finished its physics programs in summer 2016.

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

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 in preparation.

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

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List of Publications & Presentations

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RIBF 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-a) 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-b) 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-c) 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-d) 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*, 2*p*)-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}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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Chief Scientist (Lab. Head)

Tomohiro UESAKA

Research & Technical Scientists

Masaki SASANO (Research Scientist)
Sarah NAIMI (Research Scientist)
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List of Publications & Presentations

Publications
[Journal]

(Original Papers) *Subject to Peer Review

L. Stuhl, M. Sasano, K. Yako, J. Yasuda, H. Baba, S. Ota, T. Uesaka, "PANDORA, a large volume low-energy neutron detector with real-time neutron–gamma discrimination," Nucl. Instrum. Methods Phys. Res. A **866**, 164−171 (2017).

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T. Uesaka, "Studies of neutron-rich nuclei at RIBF — From tetraneutron to fission," Proceedings of the Sixth International Conference on ICFN6, Fission and Properties of Neutron-Rich Nuclei: pp. 47−47 (2017).

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Oral Presentations

[International Conference etc.]

V. Panin, "Dissociation of proton-rich nuclei at SAMURAI as a method to study the most critical (p, γ) reaction rates in stellar nucleosynthesi," KPS 2017 meeting, Daejeon, South Korea, April 20, 2017.

S. Naimi, "Rare-RI Ring (R3) at RIBF/RIKEN: Mass measurement of r-process nuclei," Workshop on Nuclear Astrophysics at Rings and Recoil Separators, GSI Darmstadt, Germany, March 13–15, 2018.

S. Naimi," The Rare-RI Ring Ready to Explore Terra Incognita," International Conference on Advances in Radioactive Isotope Science, ARIS 2017, Colorado, USA, May 28–June 2, 2017.

H. Sagawa, "Spin and spin-isospin responses and isoscalar spin-triplet pairing," Int. Symp. on Physics of Unstable Nuclei (ISPUN) 2017, Ha Long Bay, Vietnam, September 25–30, 2017.

H. Sagawa, "Three-body model for nuclei near and beyond drip line," Ischia Nuclear Structure workshop, Ischia, Italy, May 15–19, 2017.

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Y. Kubota, “Probing neutron-neutron correlation in 11Li via the quasi-free (*p*, *pn*) reaction,” Hadrons and Nuclear Physics meet ultracold atoms: a French Japanese workshop, Paris, France, January 29–February 2, 2018.

Y. Kubota, “Probing neutron-neutron correlation in ^{11}Li through the quasi-free (*p*, *pn*) reaction,” The 244th RIKEN RIBF Nuclear Physics Seminar, Saitama, Japan, December 19, 2017.

Y. Kubota, “Neutron-neutron correlation in Borromean nucleus ^{11}Li,” SAMURAI International Collaboration Workshop 2017, Darmstadt, Germany, August 8–11, 2017.

Y. Kubota, “Dineutron correlation in Borromean nuclei,” 3rd International Workshop on Quasi-Free Scattering with Radioactive-Ion Beams: QFS-RB 17, York, United Kingdom, July 24–27, 2017.

Z. H. Yang, “Studies of multi-neutron systems with (*p*, 2*p*) reactio,” SAMURAI International Collaboration Workshop 2017, Darmstadt, Germany, August 2017.

[Domestic Conference]

H. Sagawa, “Spin and spin-isospin responses in $N = Z$ nuclei and isoscalar spin-triplet pairing,” Interdisciplinary symposium on modern density functional theory, RIKEN, June 19–23, 2017.

H. Sagawa, “The nuclear symmetry energy and the breaking of isospin symmetry,” Workshop on “Nuclear matter in neutron stars,” RIKEN, December 1–3, 2017.

H. Sagawa, “Microscopic models for spin, isospin and spin-isospin responses,” Yukawa Institute of Theoretical Physics (YITP) school "Recent Progress of Nuclear Structure and Reaction Physics", Kyoto, December 18–22, 2017.

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

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原田知也,「大強度イオンビーム用の Xe ガスシンチレーション検出器の開発」, 日本物理学会第 73 回年次大会, 2018 年 3 月 22–25 日.

松本翔汰,「BigRIPS における高精度パイ中間子原子分光・二重 Gamow-Teller 巨大共鳴探索実験に向けた新検出器システムの性能評価(ii)」, 日本物理学会第 73 回年次大会, 2018 年 3 月 22–25 日.

高橋祐羽,「パラ水素を用いた薄型自己保持固体水素標的の開発」, 日本物理学会 2017 年秋季大会, 2017 年 9 月 12–15 日.

Poster Presentations

[International Conference etc.]

Z. Ge, “Development of Mirror-type MCP Detectors for Mass Measurements at the Rare-RI Ring,” The 10th International Conference on Nuclear Physics at Storage Rings (STORI’17), Kanazawa, Japan, Nov. 13–18, 2017.

RIBF Research Division
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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, 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 with spin-oriented RI beams
(2) R&D studies for laser spectroscopy of stopped/slowed-down RI beams
(3) Application of RI probes
(4) Fundamental physics: Study of symmetry

3. Summary of Research Activity

(1) Nuclear spectroscopy with spin-oriented 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 nuclear moments of nuclei far from the stability have 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. To extend these observations to extremely rare RIs, development of a new apparatus to produce highly spin-polarized RI beams will be conducted by extending the atomic beam resonance method to fragmentation-based RI beams.

(2) R&D studies for laser spectroscopy of stopped/slowed-down RI beams

For the measurement of electromagnetic nuclear properties such as spin, isotope shift, and electromagnetic nuclear moments at RIBF, we have been conducting R&D studies on nuclear laser spectroscopy. One is development of a new laser-spectroscopy system utilizing superfluid helium (He II) as a stopping medium of energetic RI beams, where characteristic atomic properties of ions surrounded by liquid helium enable us to perform unique nuclear laser spectroscopy. The other is a system for collinear laser spectroscopy for a large variety of elements using slowed-down RI beams produced via projectile-fragmentation reaction at RIBF, which can be achieved only by a universal low-energy RI-beam delivery system SLOWRI.

(3) Application of RI probes

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 the β-NMR/nuclear quadrupole resonance (NQR) methods, in-beam Mössbauer spectroscopy and the γ-ray time differential perturbed angular correlation (γ-TDPAC) spectroscopy.

(4) Fundamental physics: Study of symmetry

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

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List of Publications & Presentations

Publications

[Journal]

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RIBF Research Division
High Energy Astrophysics Laboratory

1. Abstract
Immediately after 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 the course of 13.8 billion years led to the evolution of a world brimming with the many different elements we have today. By using man-made satellites 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 using an accelerator.

2. Major Research Subjects
(1) Connect missing links of nucleosynthesis in our universe
(2) Reveal the particle acceleration mechanism in astronomical objects, planets and inter-planetary space
(3) Discover new physics in extremely strong magnetic and gravitational environment
(4) Research and development of innovative X-ray and gamma-ray detectors

3. Summary of Research Activity
We have performed data analysis of Japanese X-ray satellite Hitomi, which was lost by an accident one month after the launch in 2016, and obtained many new research achievements on neutron stars, supernova remnants, galaxies, and cluster of galaxies. Some of them are verification of solar abundance of Perseus cluster, and non-detection of dark matter signal at 3.5 keV. We have contributed to the new X-ray polarimeter mission IXPE (Imaging X-ray Polarimeter Explorer) and provided gas electron multiplier foils. We have studied particle acceleration around Jupiter with Hisaki/Juno/Hubble space telescope, and pursued the gamma-ray emission mechanism of thundercloud.

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Miho OKUBO (Tokyo Univ. of Sci.)
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木村智樹,「リモートセンシングと探査機その場観測の連携で取り組む回転惑星磁気圏のリコネクションと粒子加速」, 磁気リコネクション・粒子加速勉強会, 東京大学, 2017 年 6 月.

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玉川 徹,「ガス電子増幅フォイルの X 線検出器ならびに X 線発生装置への応用 」, 学振 186 委員会・第 24 回研究会, 東京大学, 2017 年 7 月.

RIBF Research Division
Astro-Glaciology Research Unit

Summary of Research Activities

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

On the experimental side, we analyze ice cores drilled at the Dome Fuji station, in Antarctica, in collaboration with the National Institute of Polar Research (NIPR, Tokyo). These ice cores are time capsules. In particular, the ice cores obtained at Dome Fuji are known to be unique because they contain much more information on conditions in the stratosphere than any other ice cores recovered from other locations in either hemisphere. This means that there are significant advantages in using Dome Fuji ice cores if we wish to study astronomical phenomena of the past. Since gamma-rays and high-energy protons that are emitted in certain astronomical processes affect the chemical and isotopic compositions in the stratosphere but not those in the troposphere, we have been measuring:

(1) Variations in the nitrate ion (NO_3^-) concentrations in the ice cores, in an effort to establish a new proxy for supernova explosions in our own galaxy as well as past solar activity.

(2) Variations in the water isotopes (^{18}O and ^{2}H) in the ice cores, in order to construct in more detail records of past changes in the temperature of the surface of the earth; and

(3) Variations in the nitrogen isotope (^{15}N) in the nitrates contained in the ice cores, in order to investigate the possibility of utilizing ^{15}N as a new and more stable proxy for galactic supernovae explosions and past solar activity.

In the case of items (1), (2), and (3), our analyses of Dome Fuji ice cores cover the most recent 2000 years. The temporal resolution of the results of our research is currently 12 months. We intend to compare the results obtained in item (1) with those in item (2), in order to understand better the relationships between solar activity and long-term changes in the temperature of the earth. The underlying assumptions in item (2) are already well accepted in glaciology. Item (3) refers to one of the very first measurements of ^{15}N concentrations in ice cores.

On the theoretical side, we are simulating numerically:

(4) Changes in the chemical composition of the stratosphere induced by gamma-rays and/or high-energy particles emitted from explosive astronomical phenomena, such as galactic supernovae and solar proton events; and

(5) The explosive nucleosynthesis (including the r-process, the rapid neutron capture process, which creates elements heavier than iron) that arises in the environment of core-collapse supernova explosions.

Items (4) and (5) in our list, the chemical composition of the stratosphere and explosive nucleosynthesis, are very important in solar–terrestrial research and nuclear astrophysics; furthermore, these simulations provide a theoretical support when considering the characteristics of supernova explosions and solar activity, as seen in our ice core data. These studies are also important because it is necessary to discount the effects of the meteorological noise.

It is noteworthy that the as yet not fully understood frequency of supernova explosions in our galaxy is crucial to an understanding of the r-process nucleosynthesis. The results obtained from items (1) and (3) are expected to reveal the average rate of supernova explosions in our galaxy during the past million years of ice deposition.

Members

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

E. Tsantini, T. Minami, K. Takahashi, and M. A. C. Ontiveros, "Analysis of sulfur isotopes to identify the origin of cinnabar in the Roman wall paintings from Badalona (Spain)," J. Arcaeological Science, **18**, 300−307 (2018).*

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M. Maruyama, M. Yumoto, K. Kase, K. Takahashi, Y. Nakai, S. Wada, Y. Yano and Y. Motizuki, "A prototype novel laser-melting sampler for analyzing ice cores with high depth resolution and high throughput," RIKEN Accel. Prog. Rep. **51**, in press.*

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(Invited talk) S. Hayashi and Y. Motizuki, "Mighty minority of women in Astronomy in Japan," IMU-led, ICSU-sponsored Workshop on "Gender gap in mathematical and other natural sciences", Taipeh, Taiwan, Nov. 7–8, 2017.

(Invited talk) K. Tanabe and Y. Motizuki, "Symbiotic Binary R Aquarii and Gamma-ray Astronomy," PALERMO WORKSHOP 2017 "The Golden Age of Cataclysmic Variables and Related Objects – IV," Palermo, Italy, Sep. 11–16, 2017.

(Invited talk) Yuko Motizuki, "Supernova signatures in polar ice cores," International Symposium on Origin of Matter and Evolution of Galaxies 2017 (OMEG 2017), Daejeon, Korea, June 27–30, 2017.

T. Minami, E. Tsantini, and K. Takahashi, "Effect of Gypsum on Sulfur Isotope Ratio of Vermilion Painted on Gypsum Wall," the Colloquium Spectroscopicum Internationale XL, Pisa, Italy, June, 2017.

(Invited talk) H. Akiyoshi, Y. Nakai, Y. Motizuki, T. Imamura, Y. Yamashita, "A preliminary result of NOx and ozone change simulation for a solar proton event using a nudged CCM and box chemistry model," Int. Workshop on Solar Cycle Activity and Impact on Climate for The 2nd PSTEP International symposium (PSTEP-2) , Kyoto, March 22, 2017.

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（招待講演）望月優子,「アイスコアからさぐる天文・宇宙のサイエンス – 過去の超新星爆発と太陽活動, 地球への影響 – 」, 埼玉大学理学部物理量子力学特別講義, さいたま, 2018 年 1 月 22 日.

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（招待講演）望月優子,「宇宙と生命とのつながり～生命と元素、星、宇宙のリズム～」, 理化学研究所 和光地区一般公開サイエンスレクチャー, 和光, 2017 年 4 月 22 日.

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Poster Presentations

[International Conference etc.]

K. Takahashi, “New method for comprehensive detection of trace elements in environmental or biochemical materials using an electron-cyclotron-resonance ion-source mass spectrometer”(A poster paper), the 4th World Congress on Mass Spectrometry, London, UK, June 2017.

Y. Nakai, N. Watanabe, Y. Oba, “Hydrogenation of C_{60} deposited on a substrate under low temperature condition” (A poster paper), The 30th International Conference on Photonic, Electronic and Atomic Collisions, Cairns Australia, August 2017.

RIBF Research Division
Research Group for Superheavy Element

1. Abstract
The elements with their atomic number $Z > 103$ are called as trans-actinide or superheavy elements. The chemical properties of those elements have not yet been studied in detail. Those elements do not exist in nature. Therefore, they must be produced by artificially for the scientific study of those elements. In our laboratory, we have been studying the physical and chemical properties of the superheavy elements utilizing the accelerators in RIKEN and various methods of efficient production of the superheavy elements.

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

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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Publications
[Journal]

T. Tanaka, Y. Narikiyo, K. Morita, K. Fujita, D. Kaji, K. Morimoto, S. Yamaki, Y. Wakabayashi, K.Tanaka,M. Takeyama, A. Yoneda, H. Haba, Y. Komori, S. Yanou, B.J. Gall, Z. Asfari, H. Faure, H. Hasebe, M. Huang, J. Kanaya, M. Murakami, A. Yoshida, T. Yamaguchi, F. Tokanai, T. Yoshida, S. Yamamoto, Y. Yamano, K. Watanabe, S. Ishizawa, M. Asai, R. Aono, S. Goto, K. Katori, and K. Hagino, "Determination of fusion barrier distributions from quasielastic scattering cross sections towards superheavy nuclei synthesis," J. Phys. Soc. Jpn. **87**, 014201 (2018).

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K. Morimoto, "Discovery of new element 'Nihonium'," International Symposium on Radiation Detectors and Their Uses (ISRD2018), Tsukuba Univ., January 23, 2018.

D. Kaji, "Hot fusion study using a new separator GARIS-II," 3rd International Symposium on Super-Heavy Elements (SHE2017), Poland, September 10, 2017.

[Domestic Conference]

T. Niwase, M. Wada, P. Schury, Y. Ito, S. Kimura, M. Rosenbusch, D. Kaji, K. Morimoto, H. Haba, S. Yamaki, T. Tanaka, K. Morita, A. Takamine, H. Miyatake, Y. Hirayama, Y. Watanabe, J. Y. Moon, M. Mukai, H. Wollnik, "High-precision mass measurements of short-lived nuclei with MRTOF+GARIS-II, " 第 61 回放射化学討論会, Tsukuba University Japan, September 6–8 2017.

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T. Niwase, M. Wada, P. Schury, Y. Ito, M. Rosenbusch, D. Kaji, K. Morimoto, H. Haba, S. Ishizawa, K. Morita, H. Wollnik, "Development Alpha-ToF detector for high precision mass spectrometry of superheavy nuclei," JPS 73th Annual Meeting (2018), Tokyo University of Science Japan, March 22–25 2018.

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森田浩介,「新元素の探索」, 別府市鶴見丘高等学校, 2017 年 9 月 2 日.
森田浩介,「新元素の探索」, 日本甲状腺学会特別講演, 別府市, 2017 年 10 月 7 日.
森田浩介,「新元素の探索」, アカデミックフェスティバル, 九州大学椎木講堂, 2017 年 10 月 21 日.

RIBF Research Division
Research Group for Superheavy Element
Superheavy Element Production Team

1. Abstract
The elements with their atomic number $Z > 103$ are called as trans-actinide or superheavy elements. The chemical properties of those elements have not yet been studied in detail. Those elements do not exist in nature. Therefore, they must be produced by artificially for the scientific study of those elements. In our laboratory, we have been studying the physical and chemical properties of the superheavy elements utilizing the accelerators in RIKEN and various methods of efficient production of the superheavy elements.

2. Major Research Subjects
(1) Search for new supreheavy elements
(2) Decay spectroscopy of the heaviest nuclei
(3) Study of the chemical properties of the heaviest elements
(4) Study of the reaction mechanism of the fusion process (theory)

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.

Members

Team Leader
Kosuke MORITA (concurrent; Group Director, Research Group for Superheavy Element)

Research & Technical Scientist
Kouji MORIMOTO (Senior Research Scientist, concurrent; Team Leader, Superheavy Element Device Development Team)

Nishina Center Research Scientist
Daiya KAJI (concurrent; Superheavy Element Device Development Team)

Nishina Center Technical Scientist-Consultant
Akira YONEDA

Research Consultant
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Visiting Scientists
Hiroyuki KOURA (JAEA)
Benoit Jean-Paul GALL (Strasbourg Univ.)
Olivier DORVOUX (Strasbourg Univ.)
Marc ASFARI (Institut Pluridisciplinaire Hubert Curien)
Mirei TAKEYAMA (Yamagata Univ.)

Student Trainees

Toshitaka NIWASE (Kyushu Univ.)
Takeshi HIRANO (Kyushu Univ.)
Shun MITSUOKA(Kyushu Univ.)
Pierre BRIONNET (Strasbourg University)

Publications

[Journal]

T. Tanaka, Y. Narikiyo, K. Morita, K. Fujita, D. Kaji, K. Morimoto, S. Yamaki, Y. Wakabayashi, K.Tanaka,M. Takeyama, A. Yoneda, H. Haba, Y. Komori, S. Yanou, B.J. Gall, Z. Asfari, H. Faure, H. Hasebe, M. Huang, J. Kanaya, M. Murakami, A. Yoshida, T. Yamaguchi, F. Tokanai, T. Yoshida, S. Yamamoto, Y. Yamano, K. Watanabe, S. Ishizawa, M. Asai, R. Aono, S. Goto, K. Katori, and K. Hagino, "Determination of fusion barrier distributions from quasielastic scattering cross sections towards superheavy nuclei synthesis," J. Phys. Soc. Jpn. **87**, 014201 (2018).

D. Kaji, K. Morimoto, H. Haba, Y. Wakabayashi, M. Takeyama, S. Yamaki, Y. Komori, S. Yanou, S. Goto, and K. Morita, "Decay Measurement of ^{283}Cn Produced in the ^{238}U(^{48}Ca, 3*n*) Reaction Using GARIS-II," J. Phys. Soc. Jpn. **86**, p.085001 (2017).

D. Kaji, K. Morita, K. Morimoto, H. Haba, M. Asai, K. Fujita, Z. Gan, H. Geissel, H. Hasebe, S. Hofmann, M. Huang, Y. Komori, L. Ma, J. Maurer, M. Murakami, M. Takeyama, F. Tokanai, T. Tanaka, Y. Wakabayashi, T. Yamaguchi, S. Yamaki, and A. Yoshida, "Study of the reaction ^{48}Ca + ^{248}Cm → ^{296}Lv* at RIKEN-GARIS," J. Phys. Soc. Jpn. **86**, 034201 (2017).

[和文]

森本幸司,「元素『ニホニウム』の発見と意義」, 維学会誌 pp. 83 第 74 巻 3 号, 2018 年 3 月.

Oral Presentations

[International Conference etc.]

K. Morimoto, "Status and future plan of SHE experiment at RIKEN," 3rd International Symposium on Super-Heavy Elements (SHE2017), Poland, September 10, 2017.

K. Morimoto, "Discovery of new element 'Nihonium'," International Symposium on Radiation Detectors and Their Uses (ISRD2018), Tsukuba Univ., January 23, 2018.

D. Kaji, "Hot fusion study using a new separator GARIS-II," 3rd International Symposium on Super-Heavy Elements (SHE2017), Poland, September 10, 2017.

[Domestic Conference]

T. Niwase, M. Wada, P. Schury, Y. Ito, S. Kimura, M. Rosenbusch, D. Kaji, K. Morimoto, H. Haba, S. Yamaki, T. Tanaka, K. Morita, A. Takamine, H. Miyatake, Y. Hirayama, Y. Watanabe, J. Y. Moon, M. Mukai, H. Wollnik, "High-precision mass measurements of short-lived nuclei with MRTOF+GARIS-II, " 第 61 回放射化学討論会, Tsukuba University Japan, September 6–8 2017.

T. Niwase, M. Wada, P. Schury, Y. Ito, M. Rosenbusch, D. Kaji, K. Morimoto, H. Haba, S. Ishizawa, K. Morita, H. Wollnik, "Development of Alpha-ToF detector for mass measurements of superheavy nuclides," 123th Annual Meeting of Kyushu Branch of JPS, Kagoshima University Japan, December 6 2017.

T. Niwase, M. Wada, P. Schury, Y. Ito, M. Rosenbusch, D. Kaji, K. Morimoto, H. Haba, S. Ishizawa, K. Morita, H. Wollnik, "Development Alpha-ToF detector for high precision mass spectrometry of superheavy nuclei," JPS 73th Annual Meeting (2018), Tokyo University of Science Japan, March 22–25 2018.

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加治大哉,「スパッタ法による厚い金属ウラン標的の調整と照射試験」第 61 回放射化学討論会, 2017 年 9 月 6 日.

[Others]

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K. Morimoto, "Discovery of new chemical element Nihonium," The 112th ISAS Space Science Colloquim, Sagamihara, ISAS/JAXA, March 28, 2018.

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森田浩介,「新元素の探索」, アカデミックフェスティバル, 九州大学椎木講堂, 2017 年 10 月 21 日.

RIBF Research Division
Research Group for Superheavy Element
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 maintain, improve, develop and operate the separators and related devices. There are two gas-filled recoil ion separators installed at RILAC experimental hall. One is GARIS that is designed for symmetric reaction such as cold-fusion reaction, and the other is newly developed GARIS-II that is designed for an asymmetric reaction such as hot-fusion reaction. New elements ^{278}Nh were produced by ^{70}Zn + ^{209}Bi reaction using GARIS. Further the new element search $Z > 118$ are preparing by using GARIS-II.

2. Major Research Subjects

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

3. Summary of Research Activity

The GARIS-II is newly developed which has an acceptance twice as large as existing GARIS, in order to realize higher sensitivity for asymmetric reaction such as a hot fusion reaction. After some commissioning works, the GARIS-II has been ready for new element research. We will also offer user-support if a researcher wishes to use the devices for his/her own research program.

Members

Team Leader
Kouji MORIMOTO

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Yuta ITO

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Katsuhisa NISHIO (JAEA)
Yuta ITO (McGill University)

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Satoshi ISHIZAWA (Yamagata Univ.)
Ryutaro ITO (Yamagata Univ.)
Yuichiro INOMATA (Yamagata Univ.)
Keigo BANDO(Kyushu Univ.)
Takao SAITO (Kyushu Univ.)
Kenta MANABE (Kyushu Univ.)

Publications

[Journal]

T. Tanaka, Y. Narikiyo, K. Morita, K. Fujita, D. Kaji, K. Morimoto, S. Yamaki, Y. Wakabayashi, K.Tanaka,M. Takeyama, A. Yoneda, H. Haba, Y. Komori, S. Yanou, B.J. Gall, Z. Asfari, H. Faure, H. Hasebe, M. Huang, J. Kanaya, M. Murakami, A. Yoshida, T. Yamaguchi, F. Tokanai, T. Yoshida, S. Yamamoto, Y. Yamano, K. Watanabe, S. Ishizawa, M. Asai, R. Aono, S. Goto, K. Katori, and K. Hagino, "Determination of fusion barrier distributions from quasielastic scattering cross sections towards superheavy nuclei synthesis," J. Phys. Soc. Jpn. **87**, 014201 (2018).

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D. Kaji, K. Morita, K. Morimoto, H. Haba, M. Asai, K. Fujita, Z. Gan, H. Geissel, H. Hasebe, S. Hofmann, M. Huang, Y. Komori, L. Ma, J. Maurer, M. Murakami, M. Takeyama, F. Tokanai, T. Tanaka, Y. Wakabayashi, T. Yamaguchi, S. Yamaki, and A. Yoshida, "Study of the reaction ^{48}Ca + ^{248}Cm → ^{296}Lv* at RIKEN-GARIS," J. Phys. Soc. Jpn. **86**, 034201 (2017).

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Oral Presentations

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D. Kaji, “Hot fusion study using a new separator GARIS-II,” 3rd International Symposium on Super-Heavy Elements (SHE2017), Poland, September 10, 2017.

[Domestic Conference]

T. Niwase, M. Wada, P. Schury, Y. Ito, S. Kimura, M. Rosenbusch, D. Kaji, K. Morimoto, H. Haba, S. Yamaki, T. Tanaka, K. Morita, A. Takamine, H. Miyatake, Y. Hirayama, Y. Watanabe, J. Y. Moon, M. Mukai, H. Wollnik, “High-precision mass measurements of short-lived nuclei with MRTOF+GARIS-II, ” 第 61 回放射化学討論会, Tsukuba University Japan, September 6–8 2017.

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T. Niwase, M. Wada, P. Schury, Y. Ito, M. Rosenbusch, D. Kaji, K. Morimoto, H. Haba, S. Ishizawa, K. Morita, H. Wollnik, “Development Alpha-ToF detector for high precision mass spectrometry of superheavy nuclei,” JPS 73th Annual Meeting (2018), Tokyo University of Science Japan, March 22–25 2018.

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森本幸司,「ニホニウム 113 番元素の発見」図書館まつり, 和光市立図書館, 2017 年 10 月 28 日.

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森本幸司,「新元素“ニホニウムの発見”」, 滋賀大学教育学部, 2018 年 2 月 28 日.

K. Morimoto, “Discovery of new chemical element Nihonium,” The 112th ISAS Space Science Colloquim, Sagamihara, ISAS/JAXA, March 28, 2018.

森田浩介,「新元素の探索」, 別府市鶴見丘高等学校, 2017 年 9 月 2 日.

森田浩介,「新元素の探索」, 日本甲状腺学会特別講演, 別府市, 2017 年 10 月 7 日.

森田浩介,「新元素の探索」, アカデミックフェスティバル, 九州大学椎木講堂, 2017 年 10 月 21 日.

RIBF Research Division
Nuclear Transmutation Data Research Group

1. Abstract

The disposal of high-level radioactive wastes from nuclear power plants is a problem considered to be one of the most important issues at both national and international levels. As a fundamental solution to the problem, the establishment of nuclear transmutation technology where long-lived nuclides can be changed to short-lived or stable ones will be vital. Progress in R & D in the transmutation of long-lived fission products (LLFP) in the nuclear wastes however, has been slow. Our group aims to obtain reaction data of LLFP at RIBF and other facilities which 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 for LLFP in inverse kinematics at RIBF. The third Team "Muon Data Team" is to obtain muon capture data of LLFP at muon facilities. All 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 and Coulomb breakup reaction with the beams at 100−200 MeV/nucleon were successfully organized by using the ZeroDegree and SAMURAI spectrometers at RIBF in 2015−2016. In 2017, a physics run with an energy-decelerated radioactive beam was conducted under collaboration with CNS, Univ. of Tokyo. The muon program started at J-PARC and RCNP (Osaka University) in spring 2016. A neutron detection array was newly developed to measure evaporation neutrons after muon capture process, and was utilized at an experiment at RCNP in February 2017. In 2017 and 2018, experiments were organized at both RAL and RCNP to have complete sets of the muon data for a specific LLFP nuclide.

Members

Group Director

Hiroyoshi SAKURAI (concurrent: Chief Scientist, RI Physics Lab.)

Assitant

Izumi YOSHIDA
Asako TAKAHASHI

List of Publications & Presentations

[Others]

櫻井博儀,「核廃棄物の核変換処理と核反応率」, パリティ, 2018 年 1 月.

Oral Presentations

[International Conference etc.]

H. Sakurai, "Reduction and resource recycling of high-level radioactive wastes through nuclear transmutation – Accelerator transmutation system and related developments for element technology," Global 2017 International Nuclear Fuel Cycle Conference, Seoul, Korea, Sept. 2017.

H. Sakurai, "Nuclear data of long-living products," Korea-Japan Workshop on P&T for Long-living Products, Wako, Japan, January 2018.

H. Sakurai, "Nuclear reactions with LLFP in high level radioactive waste," The 7the Yamada Workshop on RI Science Evolution 2018 (RISE18), Osaka, Japan, March 2018.

[Domestic Conference]

櫻井博儀, "Overview of ImPACT Program," ImPACT-OEDO Workshop, Wako, Japan, July 13, 2017.

櫻井博儀,「LLFP 安定核種化・短寿命化のための核変換法の開発 (9) 負ミュオン捕獲反応」, 日本原子力学会, 札幌, 2017 年 9 月 13 日.

櫻井博儀,「LLFP 核変換のための基礎データ取得結果紹介」, ImPACT 加速器検討ワークショップ, 市ケ谷, 2018 年 1 月.

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[報道]

日経産業新聞, 先端技術, 2017 年 11 月 21 日, 朝刊 6 面.

日経産業新聞, 解剖　先端拠点, 2018 年 2 月 21 日, 朝刊 7 面.

RIBF Research Division
Nuclear Transmutation Data Research Group
Fast RI Data Team

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

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

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

2. Major Research Subjects
1) Measurement of reaction products by the interaction of LLFPs with proton, deuteron, and photon to explore candidate reactions for transmutation of LLFPs.
2) Evaluation of the cross section data for the neutron induced reactions from the obtained data.

3. Summary of Research Activity
1) Acting as collaboration hub on many groups which plan to take data using fast RI beam in RIBF facility.
2) Concentrating on take data for proton and deuteron induced spallation reactions with inverse kinematics.
3) Accumulating the cross section data and evaluating them as evaluated nuclear data.
4) Evaluating cross section of neutron induced reaction on LLFP by collaborating with the nuclear model calculation and evaluation group.

Members

Team Leader
Hideaki OTSU (Concurrent: Team Leader, SAMURAI Team)

Technical Staff I
Nobuyuki CHIGA

Visiting Scientists
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Student Trainees
Keita NAKANO (Kyushu Univ.)
Ayaka IKEDA (Niigata Univ.)
Kazuya CHIKAATO (Niigata Univ.)
Shouhei ARAKI (Kyushu Univ.)
Kenji NISHIZUKA (Niigata Univ.)
Junki SUWA (Kyushu Univ.)
Yoshiki SOUDO（Miyazaki Univ.）
Akira HOMMA (Niigata Univ.)
Naoto KANDA (Niigata Univ.)
Tatsuya YAMAMOTO (Miyazaki Univ.)
Kotaro IRIBE (Kyushu Univ.)
Hiroya YOSHIDA (Kyushu Univ.)

List of Publications & Presentations

Publications
[Journal]

(Original Papers)

S. Kawase, K. Nakano, Y. Watanabe, H. Wang, H. Otsu, H. Sakurai (other 43 members), “Study of proton- and deuteron-induced spallation reactions on the long-lived fission product ^{93}Zr at 105 MeV/nucleon in inverse kinematics,” Prog. Theor. Exp. Phys. **2017**, 093D03 (2017).

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H. Wang, H. Otsu, H. Sakurai *et al*., “Spallation reaction study for fission products in nuclear waste: Cross section measurements for ^{137}Cs, ^{90}Sr and ^{107}Pd on proton and deuteron,” EPJ Web of Conf. **146**, 09022 (2017).

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[International Conference]

H. Otsu (Invited), “Nuclear reaction data of long-lived fission product,” Ito International Research Center (IIRC) Symposium “Perspectives of the Physics of Nuclear Structure,” Tokyo, Japan, November, 2017.

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[Domestic Conference]

H, Wang (Invited), “Systematic study for the spallation reaction of ^{107}Pd at different energies,” ImPACT-OEDO Workshop, Wako, Saitama, Japan, July 2017.

X. Sun, “Reaction study of ^{136}Xe on proton, deuteron and carbon at 168 *A*MeV,” ImPACT-OEDO Workshop, Wako, Saitama, Japan, July 2017.

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親跡和弥, 武智麻耶 他 29 名,「^{90}Sr および ^{89}Rb, ^{88}Kr, ^{91}Y の相互作用断面積測定」, 日本物理学会秋季大会, 宇都宮, 2017 年 9 月.

平山晃大, 中村隆司 他 12 名, ImPACT-RIBF Collaboration,「^{79}Se,^{80}Se のクーロン分解反応断面積」, 日本物理学会秋季大会, 宇都宮, 2017 年 9 月.

大津秀暁 他 3 名,「理研 RIBF での LLFP 断面積測定」, 日本原子力学会秋の大会, 札幌, 2017 年 9 月.

川瀬頌一郎 他 9 名,「^{93}Zr に対する 200 MeV/u 陽子・重陽子入射同位体生成反応の断面積測定」, 日本原子力学会秋の大会, 札幌, 2017 年 9 月.

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武内聡 他 5 名,「^{79,80}Se および ^{93,94}Zr のクーロン分解反応による光吸収断面積の導出」, 日本原子力学会秋の大会, 札幌, 2017 年 9 月.

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

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

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

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

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

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

Poster Presentations

[International Conference]

K. Nakano, “Measurement of isotopic production cross sections of proton- and deuteron-induced reactions on 93Zr at 50 MeV/nucleon in inverse kinematics,” The 9th Korea-Japan Joint Summer School on Accelerator and Beam Science, Nuclear Data, Radiation Engineering and Reactor Physics, Daejeon, Korea, Aug. 2017.

[Domestic Conference]

X. Sun, “Reaction study of ^{136}Xe on proton, deuteron and carbon at 168 *A*MeV,” Symposium on Nuclear Data, Nuclear Data Division, Atomic Energy Society of Japan, Ibaragi, Japan, November 2017.

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

Master Thesis

諏訪純貴,「陽子・重陽子に対する ^{93}Zr 入射核破砕反応による核種生成実験データの予備解析」, 九州大学大学院総合理工学府先端エネルギー理工学専攻 .

平山晃大,「^{79,80}Se のクーロン分解反応断面積測定」, 東京工業大学理学院物理学系 .

Bachelor Thesis

三木晴瑠,「^{238}U の飛行核分裂反応における低速 ^{77}Se および ^{107}Pd のアイソマー比測定」, 東京工業大学 .

受賞

H. Wang, 9th RIKEN Research Incentive Awards, 2017.

川瀬頌一郎,「^{93}Zr に対する 200 MeV/u 陽子・重陽子入射反応による同位体生成断面積測定」, 2017 年核データ研究会 最優秀ポスター賞 .

中野敬太, 日本原子力学会 2017 年春の年会 原子力・放射線分野を学び修めた学業優秀な学生に対する表彰 フェロー賞 .

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

RIBF 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.

3. Summary of Research Activity

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.

Members

Team Leader
Toshiyuki SUMIKAMA

List of Publications & Presentations

Publications
[Journal]
(Original Papers) *Subject to Peer Review

T. Sumikama, S. Nishimura, H. Baba, F. Browne, P. Doornenbal *et al*., "Observation of new neutron-rich Mn, Fe, Co, Ni, and Cu isotopes in the vicinity of ^{78}Ni," Phys Rev C **95**, 051601(R) (2017). *

F. Browne, A. M. Bruce, T. Sumikama,*et al*., "K selection in the decay of the (ν5/2[532]⊗3/2 [411]) 4^- isomeric state in ^{102}Zr," Phys. Rev. C **96**, 024309 (2017).*

Oral Presentations
[International Conference etc.]

T. Sumikama *et al*., "Pioneering work on low energy RI beams at RIBF," ImPACT-OEDO Workshop 2017, Wako, July 13−14, 2017.

T. Sumikama *et al*., "Towards lower beam energy at RIBF," ImPACT-OEDO Workshop 2017, Wako, July 13−14, 2017.

RIBF 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 the muonic atom and cascades down to the 1s 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 $^{A}_{Z}N\,(\mu^-, x\text{n}\nu)\,^{A-x}_{Z-1}N$ 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. High energy is suddenly introduced in the nuclei associated with a conversion of proton to neutron and neutrino. Many experimental results have been so far reported, but the reaction mechanism itself is not well clarified. The research team aims at obtaining the experimental data to understand the reaction mechanism of muon nuclear capture, and also at establishing the nuclear reaction theory.

2. Major Research Subjects

(1) Experimental clarification on the reaction mechanism of nuclear muon capture
(2) Establishment of the reaction theory on nuclear muon capture
(3) Interdisciplinary applications with 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) employing two experimental methods. By obtaining the experimental data on the Pd 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 targets is aiming at exploring a possible reaction path to make the nuclear transmutation of the Pd metal extracted from the spent nuclear fuel without an isotope separation process. This research was funded by the ImPACT Fujita Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

3.1 Experiments with "muon in-beam spectroscopy method"

Muon nuclear capture reactions were investigated on five isotope-enriched 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 directly gives the reaction branching ratio of $^{A}_{46}\text{Pd}(\mu^-, x\text{n}\nu)^{A-x}_{45}\text{Rh}$ 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 $^{104,\,105,\,106,\,108,\,110}$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, 500M 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.

3.2 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 $^{A}_{46}$Pd(μ⁻, xnν)$^{A-x}_{45}$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.

3.3 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 $^{A}_{40}$Zr(μ⁻, xnν)$^{A-x}_{39}$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 $^{107}_{46}$Pd(μ⁻, xnν)$^{107-x}_{45}$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 measured for the Pd target with ^{107}Pd. The reaction branching ratio of $^{107}_{46}$Pd(μ⁻, xnν)$^{107-x}_{45}$Rh reactions is finally determined. The detailed data analysis is in progress.

3.4 Comparison with theory

The muon activation method gives the reaction branching ratios. The muon in-beam method gives the neutron multiplicity and the neutron energy spectrum. These experimental results are important to investigate the compound nuclear state and neutron emission mechanism. The reaction branching ratios obtained by the muon activation method are compared with the measured neutron multiplicity. 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 results by the appropriate calculations employing the neutron emission mechanisms with an evaporation, a cascade and a direct emission processes under an assumption of the energy distribution at compound nuclear state.

Members

Team Leader
Teiichiro MATSUZAKI

List of Publications & Presentations

Oral Presentations

[Domestic Conference]

齋藤岳志,「ミュオン原子 X 線を用いた Pd 同位体の核荷電半径の測定」, 日本物理学会 第 73 回年次大会（2018 年）東京理科大学（野田キャンパス）（千葉県野田市）, 2018 年 3 月 22 日.

新倉潤,「Muon Nuclear Capture Reaction」, 第 8 回 Muon 科学と加速器研究, 高エネルギー加速器研究機構（茨城県つくば市）,2018 年 1 月 11 日.

齋藤岳志,「ミュオン原子 X 線から求める原子核荷電半径」, 第 8 回 Muon 科学と加速器研究, 高エネルギー加速器研究機構（茨城県つくば市）, 2018 年 1 月 11 日.

新倉潤,「Pd 同位体のミュオン原子核捕獲反応」, ImPACT-OEDO Workshop 2017, 理化学研究所 仁科加速器研究センター（埼玉県和光市）, 2017 年 7 月 13 日.

[特許出願]

国際特許公開：「ミュオン照射による放射性物質の製造方法およびその製造物質」, 国際出願番号：JP2017/003226, 出願人：理化学研究所, 国際出願日：2017 年 1 月 30 日, 発明者：松崎禎市郎, 櫻井博儀, 国際公開番号：WO2017/135196 A1, 国際公開日：2017 年 8 月 10 日.

RIBF Research Division
High-Intensity Accelerator R&D Group

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

(1) Based on the discussion with other research groups, R&D study of various accelerator components and elements is under progress.

Members

Group Director

Osamu KAMIGAITO (concurrent: Chief Scientist, Group Director, Accelerator Gr.)

RIBF 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
-Development of high-gradient cavites for low beta ions
-Development of power saving cryomodules

3. Summary of Research Activity
Development of highly efficient superconducting accelerator modules

Members

Team Leader
Naruhiko SAKAMOTO (concurrent: Cyclotron Team)

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

Nishina Center Research Scientist
Kenji SUDA (concurrent: Cyclotron Team)

Postdoctoral Researchers
Xingguang LIU

List of Publications & Presentations

Oral Presentations
[International Conference etc.]

N. Sakamoto, O. Kamigaito, H. Okuno, K. Ozeki, K. Suda, Y. Watanabe, K. Yamada, H. Hara, K. Sennyu, T. Yanagisawa, K. Okihara, E. Kako, H. Nakai, K. Umemori, “Construction and Performance Tests of Prototype Quarter-wave Resonator and its Cryomodule at RIKEN,” International Conference on RF Superconductivity, Lanzhou, China, July 17–21, 2107.

[Domestic Conference]

山田一成, 上垣外修一, 大関和貴, 坂本成彦, 須田健嗣, 渡邉裕, 加古永治, 仲井浩孝, 梅森健成, 宮本明啓, 仙入克也, 柳澤剛,「重イオン線形加速器用 λ/4 型超伝導加速空洞共振器プロトタイプシステムの開発」, 第 14 回日本加速器学会年会, 北海道大学, 札幌市, 2018 年 8 月 1–3 日.

山田一成, 上垣外修一, 大関和貴, 坂本成彦, 須田健嗣, 渡邉裕, 加古永治, 仲井浩孝, 梅森健成, 宮本明啓, 仙入克也, 柳澤剛,「核変換による高レベル放射性廃棄物の大幅な提言・資源化（加速器技術）(1) 超伝導用 λ/4 型共振器プロトタイプシステムの開発」, 日本原子力学会 2017 年秋の年会, 北海道大学, 札幌市, 2017年9月13−15 日.

Poster Presentations
[International Conference etc.]

X. Liu, O. Kamigaito, N. Sakamoto, K. Yamada, “Preliminary design of a high-intensity continuous-wave deuteron RFQ”, 8th International Particle Accelerator Conference, Copenhagen, Denmark, 14–19 May 2017.

Publications
[Proceedings]

X. Liu, O. Kamigaito, N. Sakamoto, K. Yamada, “Preliminary design of a high-intensity continuous-wave deuteron RFQ”, 8th International Particle Accelerator Conference, Copenhagen, Denmark, May 14−19, 2017, pp. 2287.

N. Sakamoto, O. Kamigaito, H. Okuno, K. Ozeki, K. Suda, Y. Watanabe, K. Yamada, H. Hara, K. Sennyu, T. Yanagisawa, K. Okihara, E. Kako, H. Nakai, K. Umemori, “Construction and Performance Tests of Prototype Quarter-wave Resonator and its Cryomodule at RIKEN”, International Conference on

RF Superconductivity,Lanzhou, China, July 17−21, 2107, pp. 681.
山田一成, 上垣外修一, 大関和貴, 坂本成彦, 須田健嗣, 渡邉裕, 加古永治, 仲井浩孝, 梅森健成, 宮本明啓, 仙入克也, 柳澤剛,「重イオン線形加速器用 λ/4 型超伝導加速空洞共振器プロトタイプシステムの開発」, 第 14 回日本加速器学会年会 2018年8月1–3日, 北海道大学, 札幌市, pp. 1395.

RIBF Research Division
High-Intensity Accelerator R&D Group
High-Power Target R&D Team

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

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

Members

Team Leader

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

Research and Technical Scientist

Yasuto MIYAKE (Postdoctoral Researcher)

Part-time Worker

Akira TAKAGI
YuVin SAHOO

RIBF Research Division
Accelerator Group

1. Abstract

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

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

2. Major Research Subjects

(1) Intensity upgrade of RIBF accelerators (Okuno)
(2) Effective and stable operation of RIBF accelerators (Fukunishi)
(3) Operation and maintenance of infrastructures for RIBF (Kase)
(4) Promotion of the future plan (Kamigaito, Fukunishi, Okuno)

3. Summary of Activity

(1) The maximum intensity of the uranium beam reached 71 pnA at 345 MeV/nucleon, which corresponds to 5.8 kW.
(2) The maximum intensity of the zinc beams reached 240 pnA at 345 MeV/nucleon, by using the fixed-energy mode of acceleration.
(3) An intense vanadium beam has been successfully developed at the 28-GHz ECRIS and accelerated through RRC.
(4) The overall beam availability for the RIBF experiments has been kept above 90 % since 2014.
(5) The large infrastructure was properly maintained based on a well-organized cooperation among the related sections.

Members

Group Director
Osamu KAMIGAITO

Deputy Group Directors
Hiroki OKUNO (Intensity upgrade)
Masayuki KASE (Energy-efficiency management)
Nobuhisa FUKUNISHI (Stable and efficient operation)

Postdoctoral Researcher
Joele Paulus MIRA

Junior Research Associates
Takahiro KARINO (Utsunomiya Univ.)

Part-time Worker
Akira GOTO

Research Consultant
Tadashi FUJINAWA

Visiting Scientists
Toshiyuki HATTORI (TIT)
Hirotaka NAKAI (KEK)
Kensei UMEMORI (KEK)
Eiji KAKO (KEK)
Robert JAMESON (IAP Frankfurt)
Noboru SASAO (Okayama Univ.)

Student Trainee
Akira FUJIEDA (Okayama Univ.)

Assistant
Karen SAKUMA

RIBF Research Division
Accelerator Group
Accelerator R&D Team

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

(1) Development of charge strippers for high power beams (foil, low-*Z* gas)
(H. Hasebe, H. Imao, H. Okuno)
We are developing the charge strippers for high intensity heavy ion beams. We are focusing on the developments on carbon or berrilium foils and gas strippers including He gas stripper.

(2) Upgrade of the superconducting ring cyclotron
(J. Ohnishi, H. Okuno)
We are focusing on the upgrade of the superconducting ring cyclotron.

(3) Maintenance and R&D of the electrostatic deflection/inflection channels for the beam extraction/injection
(J. Ohnishi, H. Okuno)
We are developing high-performance electrostatic channels for high power beam injection and extraction.

Members

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

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

Nishina Center Technical Scientist
Hiroo HASEBE

Visiting Scientists
Andreas ADELMANN (PSI)
Hironori KUBOKI (KEK)
Noriyosu HAYASHIZAKI (TIT.)

Junior Research Associate
Naoya IKOMA (Nagaoka Univ. of Technology)

List of Publications & Presentations

Publications
[Journal]
(Original Papers) *Subject to Peer Review

H. Hasebe, H. Okuno, H. Kuboki, H. Imao, N. Fukunishi, M. Kase, O. Kamigaito, "Development of rotating beryllium disk stripper," J. Radioanal. Nucl. Chem. **305**, 825 (2015).

[Proceedings]

(Original Papers) *Subject to Peer Review

H. Hasebe, H. Okuno, H. Kuboki, H. Imao, N. Fukunishi, M. Kase, O. Kamigaito, "History of solid disk improvement for rotating charge stripper," Proceeding of HIAT2015, MOA1C01, Yokohama, Japan (2015).

Oral Presentation

[International Conference etc.]

H. Hasebe, H. Okuno, H. Kuboki, H. Imao, N. Fukunishi, M. Kase, O. Kamigaito, "History of solid disk improvement for rotating charge stripper," HIAT2015, MOA1C01, Yokohama, Japan (2015).

Poster Presentation

[International Conference etc.]

H. Imao, H. Kuboki, H. Hasebe, O. Kamigaito, M. Kase, H. Okuno, "Operation of gas strippers at RIBF ; Thining effect of high-intensity very heavy ion beams," HIAT2015, MOPA32, Yokohama, Japan (2015).

RIBF Research 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 Scientist
Takashi NAGATOMO (Technical Scientist)

Nishina Center Research Scientists
Masanori KIDERA
Yoshihide HIGURASHI

Special temporal employee
Yasuyuki KANAI

List of Publications & Presentations

Publications
[Proceedings]
(Original Papers) *Subject to Peer Review

T. Nagatomo, V. Tzoganis, J. P. Mira, T. Nakagawa and O. Kamigaito, "Residual gas effect in LEBT on transverse emittance of multiply-charged heavy ion beams extracted from ECR ion source," Proceedings of 17th International Conference on Ion Sources, ICIS17, Geneva, Switzerland, Oct. 15–20, 2017 (accepted).

Oral Presentations
[International Conference etc.]

T. Nagatomo, "Residual gas effect in LEBT on transverse emittance of multiply-charged heavy ion beams extracted from ECR ion source," ICIS2017, Geneva, Switzerland, Oct. 15−20, 2017.

RIBF Research Division
Accelerator Group
RILAC Team

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

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

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

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

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

Members

Team Leader
Eiji IKEZAWA

Research & Technical Scientist
Yutaka WATANABE (Senior Technical Scientist)

Research Consultants
Masatake HEMMI

List of Publications & Presentations

Publications
[Proceedings]

A. Yusa, E. Ikezawa, T. Ohki, H. Yamauchi, K. Oyamada, M. Tamura, K. Kaneko, Y. Watanabe, K. Suda, K. Ozeki, K. Yamada, N. Sakamoto, M. Kase, O. Kamigaito, “Present Status of RILAC,” Proceedings of the 14th Annual Meeting of Particle Accelerator Society of Japan, 1400−1403 (2017).

Poster Presentations
[Domestic Conference]

A. Yusa, E. Ikezawa, T. Ohki, H. Yamauchi, K. Oyamada, M. Tamura, K. Kaneko, Y. Watanabe, K. Suda, K. Ozeki, K. Yamada, N. Sakamoto, M. Kase, O. Kamigaito, “Present Status of RILAC,” The 14th Annual Meeting of Particle Accelerator Society of Japan, Sapporo, Japan, August 1−3, 2017.

RIBF Research 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 Scientist
Kazutaka OZEKI

Nishina Center Research Scientist
Kenji SUDA

List of Publications & Presentations

Oral Presentations
[International Conference]

N. Sakamoto, O. Kamigaito, H. Okuno, K. Ozeki, K. Suda, Y. Watanabe, K. Yamada, H. Hara, K. Sennyu, T. Yanagisawa, K. Okihara, E. Kako, H. Nakai, K. Umemori, "Construction and Performance Tests of Prototype Quarter-wave Resonator and its Cryomodule at RIKEN," International Conference on RF Superconductivity, Lanzhou, China, July17−21, 2107.

Publications
[Proceedings]

N. Sakamoto, O. Kamigaito, H. Okuno, K. Ozeki, K. Suda, Y. Watanabe, K. Yamada, H. Hara, K. Sennyu, T. Yanagisawa, K. Okihara, E. Kako, H. Nakai, K. Umemori, "Construction and Performance Tests of Prototype Quarter-wave Resonator and its Cryomodule at RIKEN," International Conference on RF Superconductivity, Lanzhou, China, July17−21, pp. 681 (2107).

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

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

Poster Presentations

[Domestic Conference]

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

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

RIBF Research Division
Accelerator Group
Beam Dynamics & Diagnostics Team

1. Abstract

The cascaded cyclotron system at RIKEN RI Beam Factory (RIBF) requires not only strict matching of operation parameters but also high stability of all the accelerator components in order to establish stable operation of the world's most intense heavy-ion beams. Beam Dynamics and Diagnostics Team is responsible for power supplies, beam instrumentation, computer control and beam dynamic of the RIBF accelerator complex and strongly contributes to the performance upgrade of the RIBF.

2. Major Research Subjects

(1) Extracting the best performance of the RIBF accelerator complex based on the precise beam dynamics study.
(2) Maintenance and developments of the beam instrumentation, especially non-destructive monitors.
(3) Upgrade of the computer control system of the RIBF accelerator complex.
(4) Maintenance and improvements of the magnets and their power supplies.
(5) Upgrade of the existing beam interlock system for higher-intensity beams.

3. Summary of Research Activity

(1) High-intensity heavy-ion beams including 70-pnA uranium, 102-pnA xenon, 486-pnA krypton, and 740-pnA calcium beams have been obtained.
(2) The world-first high-T_c SQUID beam current monitor has been developed.
(3) The bending power of the fixed-frequency Ring Cyclotron has been upgraded to 700 MeV. It enables us to accelerate $^{238}U^{64+}$ ions obtained by the helium gas stripper.
(4) An EPICS-based control system and a homemade beam interlock system have been stably operated. Replacements of the existing legacy control system used in the old half of our facility is ongoing. Construction of the new control system for the new injector RILAC2 was successfully completed, where the embedded EPICS system running on F3RP61-2L CPU module, developed by KEK and RIKEN control group, was used.
(5) We replaced some dated power supplies of RIKEN Ring Cyclotron by new ones, which have better long-term stability than the old ones. The other existing power supplies (~900) are stably operated owing to elaborate maintenance work.
(6) We have contributed to RILAC2 construction, especially in its beam diagnosis, control system, magnet power supplies, vacuum system, high-energy beam transport system etc.

Members

Team Leader

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

Research & Technical Scientists

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

Nishina Center Technical Scientists

Misaki KOMIYAMA
Akito UCHIYAMA

Part-time Workers

Makoto NAGASE

Visiting Scientists

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

Visiting Technician

Jun-ichi ODAGIRI (KEK)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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

T. Maeyema, N. Fukunishi, K.L. Ishikawa, K. Fukasaku, S. Fukuda, "Organic-gelatin-free nanocomposite Fricke gel dosimeter," J. Phys. Chem. B, **2017**, 121 (16), pp. 4238−4246, doi:10.1021/acs.jpcb.6b11936 (2017).

Oral Presentations

[International Conference etc.]

A. Uchiyama, M. Komiyama, N. Fukunishi, "Implementation of web-based operational log system at RIBF," The 16th Int. Conf. on Accelerator and Large Experimental Control System (ICALEPCS2017), Barcelona, Spain, October 2017, THAPL01, doidoi:10.18429/JaCOW-ICALEPCS2017-THAPL01 (2017).

Poster Presentations

[International Conference etc.]

M. Komiyama, M. Fujimaki, N. Fukunishi, A. Uchiyama, M. Hamanaka, T. Nakamura, "Recent update of the RIKEN RI beam factory control system," The 16th Int. Conf. on Accelerator and Large Experimental Control System (ICALEPCS2017), Barcelona, Spain, October 2017, TUPHA028, doi:10.18429/JaCOW-ICALEPCS2017-TUPHA028 (2017).

[Domestic Conference]

T. Watanabe, N. Fukunishi, M. Fujimaki, R. Koyama, T. Toyama, T. Miyao, A. Miura, "Development of beam energy and position monitor system at RIBF," 14th Annual Meeting of Particle Accelerator Society of Japan, August 2017, Sapporo, Japan, pp. 1112−1117 (2017).

A. Uchiyama, M. Komiyama, "Improvement of data archive system at RIBF," 14th Annual Meeting of Particle Accelerator Society of Japan, August 2017, Sapporo, Japan, pp. 644−647 (2017).

RIBF Research Division
Accelerator Group
Cryogenic Technology Team

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

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

Members

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

Research & Technical Scientist
Masato NAKAMURA (Senior Technical Scientist)

Nishina Center Technical Scientist
Takeshi MAIE

Technical Staff I
Tomoyuki DANTSUKA

Part-time Worker
Shizuho TSURUMA

Mayumi KUROIWA

RIBF Research Division
Accelerator Group
Infrastructure Management Team

1. Abstract

The RIBF facility is consisting of many accelerators and its infrastructure is very important in order to make an efficient operation of RIBF project. We are maintaining the infrastructure of the whole system and to support the accelerator operation with high performance. We are also concerning the contracts of gas- and electricity-supply companies according to the annual operation plan. The contracts should be reasonable and also flexible against a possible change of operations. And we are searching the sources of inefficiency in the operation and trying to solve them for the high-stable machine operation.

2. Major Research Subjects

(1) Operation and maintenance of infrastructure for RIBF accelerators.
(2) Renewal of the old equipment for the efficient operation.
(3) Support of accelerator operations.

Members

Team Leader
Masayuki KASE (concurrent; Deputy Group Director, Accelerator Gr.)

Research & Technical Scientists
Shu WATANABE (Senior Technical Scientist)

Research Consultant
Hideyuki YAMASAWA

Visiting Scientist
Hideshi MUTO (Tokyo Univ. of Sci. Suwa)

RIBF Research Division
Instrumentation Development Group

1. Abstract

This group develops core experimental installations at the RI Beam factory. They are a slow-RI beam facility (SLOWRI), and highly program specific facilities of SCRIT and Rare-RI Ring (R3). All were designed to maximize the research potential of the world's most intense RI beams, made possible by the exclusive equipment available at the RI Beam Factory. While SLOWRI is under preparation for commissioning, physics experiments conducted in storage rings have been just started at SCRIT and R3 facilities. Beam manipulation techniques, such as a beam accumulation and a beam cooling, 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

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 (SCRIT and R3). 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. SCRIT is now under test experimental phase in which the angular distribution of scattered electrons from ^{132}Xe isotopes has been successfully measured and the nuclear charge density distribution has been obtained. Electron scattering off unstable nuclei is now under preparation for the first experiment in 2018. Rare RI Ring was commissioned in four-times machine-study experiments, and we have demonstrated that the ring has an ability for precision mass measurement with the accuracy of better than 10 ppm. We will be able to try to measure masses of nuclei $^{74\text{-}76}$Ni in 2018 and continuously make improvement in the accuracy. Construction of the SLOWRI system is now in tuning phase and it will be commissioned in 2018. PALIS device was commissioned in 2015 and 2016, and basic functions such as the RI-beam stopping in argon gas cell and the extraction with the gas flow were confirmed. Other devices are now under setting up for the first commissioning.

Members

Group Director
Masanori WAKASUGI

Visiting Scientist
Akira OZAWA (Univ. of Tsukuba)

Student Trainees
So SATO (Rikkyo Univ.)
Moe NAKANO (Rikkyo Univ.)

List of Publications & Presentations

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

RIBF Research 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. Two major online prototype setups have been successfully tested. The first was a large room-temperature gas cell with an RF-carpet structure. With this setup, the hyperfine structure constants of all odd Be isotopes were precisely measured by laser-microwave double resonance spectroscopy of trapped Be ions, following which the first online mass measurement with a multi-reflection time-of-flight mass spectrograph (MRTOF) was performed on $^{8}Li^{+}$ ions. The second prototype is a medium-sized cryogenic RF carpet gas cell for the SHE-Mass project that aims to measure the masses of trans-uranium elements at the GARIS-II facility. This prototype showed that a traveling-wave RF-carpet works fine and the cryogenic gas cell dominantly provides doubly charged ions even for Fr isotopes. Using the SHE-Mass setup, more than 80 nuclear masses have been measured including the first mass measurements of Md and Es isotopes.

2. Major Research Subjects

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

3. Summary of Research Activity

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

Installation of SLOWRI began in FY2013. It consists of two gas catchers (RF Carpet gas cell and PALIS gas cell), magnetic mass separators, a 50-m 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. This gas catcher comprises a large cryogenic He gas cell with a large traveling wave RF carpet. It will convert main beams of BigRIPS to low-energy, low-emittance beams without any restrictions from the chemical properties of the elements. The PALIS gas cell will be installed in the vicinity of the second focal plane slit of BigRIPS. It will provide parasitic RI beams from the ions normally lost in the slits during other experiments. In this gas catcher, thermalized RIs quickly become neutralized and will be selectively re-ionized by resonant laser radiations. These gas catchers have been tested off-line. The 50 m beam transport line consists of four dipole magnets (SD1 to SD4), two focal plane chambers, 62 electrostatic quadrupole singlets, 11 electrostatic quadrupole quartets (EQQ1 to EQQ11) and 7 beam profile monitors (BPMs). SD1 and SD2, located immediately after the gas catchers, will be used for isotope separation. After eliminating contaminant ions at the focal plane chamber, the low energy beam will be transported by a FODO lattice structure with phase space matching using EQQs. The EQQs have multipole elements made of 16 rods on which various potentials can be applied to produce 6-pole and 8-pole fields simultaneously to compensate for ion optical aberrations. This multipole element can also produce dipole fields for steering and scanning the beam. The BPMs have a classical cross-wire beam monitor as well as a channel electron multiplier with a pinhole collimator. Combining the scanning capability of the EQQs and the pinhole detector, we can observe a beam profile even for very-low-intensity RI beams. Off- and on-line commissioning is underway.

Based on test experiments with the prototype setups, the large RF-carpet gas cell contains a three-stage RF-carpet structure: a gutter RF carpet for the collection of thermal ions in the cell into a small slit, a narrow (≈10 mm) traveling-wave RF carpet for the collection of ions from the gutter carpet and for transporting the ions toward the exit, and a small RF carpet for extraction from the gas cell. An off-line test of the gutter structure has shown a high collection efficiency of ions in the gas cell.

(2) Laser spectroscopy of trapped radioactive beryllium isotope ions

As the first application of the prototype SLOWRI setup, we applied hyperfine structure spectroscopy on beryllium isotopes to determine, in particular, the anomalous radius of the valence neutron of the neutron halo nucleus ^{11}Be, and to determine the charge radii of these beryllium isotopes through laser-laser double resonance spectroscopy of laser-cooled ions. Laser cooling is an essential prerequisite for these planned experiments. The first laser spectroscopy experiments for beryllium isotopes were performed to measure the resonance frequencies of the 2s $^{2}S_{1/2}$ - 2p $^{2}P_{3/2}$ transition in $^{7}Be+$, $^{9}Be+$, $^{10}Be^{+}$ and $^{10}Be+$ ions and the nuclear charge radii of these isotopes were determined. The hyperfine structures of $^{11}Be^{+}$ and $^{7}Be^{+}$ ions were also determined using laser-microwave double resonance spectroscopy and the magnetic hyperfine constants of $^{7}Be^{+}$ and $^{11}Be^{+}$ ions were determined with accuracies better than 10^{-7}. A new combined-trap setup for high-precision determination of nuclear g-factors of the odd Be isotopes using a superconducting Helmholtz magnet is under preparation at the SLOWRI experimental area in collaboration with the Ueno nuclear spectroscopy laboratory.

(3) 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 by various methods since the early days of modern physics. From among many methods we have chosen a multi-reflection time-of-flight (MR-TOF) mass spectrometer. Slow RI beams extracted from the RF ion guide are bunched and injected into the spectrometer with a repetition rate of ~100 Hz. The spectrometer consists of two electrostatic mirrors between which the ions travel back and forth repeatedly. These mirrors are designed such that energy isochrononicity in the flight time is guaranteed during the multiple reflections, while the flight time varies with the masses of ions. A mass-resolving power of 170,000 has been obtained within a 2-ms flight time for the $^{40}K^{+}$ and $^{40}Ca^{+}$ isobaric doublet. This mass-resolving power should allow determination of ion masses with an accuracy of ≤ 10^{-7}. On-line mass measurement for the radioactive isotope ^{8}Li has been performed with the prototype SLOWRI setup.

The MR-TOF mass spectrograph has been placed under the GARIS-II separator with the goal of direct mass measurements of trans-uranium elements. A cryogenic gas catcher cell was placed at the focal plane box of GARIS-II and bunched low-energy heavy ion beams were transported to the trap of MR-TOF. In on-line commissioning experiments using No isotopes, an extraction efficiency greater than 30% was achieved from the cryogenic gas cel. In FY2016, 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 at GARIS-II in collaboration with the KEK Wako Nuclear Science Center and the Super Heavy Element Synthesis team of RIKEN. The highest precisions, achieved for Ga isotopes, reached a level of 0.03 ppm. For most of the well-known nuclides, agreement with the literature mass values was found. However, discrepancies were found in some literature values derived from pre-1980 indirect measurements. This suggests that such indirect measurements must be revised with comprehensive direct mass measurements. The masses of four isotopes of Es and Md were measured for the first time, allowing for confirmation of the N = 152 shell closure in Md. Using these new mass data as anchor points, the masses of seven isotopes of super-heavy elements up to Mt were indirectly determined and comparisons with various nuclear mass models were performed.

For comprehensive mass measurements of all available nuclides, multiple units of gas catchers and MR-TOF devices will be placed at the new GARIS-II, KISS, as well as the BigRIPS + SLOWRI facilities of RIBF.

(4) 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.

(5) 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 RIs using a compact gas catcher cell and resonance laser ionization, was proposed as a part of SLOWRI. The thermalized RI ions in a gas 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 ionized RI ions can be further selected by a magnetic mass separator and transported to the SLOWRI experimental area for various experiments. The resonance ionization scheme itself can also be a useful method to perform hyperfine structure spectroscopy of RIs of many elements.

A prototype setup has been used to test resonance ionization schemes of several elements, extraction from the cell, and transport to a high-vacuum chamber. An online setup was fabricated in FY2013 and the first online commissioning took place in FY2015. It was confirmed that the PALIS gas cell is not deleterious for BigRIPS experiments, and a reasonable amount of radioactive Cu isotopes were extracted from the cell by gas flow. Technical developments are in progress in on- and off-line commissioning.

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

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

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List of Publications & Presentations

Publications

[Journal]

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

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1. Abstract

Mass measurement is one of the most important contributions to a nuclear property research especially for 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. We chose a method of time-of-flight isochronous mass spectrometry (IMS) to make a measurement time shorter than 1 ms. Heavy-ion storage ring named "Rare-RI Ring (R3)" has been constructed until the end of 2014 and commissioning experiments were successfully performed in 2015. Our target performance in the mass determination is to achieve accuracy of the order of 1 ppm (~100 keV) even if we get only one event. Since an isochronism in R3 is established over a wide range of the momentum, rare-RIs with a large momentum spread, $\Delta p/p = \pm 0.5\%$, are acceptable. Another significant feature of the R3 system is an individual injection scheme in which a produced rare-RI itself triggers the injection kicker. In the first commissioning experiment using primary ^{78}Kr beam, we demonstrated a high ability of R3 as a storage ring and succeed in establishing the individual injection scheme for the first time. In 2016, we performed the third commissioning experiment using isotopes around ^{78}Ge. We successfully extracted several kinds of isotopes, ^{79}As, ^{77}Ga, ^{76}Zn, and ^{75}Cu from the R3 in the same setting and established the mass measurement method. In 2017, we were able to improve the extraction efficiency by a factor of 10 and be ready to conduct the first mass measurement experiment with R3. We have plan to measure masses for isotopes around ^{75}Ni and ^{124}Pd regions in 2018.

2. Major Research Subjects

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

3. Summary of Research Activity

Since the lattice design of R3 is based on the cyclotron motion, it can provide an isochronism in a wide range of the momentum. We expect a great improvement in mass resolution in IMS as long as the isochronous field is precisely formed in R3. Therefore, IMS using R3 is capable of both a high-precision measurement and a fast measurement. All the devices in R3 was designed under the assumption that an incoming beam has an energy of less than 200 MeV/nucleon and a charge to mass ratio, m/q, of less than 3. The ring structure was designed with a similar concept of a separate-sector ring cyclotron. It consists of six sectors and 4.02-m straight sections, and each sector consists of four rectangular bending magnets. A radially homogeneous magnetic field is produced in the magnet, and a magnetic rigidity is 6.5 Tm at maximum, for instance, ^{78}Ni with the magnetic rigidity of 5.96 Tm. Two magnets at both ends of each sector are additionally equipped with ten trim coils to form a precise isochronous magnetic field. For $\Delta p = 0$ particle, the circumference is 60.35 m and the betatron tunes are ν_x = 1.21 and ν_y = 0.84 in horizontal and vertical directions, respectively. The momentum acceptance is $\Delta p/p = \pm 0.5\%$, and the transverse acceptances are 150π mmmrad and 30π mmmrad in horizontal and vertical directions with $\Delta p/p = 0.0\%$, respectively.

Another performance required for R3 is to efficiently seize hold of an opportunity of the measurement for rare-RIs produced unpredictably. We adopted an individual injection scheme in which the produced rare-RI itself triggers the injection kicker magnets. Full activation of the kicker magnetic field has to 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. We successfully developed an ultra-fast response kicker system working with the repetition rate of 100 Hz.

Since R3 accumulates, in principle, only single ion, we need high-sensitive beam diagnostic devices in the ring, and they should be applicable even for a single particle circulation. One of them is a cavity type of Schottky pick-up installed for tuning of isochronous field. A resonance frequency is 171 MHz, a measured quality factor is about 1945, and shunt impedance is 190 kΩ. Another is a timing monitor, which detects secondary electrons emitted from thin carbon foil placed on the accumulation orbit. The thickness of the foil will be 50 μg/cm^2. The rare-RI with the energy of 200 MeV/nucleon survives only for first 100 turns because of an energy loss at the foil.

In 2015, we had two times of commissioning experiments. In the first commissioning, we used primary ^{78}Kr^{36+} beam with the energy of 168 MeV/nucleon. We succeeded in beam injection particle by particle in individual injection scheme, beam extraction after 700-μs accumulation (~1860 turns), and measurements of the TOF from the injection to the extraction. It was demonstrated that R3 works well as a storage ring and a single particle is certainly manipulated in this storage ring system. The individual injection scheme was established for the first time in the world. In addition, the Schottky pick-up monitored a single ^{78}Kr^{36+} particle circulation with the measuring time of less than 10 ms. That demonstrated that our pick-up is world most sensitive non-destructive monitor. In this experiment, we could tune completely the first order isochronism, but higher order components were remained, consequently, the 10-ppm accuracy of the isochronism was obtained. More precise tuning is possible with reference the Schottky data. In the second commissioning, we injected two isotopes, ^{36}Ar and ^{35}Cl, selected in the secondary beams into the ring, in which the isochronism is tuned for ^{36}Ar. It was obviously demonstrated that the mass of ^{35}Cl relative to ^{36}Ar is determined by comparing the TOF values for both isotopes, and the accuracy was ~20 ppm, which is one-order less than our target value of a few ppm. We found that the imperfection of isochronism significantly contributes to the time resolution of measured TOF values.

In 2016, we performed the third commissioning experiment using unstable nuclei. In this experiment, the 5-ppm accuracy of isochronism was obtained for the reference isotope ^{78}Ge by adjusting the isochronism up to second order. In addition, we derived the masses of ^{79}As, ^{77}Ga, ^{76}Zn, and ^{75}Cu relative to ^{78}Ge by determining its revolution time with beta correction. We found that not only the imperfection of isochronism but also the insufficient resolution of beta measurement significantly contributes to the mass resolution.

Detailed analysis is ongoing. In 2017, we performed the forth commissioning experiment using ^{78}Ge. In this experiment, we improved the extraction efficiency to 2% by considering the emittance matching. Since R3 is ready for mass measurement experiments, we will measure masses for isotopes around ^{75}Ni and ^{124}Pd regions in 2018.

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List of Publications & Presentations

Publications
[Journal]

(Review)

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RIBF Research Division
Instrumentation Development Group
SCRIT Team

1. Abstract

The SCRIT Electron Scattering Facility has been constructed at RIKEN RIBF. This aims at investigation of internal nuclear structure for short-lived unstable nuclei by means of electron scattering. SCRIT (Self-Confining RI Ion Target) is a novel method to form internal targets in an electron storage ring. This is a unique method for making electron scattering experiments for unstable nuclei possible. Construction of the facility has been started in 2009. This facility consists of an electron accelerator (RTM), a SCRIT-equipped electron storage ring (SR2), an electron-beam-driven RI separator (ERIS), and a window-frame spectrometer for electron scattering (WiSES) which consists of a large window-frame dipole magnet, drift chambers and trigger scintillators. Installation of all components in the facility was completed in 2015. After the comprehensive test and tuning, the luminosity was reached to 3×10^{27}/(cm^{2}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 3×10^{27}/(cm^{2}s) at maximum and the averaged value was 1.2×10^{27}/(cm^{2}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 will remodel the SCRIT electrodes. The vacuum pump system at the SCRIT device will be upgraded to reduce the contribution of residual gases. Luminosity for radioactive Xe isotopes is expected to be more than 10^{26}/(cm^{2}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 2017, several developments were started. 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 are in progress and they help to realize experiments for unstable nuclei.

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List of Publications & Presentations

Publications

[Journals]

K. Tsukada, A. Enokizono, T. Ohnishi, K. Adachi, T. Fujita, M. Hara, M. Hori, T. Hori, S. Ichikawa, K. Kurita, K. Matsuda, T. Suda, T. Tamae, M. Togasaki, M. Wakasugi, M. Watanabe, and K. Yamada, "First elastic electron scattering from ^{132}Xe at the SCRIT facility," Phys. Rev. Lett. **118**, 262501 (2017).

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Poster Presentations

[International Conference etc.]

T. Ohnishi, K. Adachi, A. Enokizono, T. Fujita, M. Hara, M. Hori, T. Hori, S. Ichikawa, K. Kasama, K. Kurita, T. Suda, T. Tamae, M. Togasaki, K. Tsukada, N. Uchida, M. Wakasugi, M. Watanabe, K. Yamada, "THE SCRIT electron scattering facility at RIKEN RI Beam Factory," 10th International Conference on Nuclear Physics at Storage Rings (STORI17), Kanazawa, Japan, November 13−17, (2017).

RIBF Research 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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RIBF Research Division
Research Instruments Group
BigRIPS Team

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

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

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

The research subjects may be summarized as follows:

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

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Shunki ISHIKAWA (Tohoku University)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

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Oral Presentations

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K. Kusaka, “RadiationEffects in Superconducting Quadruoles for BigRIPS In-flight Separator at RIKEN,” 13th European Conference on Applied Superconductivity, Geneva, Switzerland, September 17–21, 2017.

[Domestic Conference]

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RIBF Research Division
Research Instruments Group
SAMURAI Team

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

The current research subjects are summarized as follows:

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

Members

Team Leader
Hideaki OTSU

List of Publications & Presentations

Publications

[Journal]

(Original Papers)

S Chebotaryov *et al*., "Proton elastic scattering at 200 *A* MeV and high momentum transfers of 1.7–2.7 fm-1 as a probe of the nuclear matter density of ^{6}He," Prog. Theo. Exp. Phys., Volume **2018**, Issue 5, 1, 053D01 (20 pages).

J.W. Hwang, S. Kim, Y. Satou, N.A. Orr, Y. Kondo, T. Nakamura, J. Gibelin, N.L. Achouri, T. Aumann, H. Baba, F. Delaunay, P. Doornenbal, N. Fukuda, N. Inabe, T. Isobe, D. Kameda, D. Kanno, N. Kobayashi, T. Kobayashi, T. Kubo, S. Leblond, J. Lee, F.M. Marqués, R. Minakata, T. Motobayashi, D. Murai, T. Murakami, K. Muto, T. Nakashima, N. Nakatsuka, A. Navin, S. Nishi, S. Ogoshi, H. Otsu, H. Sato, Y. Shimizu, H. Suzuki, K. Takahashi, H. Takeda, S. Takeuchi, R. Tanaka, Y. Togano, A.G. Tuff, M. Vandebrouck, K. Yoneda, "Single-neutron knockout from ^{20}C and the structure of ^{19}C," Phys. Lett. B **769**, 503 (2017).

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J. Kahlbow, C. Caesar, T. Aumann, V. Panin, S. Paschalis, H. Scheit, H. Simon, "Neutron radioactivity—Lifetime measurements of neutron-unbound states," Nucl. Instrum. Methods Phys. Res. A **866**, 265（7 pages） (2017).

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Y. Kondo, (Invited) "Studies of neutron-neutron correlation near the drip line with SAMURAI at RIBF," International symposium on RI beam physics in the 21st century: 10th anniversary of RIBF, December 4–5, 2017, RIKEN.

S. Koyama, (Invited) "Study of cluster structure in ^{16}C," Workshop on Nuclear Cluster Physics 2017, 25th October, Sapporo, Japan.

V. Panin, (Invited) “Dissociation of proton-rich nuclei at SAMURAI as a method to study the most critical (p,γ) reaction rates in stellar nucleosynthesi,” KPS 2017 meeting, Daejeon, South Korea, Apr, 2017.

Y. Kubota, (Invited) “Probing neutron-neutron correlation in ^{11}Li via the quasi-free (p,pn) reaction,” Hadrons and Nuclear Physics meet ultracold atoms: a French Japanese workshop, Paris, France, 29 January–2 February, 2018.

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Y. Kubota, (Invited) “Dineutron correlation in Borromean nuclei,” 3rd International Workshop on Quasi-Free Scattering with Radioactive-Ion Beams: QFS-RB 17, York, United Kingdom, July, 24–27, 2017.

T.Nakamura, (Invited) “Spectroscopy of drip-line nuclei using the large acceptance spectrometer SAMURAI,” October 19–20, 2017, Collaboration Workshop on RI and Heavy-ion Sciences, Ewha Womans University, Seoul, South Korea.

T.Nakamura, (Invited) “Exploring Neutron Drip Line and Beyond by Breakup Reactions,” June 18–23, 2017, Nuclear Chemistry, Gordon Research Conference, Colby-Sawyer College, New London, NH, USA, Ewha Womans University, Seoul, South Korea.

T.Nakamura, (Invited) “Correlated neutron states near and beyond the neutron drip line,” December 18–22, 2017, International Workshop on Hadron and Nuclear Physics (HNP2017), RIKEN, Wako, Japan.

T.Nakamura, (Invited) “Study of neutron drip line nuclei by breakup reactions,” May 14–19, 2017, Int. Conf. on Isospin, STructure, Reactions and energy Of Symmetry (ISTROS), Casta Papiernicka, Slovakia.

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T.Nakamura, (Invited) “Exploring Nuclei beyond the Neutron Drip Line,” November 1–4, 2017, IIRC Symposium, Perspectives of the Physics of Nuclear Structure, Koshiba-Hall, U. of Tokyo, Tokyo, Japan.

A. Corsi, “Dineutron correlation in ^{14}Be and Spectroscopy of ^{13}Be probed via QFS reactions,” QFS workshop, York, July 24–26 2017.

T.Nakamura, “Exclusive Coulomb breakup of neutron drip-line nuclei,” August 8–11, 2017, SAMURAI International Collaboration Workshop, Lichtenberghus, Darmstadt, Germany.

Y. Kubota, “Neutron-neutron correlation in Borromean nucleus ^{11}Li,” SAMURAI International Collaboration Workshop 2017, Darmstadt, Germany, August 8–11, 2017.

S. Sakaguchi for SAMURAI13 collaboration, “Elastic scattering of polarized proton from ^{6}He,” SAMURAI International Collaboration Workshop 2017, Darmstadt, Germany, August 8–11, 2017.

Y. Kondo, “Status report of the SAMURAI21 experiment,” SAMURAI International collaboration workshop 2017, Darmstadt Germany, 8–11 August.

Y. Togano, “Progress report on the electric dipole response of n-ich Ca isotopes,” SAMURAI International collaboration workshop 2017, Darmstadt Germany, 8–11 August.

A. Saito, “Development of high resolution neutron detector HIME,” SAMURAI International collaboration workshop 2017, Darmstadt Germany, 8–11 August.

T. Tomai, “The SAMURAI27 experiment: Spectroscopy of ^{31}Ne using breakup reactions,” SAMURAI International collaboration workshop 2017, Darmstadt Germany, 8–11 August.

[Domestic Conference]

T.Nakamura, “Clustering and hierarchical structure of strongly-interacting systems,” 2017 年 9 月 13 日, 日本物理学会秋の分科会シンポジウム “Clustering as a window on the hierarchical structure of quantum systems,” 宇都宮.

近藤洋介 他, 「魔法数 $N = 20$ 近傍の非束縛酸素同位体の研究」, 日本物理学会 2017 年秋季大会, 2017 年 9 月 12–15 日, 宇都宮.

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栂野泰宏,「^{50,52}Ca の E1 応答測定」, 2017 年 9 月, 日本物理学会秋季大会, 宇都宮.

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Poster Presentation

[International Conference.]

T. Tomai, "Spectroscopy of ^{31}Ne using breakup reactions," Joliot Curie School, 24–29, Sep. 2017, Les Issambres, France.

[Domestic Conference]

島田哲朗, 中村隆司, 他 9 名, SAMURAI27 Collaboration,「中性子過剰非束縛核 ^{30}F の探索」, 2018 年 3 月 日本物理学会第 73 回年次大会, 野田.

Master Thesis

斗米貴人, 「変形誘因型ハロー核 ^{31}Ne の分解反応」, 東京工業大学理学院物理学系.

平山晃大, 「^{79,80}Se のクーロン分解反応断面積測定」, 東京工業大学理学院物理学系.

Bachelor Thesis

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受賞

斗米貴人, 「東京工業大学物理学コース優秀修士論文賞」, 2017 年 3 月.

RIBF Research 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. Because seven years have passed since the installation of this sever (HP-DL380G7), we replaced the server to HP-DL380G9 and RAID file system in January 2018. The current OS is Scientific Linux 7.5. 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 noticed that virus-infected mails were occasionally not detected by PMX in the case of new types of virus. Therefore, we added a new rule to PMX to isolate and remove executable image files attached in mail because they are often aimed at virus infection. As a result, most of the viruses in mails are successfully blocked by PMX. We are operating several information servers such as Web servers, Integrated Digital Conference (INDICO) server, Wiki servers, Groupware servers, Wowza streaming servers. An anonymous ftp server, FTP.RIKEN.JP , is managed and operated at the RNC. Major Linux distributions, including Scientific Linux, Ubuntu and CentOS, are mirrored daily for the convenience of their users and for facilitating high-speed access. An HP PloLiant DL-380G6 server was installed in 2009, and it was replaced by DL-380G9 in June 2017. Simultaneously, the OS was upgraded from SL 5.11 to SL 7.3. 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. Since the devices used for the Wireless LAN access points became obsolete, all of them were replaced by WAPM-1166D in 2016 and 2017, which supports the protocols of 802.11b, 11g, 11a, 11n, and 11ac. The UPS system of RIBF 1F server room (20KVA) was replaced in the summer of 2017 because they were installed in 2005 and exceeded the design life of 10 years.

(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 parallel readout from front-end systems, the dead time could be small. 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 bit, respectively. This time stamping system is very useful for beta decay experiments such as EURICA and BRIKEN projects. The current main task 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 taken by their DAQ systems are transferred to RIBFDAQ. 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 use individual trigger for each detector system. In this case, data are merged in offline. In addition to the development DAQ system, we are developing intelligent circuits based on FPGA. Mountable Controller (MOCO) is a very fast readout controller for VME modules. General Trigger Operator (GTO) is an intelligent triggering NIM module. Functions of “common trigger management”, “gate and delay generator”, “scaler” are successfully implemented. The trigger system in BigRIPS DAQ has been successfully upgraded by 5 GTO modules.

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

We have been managing the network environment collaborating with Advanced Center for Computing and Communications (ACCC). All the Ethernet ports of the information wall sockets are capable of the Gigabit Ethernet connection (10/100/1000BT). In addition, a 10

Gbps network port has been introduced to the RIBF Experimental area in for the high speed data transfer of RIBF experiment to ACCC in near future. Approximately 65 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 ACCC.

Members

Team Leader

Takashi ICHIHARA (concurrent; Vice Chief Scientist, RI Physics Lab.)

Research & Technical Scientist

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

Nishina Center Research Scientist

Hidetada BABA

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

C. Aidala *et al*. (PHENIX Collaboration), "B-meson production at forward and backward rapidity in p+p and Cu+Au collisions at √sNN=200 GeV," Phys. Rev. C **96**, 064901 (2017).

A. Adare *et al*. (PHENIX Collaboration), "Measurements of e^+e^- pairs from open heavy flavor in p+p and d+A collisions at √sNN=200 GeV," Phys. Rev. C **96**, 024907 (2017).

C. Aidala *et al*. (PHENIX Collaboration), "Cross section and transverse single-spin asymmetry of muons from open heavy-flavor decays in polarized p+p collisions at √s = 200 GeV," Phys. Rev. D **95**, 112001 (2017).

A. Adare *et al*. (PHENIX Collaboration), "Angular decay coefficients of J/ψ mesons at forward rapidity from p+p collisions at √s=510 GeV," Phys. Rev. D **95**, 092003 (2017).

C. Aidala *et al*. (PHENIX Collaboration), "Measurements of B→J/ψ at forward rapidity in p+p collisions at √s=510 GeV, Phys. Rev. D **95**, 092002 (2017).

A. Adare *et al*. (PHENIX Collaboration), "Nonperturbative-transverse-momentum effects and evolution in dihadron and direct photon-hadron angular correlations in p+p collisions at √s=510 GeV," Phys. Rev. D **95**, 072002 (2017).

Oral Presentations

[International Conference]

H. Baba, "Study of low-lying states in unstable oxygen isotopes using isoscalar and isovector probes," IVth Topical Workshop on Modern Aspects in Nuclear Structure, Bormio, Italy, 19−25th February, 2018 (Invited).

[Domestic Conference]

H. Baba, "Development of the multihost-type DAQ front-end system," JPS Annual Meeting, 22−25th March, Noda, Chiba, Japan, 2018.

RIBF Research 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 and Technical Scientist
Tokihiro IKEDA (Senior Research Scientist)

Special Temporary Employee
Manabu HAMAGAKI

Visiting Scientist
Takeshi KOIKE (Tohoku University)

Student Trainee
Itaru HAKAMADA (Tokyo University)
Kanji HIROSE (Toho University)
Kenta SATO (Toho University)

List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

J.W. Hwang, S. Kim, Y. Satou, N.A. Orr, Y. Kondo, T. Nakamura, J. Gibelin, N.L. Achouri, T. Aumann, H. Baba, F. Delaunay, P. Doornenbal, N. Fukuda, N. Inabe, T. Isobe, D. Kameda, D. Kanno, N. Kobayashi, T. Kobayashi, T. Kubo, S. Leblond, J. Lee, F.M. Marques, R. Minakata, T. Motobayashi, D. Murai, T. Murakami, K. Muto, T. Nakashima, N. Nakatsuka, A. Navin, S. Nishi, S. Ogoshi, H. Otsu, H. Sato, Y. Shimizu, H. Suzuki, K. Takahashi, H. Takeda, S. Takeuchi, R. Tanaka, Y. Togano, A.G. Tuff, M. Vandebrouck, K. Yoneda, "Single-neutron knockout from C-20 and the structure of C-19," Phys. Lett. B **769**, 503−508 (2017). *

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N. Fukuda, T. Kubo, D.,Kameda, N. Inabe, H. Suzuki, Y. Shimizu, H. Takeda, K. Kusaka, Y. Yanagisawa1 M. Ohtake, K. Tanaka, K. Yoshida, H. Sato, H. Baba, M. Kurokawa, T. Ohnishi, N. Iwasa, A. Chiba, T. Yamada, E. Ideguchi, S. Go, R. Yokoyama, T. Fujii, H. Nishibata, K. Ieki, D. Murai, S. Momota, D. Nishimura, Y. Sato, J.W. Hang, S. Kim, O.B. Tarasov, D.J. Morrissey, G. Simpson, "Identification of New Neutron-Rich Isotopes in the Rare-Earth Region Produced by 345 MeV/nucleon U-238," J Phys. Soc. Jpn. **87**, 014202 (2018). *

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J. A. Tanis, D. Keerthisinghe, S. Wichhramarachchi, T. Ikeda, and N. Stolterfoht, "Charge deposition dependence of electron transmission through PET nanocapillaries and a tapered glass microcapillary," Nucl. Instrum. Methods Phys. Res. **B** 423, 1−6 (2018). *

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[International Conference etc.]

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T. Ikeda, T. M. Kojima, Y. Natsume, J. Kimura, and T. Abe, "Active discharging method for stable transmission of slow highly-charged ions through sub-micron glass capillary," The 25th International Symposium on Ion-Atom Collisions (ISIAC 2017), (Hotel Grand Chancellor), Palm Cove, Queensland, Australia, July (2017).

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[Domestic Conference]

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Poster Presentations

[International Conference etc.]

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T. Ikeda, T. M. Kojima, Y. Natsume, J. Kimura, and T. Abe, "Active discharging method for stable sub-micron sized beams of slow highly charged ions using tapered glass capillary with electrodes," the 30th International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC XXX), (Cairns Convention Centre), Cairns, Queensland, Australia, August (2017).

M. Matsubara, T. Masuyama, T. Ikeda, T. Minowa, and W.-G.Jin, "Propagation of Laser Light Through Glass Capillaries for Ultraviolet Microbeams," International Conference on Quantum Atomic, Molecular and Plasma Physics, (Hilton Glasgow Grosvenor Hotel), Glasgow, UK, September (2017).

J. Tanis, D. Keerthisinghe, S. Wichhramarachchi, T. Ikeda, and N. Stolterfoht, "Charge (time) dependence of electron transmission through PET and tapered glass capillaries," 22nd International Workshop on Inelastic Ion-Surface Collisions (IISC-22), (Hotel Schloss Eckberg), Dresden, Germany, September (2017).

RIBF Research Division
Accelerator Applications Research Group

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

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

Members

Group Director

Tomoko ABE

List of Publications & Presentations

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

RIBF Research Division
Accelerator Applications Research Group
Ion Beam Breeding Team

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

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

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

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

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

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

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

(3) Innovative application of heavy-ion beams

We have formed a consortium for ion-beam breeding. It consisted of 24 groups in 1999, in 2017, it consisted of 176 groups from Japan and 11 from overseas. Breeding was performed previously using mainly flowers and ornamental plants. We have recently put a new sweet-smelling onion cultivar with tearless and non-pungent, ‘Smile Balls’ on the market. Beneficial variants have been grown for various plant species, such as high yield rice, semi-dwarf early rice, semi-dwarf buckwheat, semi-dwarf barley, hypoallergenic peanut, spineless oranges, non-flowering Eucalyptus and lipids-hyperaccumulating unicellular alga. The target of heavy-ion breeding is extended from flowers to crops so that it will contribute to solve the global problems of food and environment. We collaborate with the National Research and Development Agency, Japan Fisheries Research and Education Agency and Nagasaki University. The monogonont rotifer (*Brachionus* spp.) is a complex species and an essential food source for finfish aquaculture. The *B. plicatilis* is divided into three major clades (small, medium and large(L)) based on body length. Although the body size ranges from 100 to 300 μm in length, a mutation breeding of rotifers with larger size is expected for the purpose of productivity improvement in the aquaculture industry. Therefore, we conducted a large-scale screening to isolate gigantic rotifers by heavy-ion-beam irradiation to L-type rotifers. Then we have established some dozens of mutant lines that have an average length of over 350 μm (a maximum length reached 394 μm) through over ten thousand of individual mutagenized lines. These data will be useful to choose the suitable lines that satisfies the request of the aquaculture industry.

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List of Publications & Presentations

Publications

[Journal]

(Original Papers) *Subject to Peer Review

M. Amino, K. Yoshioka, Y. Furusawa, S. Tanaka, N. Kawabe, T. Hishida, T. Tsukada, M. Izumi, S. Inokuchi, T. Abe, T. Tanabe, Y. Ikari, “Inducibility of Ventricular Arrhythmia 1 Year Following Treatment with Heavy Ion Irradiation in Dogs with Myocardial Infarction,” Pacing Clin. Electrophysiol. **40**(4), 379−390 (2017). *

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Poster Presentations

[International Conference]

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RIBF Research Division
Accelerator Applications Research Group
RI Applications Team

1. Abstract

The RI Applications Team develops production technologies of radioisotopes (RIs) at RIKEN RI Beam Factory (RIBF) for application studies in the fields of physics, chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences. We use the RIs mainly for nuclear and radiochemical studies such as RI production and superheavy element chemistry. The purified RIs such as ^{65}Zn, ^{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 also develop chemical materials for ECR ion sources of heavy-ion accelerators in RIBF.

2. Major Research Subjects

(1) Research and development of RI production technology at RIBF
(2) RI application researches
(3) Development of trace element and isotope analyses and their applications to geoscience and environmental science
(4) Development of chemical materials for ECR ion sources of heavy-ion accelerators in RIBF

3. Summary of Research Activity

(1) Research and development of RI production technology at RIBF and RI application studies

Due to its high sensitivity, the radioactive tracer technique has been successfully applied for investigations of the behavior of elements in the fields of chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences. We have been developing production technologies of useful radiotracers at RIBF and conducting their application studies in collaboration with many researchers in various fields. With 14-MeV proton, 24-MeV deuteron, and 50-MeV alpha beams from the AVF cyclotron, we presently produce about 50 radiotracers from ^{7}Be to ^{211}At. Among them, ^{65}Zn, ^{85}Sr, ^{88}Y, and ^{109}Cd are delivered to Japan Radioisotope Association for fee-based distribution to the general public in Japan. Our RIs are also distributed to researchers under the Supply Platform of Short-lived Radioisotopes for Fundamental Research, supported by MEXT KAKENHI. On the other hand, radionuclides of a large number of elements are simultaneously produced from metallic targets such as ^{nat}Ti, ^{nat}Ag, ^{nat}Hf, and ^{197}Au irradiated with a 135-MeV nucl.$^{-1}$ ^{14}N beam from the RIKEN Ring Cyclotron. These multitracers are also supplied to universities and institutes as collaborative researches.

In 2017, we developed production technologies of radioisotopes such as ^{24}Na, ^{42,43}K, ^{44m}Sc, ^{48,51}Cr, ^{67}Cu, ^{74}As, ^{88}Y, ^{135m}Ba, ^{139}Ce, ^{143}Pm, ^{206}Bi, and ^{211}At which were strongly demanded but lack supply sources in Japan. We also investigated the excitation functions for the ^{64}Ni(α, x), ^{89}Y(α, x), ^{nat}Zr(α, x), ^{nat}In(α, x), ^{169}Tm(α, x), ^{nat}Yb(α, x), ^{nat}Hf(α, x), and ^{nat}W(α, x) reactions to quantitatively produce useful RIs. We used radiotracers of ^{48,51}Cr, ^{74}As, ^{88}Y, ^{135m}Ba, ^{139}Ce, ^{143}Pm, ^{206}Bi, and ^{211}At for application studies in chemistry, ^{24}Na, ^{42,43}K, ^{44m}Sc, ^{67}Cu, and ^{211}At in nuclear medicine, and ^{88}Zr and ^{175}Hf in geochemistry. We also produced ^{65}Zn, ^{85}Sr, ^{88}Y, and ^{109}Cd for our scientific researches on a regular schedule and supplied the surpluses through Japan Radioisotope Association to the general public. In 2017, we accepted 2 orders of ^{65}Zn with a total activity of 5.5 MBq, 1 order of ^{85}Sr with 3.7 MBq, and 2 orders of ^{88}Y with 2 MBq. We also distributed ^{44m}Sc (5 MBq × 1), ^{67}Cu (10 MBq × 1), ^{88}Zr (1 MBq × 1 and 2 MBq × 1), ^{121m}Te (2 MBq × 1), and ^{211}At (40 MBq × 3) 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 radiation 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. 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 installed a gas-jet coupled target system and a safety system for a radioactive ^{248}Cm target on the beam line of AVF. A chemistry laboratory, AVF hot laboratory, was also constructed on the upper floor of AVF. Aqueous chemistry apparatuses for ion exchange, solvent extraction, and electrolysis are under development together with an automated α-particle detection system.

In 2017, we produced radiotracers of ^{88}Zr, ^{92m,95}Nb, ^{93m}Mo, ^{95m}Tc, ^{175}Hf, ^{179}Ta, ^{179m,181}W, and ^{183}Re at AVF and conducted model experiments for aqueous chemistry studies on Rf, Db, Sg, and Bh.

(3) Development of trace element and isotope analyses and their applications to geoscience and environmental science

We have been developing the ECR Ion Source Mass Spectrometer (ECRIS-MS) for trace element analyses. In 2017, we renovated the detection system of ECRIS-MS and evaluated 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. This technique is expected to monitor the atmosphere around nuclear power plants.

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 lead and sulfur isotope ratios on cinnabar and asphalt samples from ancient ruins in Japan to elucidate the distribution of goods in the archaic society and to reveal the establishment of the Yamato dynasty in the period from Jomon to Tumulus. In 2017, we improved the sensitivity for the sulfur isotope ratios with the "trapping and focusing" techniques using a cryo-system and applied the analyses of pigment from Roman ruins, such as Badalona (Spain).

(4) Development of chemical materials for ECR ion sources of RIBF

In 2017, 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

[Journal]

(Original Papers) *Subject to Peer Review

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[International Conference etc.]

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RIBF Research Division
User Liaison and Industrial Cooperation Group

1. Abstract

The essential mission of the "User Liaison and Industrial Cooperation (ULIC) Group" is to maximize the research activities of RIBF by attracting users in various fields with a wide scope.

The ULIC Group consists of two teams.

The RIBF User Liaison Team provides various supports to visiting RIBF users through the User's Office. The Industrial Cooperation Team supports potential users in industries who use the beams for application purposes or for accelerator related technologies other than basic research. Production of various radioisotopes by the AVF cyclotron is also one of the important mission. The produced radioisotopes are distributed to researchers in Japan for a charge through the Japan Radioisotope Association.

In addition the ULIC Group takes care of laboratory tours for RIBF visitors from public. The numbers of visitors amounts to 2,300 per year.

Members

Group Director
Hideyuki SAKAI

Special Temporary Employee
Tadashi KAMBARA

Senior Visiting Scientists
Ikuko HAMAMOTO (Lund Univ.)
Munetake ICHIMURA (Univ. of Tokyo)

Assistants
Tomomi OKAYASU
Yoko FUJITA
Yu NAYA
Midori YAMAMOTO

RIBF Research Division
User Liaison and Industrial Cooperation Group
RIBF User Liaison Team (User Support Office)

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

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Ken-ichiro YONEDA

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RIBF Research Division
User Liaison and Industrial Cooperation Group
Industrial Cooperation Team

1. Abstract
Industrial cooperation team handles non-academic activities at RIBF corresponding to industries and to general public.

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

3. Summary of Research Activity
(1) Fee-based distribution of radioisotopes

This team has been handling fee-based distribution of radioisotopes since 2007. Radionuclides of Zn-65, Sr-85, Y-88 and Cd-109, which are produced by the RI application team at the AVF cyclotron, are distributed to nonaffiliated users under a Material Transfer Agreement (MTA) between Japan Radioisotope Association and RIKEN. In FY 2017, we delivered 2 shipments of Zn-65 with a total activity of 4.2 MBq, one shipment of Y-88 with an activity of 1 MBq and one shipment of Sr-85 with an activity of 3.7 MBq. The final recipients of the RIs were two universities and two research institutes.

(2) Support of Industrial application using RIBF

RNC promote facility-sharing program "Promotion of applications of high-energy heavy ions and RI beams." In this program, RNC opens the old part of the RIBF facility, which includes the AVF cyclotron, RILAC, RIKEN Ring Cyclotron and experimental instruments, to non-academic proposals from users including private companies. The proposals are reviewed by a program advisory committee, industrial PAC (InPAC). The proposals which have been approved by the InPAC 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 January 2018, the seventh InPAC met and reviewed one fee-based proposal from a private company. In February 2018, a fee-based beamtime was performed with a Kr-84 (70 MeV/A) beam at the E5A beamline for 4 days. The client used the beam to simulate single-event effects of space-use semi-conductors by heavy-ion components of cosmic rays. In the same month, we performed a test beamtime at the same beamline to study the characteristics of a higher LET Xe-136 (10.75 MeV/A) beam.

(3) Development of real-time wear diagnostics 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. This method can be used for real-time inspection of a closed system in a running machine. In 2017, we performed single-photon emission computer tomography (SPECT) mode measurement with sources of Cs-137, Eu-152 and Na-22.

Members

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List of Publications & Presentations
Publications
[Journal]

(Original Papers) *Subject to Peer Review

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[Domestic Conference]

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List of Intellectual Properties

Patents

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

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RIBF Research Division
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 radiation shield on the beam line between SRC and BigRIPS was installed. Though there was future risk of radiation dose level higher than legal limit, it was reduced to about 1/10.

The radiation control system for RILAC accelerator were newly developed. The RILAC accelerator will be upgraded and new radiation control system is required. The software development was completed. It will set in the next year.

Minor improvements of the radiation safety systems were also done. The radiation monitors at the Nishina building has been replaced annually from 2015 because they get older, which were installed in 1986.

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List of Publications & Presentations

Oral Presentations

[International Conference etc.]

K. Tanaka, "Improvement of emergency evacuation from underground at RIBF accelerator facility", International Technical Safety Forum 2017 (ITSF2017), Vancouver, Canada, September (2017).

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赤塩敦子, 杉原健太, 執行信寛, 田中鐘信,「345MeV/u ウランビームを用いた放射線評価」, 日本原子力学会 2018 年春の年会, 吹田市, 3 月 (2018).

Partner Institutions

The Nishina Center established the "Research Partnership System" in 2008. This system permits an external institute to develop its own projects at the RIKEN Wako campus in equal partnership with the Nishina Center. At present, three institutes, Center for Nuclear Study, the University of Tokyo (CNS); Institute of Particle and Nuclear Studies, KEK (KEK); and the Institute of Science and Technology, Niigata University (Niigata) are conducting research activities under the Research Partnership System.

CNS and the Nishina Center signed the partnership agreement in 2008. Until then, CNS had collaborated in joint programs with RIKEN under the "Research Collaboration Agreement on Heavy Ion Physics" (collaboration agreement) signed in 1998. The partnership agreement redefines procedures related to the joint programs while keeping the spirit of the collaboration agreement. The joint programs include experimental nuclear physics activities using CRIB, SHARAQ, and GRAPE at RIBF, theoretical nuclear physics activities with ALPHLEET, accelerator development, and activities at RHIC PHENIX.

The partnership agreement with the Niigata University was signed in 2010. The activity includes theoretical and experimental nuclear physics, and nuclear chemistry.

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. In this year, a new KEK branch, Wako Nuclear Science Center (WNSC) has been launched at the Wako campus to enhance the scientific activities of KISS.

The experimental proposals that request the use of the above-noted devices of CNS and KEK together with the other RIBF key devices are screened by the Program Advisory Committee (PAC). The PAC meetings are co-hosted by CNS and KEK.

The activities of CNS, Niigata, and KEK are reported in the following pages.

Partner Institution
Center for Nuclear Study, Graduate School of Science
The University of Tokyo

1. Abstract

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

2. Major Research Subjects

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

3. Summary of Research Activity

(1) Accelerator Physics

One of the major tasks of the accelerator group is the AVF upgrade project that includes development of ion sources, upgrading the AVF cyclotron of RIKEN and the beam line to CRIB. In 2017, the operating time of the HyperECR was 2414 hours, which is 61 % of the total operating time of the AVF cyclotron. The beam extraction system of the HyperECR is under development to realize a high intensity and low emittance beam. We have succeeded to suppress $^{12}C^{4+}$ beam which contaminated $^{18}O^{6+}$ beam by measuring the light intensity of the CIV line spectrum. The calculation model of injection beam orbit of the AVF cyclotron was completed and the adjustment of the positon and angle deviation between the measured beam orbit and the calculated beam orbit is carried on. The detailed studies on ion optics of the beamline to CRIB from AVF cyclotron were performed with beam diagnosis system and simulation code, and it turned out the loss of the beam intensity is occurred at the entrance of the vertical deflection bending magnet.

(2) Nuclear Astrophysics

The main activity of the nuclear astrophysics group in CNS is experimental studies on astrophysical reactions and special nuclear clustering using the low-energy RI beam separator CRIB. In 2017, a strong indication of an exotic linear-chain cluster structure in ^{14}C nucleus was presented based on the $^{10}Be + \alpha$ resonant scattering measurement at CRIB. To give a solution to the cosmological ^{7}Li abundance problem, two experimental projects are in progress. One is to determine the $^{7}Be(n, \alpha)/(n, p)$ astrophysical reaction rates with the Trojan Horse method, and another is the measurement of $^{7}Be(d, p)$ with a ^{7}Be-implanted target. The latter project is in collaboration with RCNP, Osaka Univ. and JAEA, and CRIB was used for the ^{7}Be target production. Based on the interest of the galactic γ-ray production, a proton resonant scattering experiment with ^{26}Al isomeric beam was performed at CRIB in Mar. 2017. With the analysis followed that, the isomeric purity was found to be about 50%. Resonances in ^{27}Si are observed in the relevant energy range of supernovae, and we may be able to discuss possible destruction of ^{26}Al in supernovae.

(3) Nuclear structure of exotic nuclei

The NUSPEQ (NUclear SPectroscopy for Extreme Quantum system) group studies exotic structures in high-isospin and/or high-spin states in nuclei. The CNS GRAPE (Gamma-Ray detector Array with Position and Energy sensitivity) is a major apparatus for high-resolution in-beam gamma-ray spectroscopy. Missing mass spectroscopy using the SHARAQ is used for another approach on exotic nuclei. In 2017, the following progress has been made. Experimental data taken under the EURICA collaboration has been analyzed for studying octupole deformation in neutron-rich Ba isotopes and preparing publication. A new experiment measuring the $^{4}He(^{8}He, ^{8}Be)4n$ reaction was performed for better statistics and better accuracy in order to verify a candidate of the ground state of the tetra neutrons just above the 4n threshold, which is under analysis.

(4) Quark Physics

Main goal of the quark physics group is to understand the properties of hot and dense nuclear matter created by colliding heavy nuclei at relativistic energies. The group has been involved in the PHENIX experiment at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, and the ALICE experiment at Large Hadron Collider (LHC) at CERN. As for ALICE, the group has involved in the data analyses, which include the measurement of low-mass lepton pairs in Pb-Pb and *p*-Pb collisions, J/ψ measurements in *p*-Pb collisions, long range two particle correlations in *p*-Pb collisions, and searches for thermal photons in *p*-Pb collisions. The group has involved in the ALICE-TPC upgrade using a Gas Electron Multiplier (GEM). Development of the new data readout system for the upgrade, which aims online data processing by utilizing FPGA and GPU, has been ongoing in 2017.

(5) Nuclear Theory

The nuclear theory group participates a project, "Priority Issue 9 to be tackled by using the Post-K Computer" and promotes computational nuclear physics utilizing supercomputers. In FY2017, we performed the Monte Carlo shell model calculations of the Sn isotopes and revealed that the anomalous enhancement of the B(E2) transition probabilities in the neutron-deficient region is caused by the proton excitation from the $1g_{9/2}$ orbit, and found that the second-order quantum phase transition occurs around $N = 66$. We also investigated the double Gamow-Teller strength distribution of double-beta decay emitters, such as ^{48}Ca. We theoretically predict a linear relation between the nuclear matrix elements of the double Gamow-Teller transition and the neutrinoless double beta decay. In parallel, we have been promoting the CNS-RIKEN collaboration project on large-scale nuclear structure calculations and performed shell-model calculations under various collaborations with many experimentalists for investing the exotic structure of neutron-rich nuclei, such as ^{35}Mg, ^{136}Ba, ^{138}Ce, and ^{135}La.

(6) OEDO/SHARAQ project

The OEDO/SHARAQ group pursues experimental studies of RI beams by using the high-resolution beamline and the SHARAQ spectrometer. A mass measurement by TOF-$B\rho$ technique for very neutron-rich successfully reaches calcium isotopes beyond $N = 34$, $^{55-57}$Ca, and the preparation of publication is ongoing. The experimental study of 0^- strength in nuclei using the parity-tansfer charge exchange (^{16}O, ^{16}F) is on progress and the data analysis is on the final stage. The OEDO beamline, which was an upgrade of the high-resolution beamline to produce low-energy RI beams, has started the operation in June and has successfully achieved the designed ion-optical performance. The first and second experiments were performed in October and November, and new data for nuclear transmutation of long lived fission products (LLFPs) were successfully obtained.

(7) Exotic Nuclear Reaction

The Exotic Nuclear Reaction group studies various exotic reactions induced by beams of unstable nuclei. One subject is inverse-kinematics (p, n) reaction. In 2017 a set of neutron counters PANDORA was used for the first time at HIMAC facility for the study of the ^{6}He(p, n) reaction. Candidate nuclei to study are high spin isomers such as ^{52}Fe(12^+). Development of isomer beam was carried out.

(8) Low Energy Nuclear Reaction Group

A recoil particle detector for missing mass spectroscopy, named TiNA, had been developed under the collaboration with RIKEN and RCNP. TiNA consists of 6 sector telescopes. Each of which as a stripped-type SSD and 2 CsI(Tl) crystals. After the test experiment at the tandem facility of Kyushu Univ., TiNA was employed at the physics experiment with OEDO. Development of the tritium target is still on-going. Several deuterium doped Ti targets were fabricated at the Toyama Univ. They were tested by using d(^{12}C, d) reaction at the tandem facility at Kyushu. The amount of deuterium was found to be scattered. The optimum condition to make the target will be sought for. The production cross section ^{178m2}Hf was evaluated for the mass production in the future. The digital signal processing devices for the GRAPE have been developed to measure the cascade transitions from the isomeric state. After chemical separation of Hf at the hot laboratory at RIBF. The week cascade decay was successfully measured.

(9) Active Target Development

Two types of gaseous active target TPCs called CAT's and GEM-MSTPC are developed and used for the missing mass spectroscopy. The CAT's are employed for the study of equation of state of nuclear matter. The measurement of giant monopole resonance in ^{132}Sn at RIBF with CAT-S and the data analysis is ongoing. In 2017, we developed a larger active target called CAT-M, which has 10-times larger active volume than that of CAT-S. The CAT-M was commissioned at HIMAC and the excitation energy spectrum of ^{136}Xe for proton scattering was measured. The GEM-MSTPC is employed for the nuclear astrophysics study. The data analysis of (α, p) reaction on ^{18}Ne and ^{22}Mg and the β-decay of ^{16}Ne followed by
α emission are ongoing.

(10) Fundamental Physics

Although the Standard Model of particle physics is being steadily and successfully verified, the disappearance of the antimatter in the universe could not be sufficiently explained; a more fundamental framework is required and has to be studied. In order to understand the mechanism of matter-antimatter symmetry violation, we are developing the next generation experiments employing ultracold atoms to search for the electron electric dipole moment (EDM) using heavy element francium (Fr) in an optical lattice at RIBF. The developments of a high intensity surface ionizer to produce Fr and a magneto-optical trap (MOT) are in progress, and Fr-MOT experiments are going on at present at CYRIC.

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List of Publications & Presentations
Publications
[Journal]

(Original Papers) *Subject to Peer Review

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S. Shimoura (Oral), “Reduction and resource recycling of high-level radioactive wastes through nuclear transmutation − Nuclear reaction data of long-lived fission products,’’ International Nuclear Fuel Cycle Conference (GLOBAL2017), September 24–29, 2017, Seoul, Korea.

S. Shimoura (Invited), “New energy-degrading beam line OEDO in RIKEN RI beam factory,’’ The International Symposium on Physics of Unstable Nuclei 2017 (ISPUN17), Halong City, Vietnam, September 25–30, 2017.

P. Schrock (oral), “Shell structure at the border of the island of inversion: Spectroscopy of neutron-rich Al isotopes.” The International Symposium on Physics of Unstable Nuclei 2017 (ISPUN17), Halong City, Vietnam, September 25–30, 2017.

S. Shimoura (invited), “Tetra-neutron system studied by (^{8}He, ^{8}Be) reaction,’’ Workshop on Nuclear Structure and Reaction Theories: Building Together for the Future, GANIL, Caen, France, October 9–13, 2017.

S. Shimoura (Invited), “Tetra-neutron system populated by RI-beam experiments,’’ Critical Stability of Quantum Few-Body Systems (crit17), MPIPKS, Dresden, Germany, October 16–20, 2017.

S. Shimoura (invited), “Experimental studies of the tetra-neutron system by using RI-beam,’’ The 23rd European Conference on Few-Body Problems in Physics, Aarhus, Denmark, Aug. 8–12, 2016.

S. Shimoura (invited), “Exotic nuclei studied by exotic reaction,’’ Ito International Research Center (IIRC) Symposium “Perspectives of the Physics of Nuclear Structure,” University of Tokyo, Tokyo, Japan, November 1–4, 2017.

S. Michimasa (invited), “Direct mass measurement of Calcium isotopes beyond N = 34,’’ International symposium “Perspectives of the physics of nuclear structure,’’ the University of Tokyo, Hongo, Tokyo, Japan, November 1–4, 2017.

S. Shimoura (invited), “Tetra-neutron system studied by ^{4}He(^{8}He, ^{8}Be),’’ Workshop on Nuclear Cluster Physics (WNCP2016), Kanto-Gakuin University, Yokohama, Japan, Oct. 17–21, 2016.

S. Shimoura (invited), “Tetra-neutron system populated by using RI-beam induced reaction,’’ 第 6 回「中性子星の核物質」研究会, RIKEN Nishina Cenger, Wako, Saitama, Japan, Dec. 1–3, 2017.

N. Imai (Invited),「将来計画ＷＧ不安定核班第 2 期からの報告", RIBF 理論若手放談会：エキゾチック核物理の広がり」, 理研神戸・融合連携イノベーション推進棟, Jul. 31−Aug. 2, 2017.

N. Imai, “Surrogate reaction of ^{79}Se(n,gamma)^{80}Se,” ImPACT-OEDO workshop, RIBF conference room, Wako, Saitama, Japan, 2017/7/13-14.

M. Dozono, “p/d iduced reaction of ^{107}Pd,” ImPACT-OEDO workshop, RIBF conference room, Wako, Saitama, Japan, 2017/7/13-14.

S. Michimasa, “Preliminary report of OEDO commissioning", ImPACT-OEDO workshop, 2017/7/13-14, RIBF conference room, Wako, Saitama, Japan.

N. Imai (invited), “Energy-degraded beam line at RIBF, OEDO,” International Workshop on “Physics Opportunities using CAGRA and RCNP tracking Ge detector” (CAGRA17) Sigma Hall, Toyonaka Campus, Osaka University, Osaka, Japan, Oct 10-12, 2017.

P. Schrock (invited), “Transfer Reactions with CAGRA at OEDO,” International Workshop on “Physics Opportunities using CAGRA and RCNP tracking Ge detector (CAGRA17)” Sigma Hall, Toyonaka Campus, Osaka University, Osaka, Japan, Oct 10−12, 2017.

O. Beliuskina, “The ultrafast dE-ToF sc diamond detector,” International Workshop on “Physics Opportunities using CAGRA and RCNP tracking Ge detector (CAGRA17)” Sigma Hall, Toyonaka Campus, Osaka University, Osaka, Japan, Oct 10−12, 2017.

N. Imai (Invited),「OEDO を用いた低エネルギーLLFP の核反応データ取得」, 東海村産業・情報プラザ (アイヴィル), 2017/11/16−17.

N. Imai (Invited), “Nuclear Data of LLFP and Future prospect of a new energy degraded beam line OEDO,” RIBF Users group meeting, RIBF Conference Room, 2017/12/6.

O. Beliuskina (oral), "The ultrafast dE-ToF single crystal diamond detector", The 6th ADAMAS Workshop, November 27−28, 2017, Zagreb, Croatia.

S. Shimoura, “Direct Reaction,’’ Rewriting Nuclear Physics Textbooks: Basic nuclear interactions and their link to nuclear processes in the cosmos and on earth, Pisa, Italy, July 24−28, 2017.

S. Ota, “Nuclear matter from low-energy reaction,’’ OEDO Workshop, CNS Wako campus, Saitama, Japan, Jul.15, 2017.

S. Ota, “Equation of state of nuclear matter from direct reactions,’’ Workshop on RI and Heavy-ion science, Ewha womans university, Seoul, Korea, Oct. 19−20, 2017.

S. Ota, “Active targets CAT’s for missing mass spectroscopy with high-intensity beams,’’ Workshop on active targets and time projection chambers for high-intensity and heavy-ion beams in nuclear physics, Santiago de Compostela University, Spain, Jan. 17−19.

T. Otsuka, “Quantum self-organization and nuclear shapes,” Advances in Radioactive Isotope Science, ARIS2017, USA, June 2017.

T. Otsuka, “Twenty years ago, twenty years later,” Perspectives of physics of nuclear structure, Tokyo, Japan, November 2017.

T. Otsuka, “Impact to shell model, impact of shell model,” Probing fundamental interactions by low energy excitations, Stockholm, Sweden, June 2017.

T. Otsuka, “Single-particle states vs. collective modes: friends or enemies,” Shapes and symmetries in nuclei: from experiment to theory, France, November 2017.

T. Otsuka, "Quantum self-organization and the structure evolution of atomic nuclei," international symposium on physics of unstable nuclei 2017, Hanoi, Vietnam, September 2017.

T. Otsuka, "Suppression of double-beta decay and quadrupole pairing," Nuclear ab initio theories and neutrino physics, Seattle, USA, March 2018.

T. Otsuka, "Quantum self-organization and nuclear collectivity," IVth Topical workshop on modern aspects in nuclear structure, Bormio Italy, February 2018.

T. Otsuka, "Single-particle states vs. collective modes: friends or enemies?" 16th International symposium on capture gamma-ray spectroscopy and related topics (CGS16), Shanghai, China, September 2017.

T. Otsuka, "Beauty and the Quantum," Academia Europaea Section Initiated Workshop - Inaugural Lectures by New Members of Physics and Engineering Sciences, Budapest Hungary, September 2017.

T. Otsuka, "Quantum self-organization and nuclear collectivities," 12th International spring seminar on nuclear physics, current problems and prospects for nuclear structure, Ischia Italy, May 2017.

T. Otsuka, "Shell-model challenges to gamma-ray spectroscopy," NUSPIN2017, GSI, Germany, June 2017.

T. Otsuka, "Shape coexistence and quantum phase transition in the Monte-Carlo Shell Model," Shape coexistence and electric monopole transitions, Salay, France, October 2017.

T. Otsuka, "Cluster and molecular structure emerging from ab initio Monte Carlo Shell Model calculations," 2nd International Workshop on Nuclear Cluster Physics (WNCP2017), Sapporo, Japan, October 2017.

T. Otsuka, "Quantum self-organization in atomic nuclei," The COPIGAL Meeting on recent results and future projects involving PARIS, AGATA, NEDA, and FAZIA detectors, Krakow, Poland, December 2017.

T. Otsuka, "Perspectives of the shell model on and beyond monopole," First Workshop on Nuclear Shell Model Developments and Applications in Eastern Asia (NuSEA2018), Shanghai, China, March 2018.

N. Shimizu, "Double Gamow-Teller transition and its relation to neutrinoless double beta decay," Nuclear ab initio Theories and Neutrino Physics, Seattle, USA, March 2018.

N. Shimizu, "Shell model study on a double-beta decay nucleus ^{48}Ca," Probing Fundamental Interactions by Low Energy Excitations, KTH Royal Institute of Technology, Stockholm, Sweden, June 2017.

T. Miyagi, "Recent progress in the unitary-model-operator approach," TRIUMF workshop on Progress in Ab Initio Techniques in Nuclear Physics, Vancouver, Canada, March 2018.

T. Miyagi, "Unitary-model-operator approach calculations with the chiral NN+3N forces," 16th CNS Summer School, RIKEN, Wako, Japan, August 2017.

T. Miyagi, "Ground-state energies and radii from the unitary-model-operator approach," Probing fundamental interactions by low energy excitations -Advances in theoretical nuclear physics, Royal Institute of Technology, Stockholm, Sweden, June 2017.

Y. Utsuno, "Shell-model study for the A ~ 130 region," Gif-Sur-Yvette, France (Conference "Shapes and Symmetries in Nuclei: from Experiment to Theory (SSNET'17)"), November 2017.

Y. Utsuno, "Consistent description of shell gaps and deformed states around O-16 and Ca-40," Mumbai, India (Conference "Frontiers in Gamma Ray Spectroscopy (FIG18)"), March 2018.

T. Abe, "Advances in the Monte Carlo Shell Model for Understanding Nuclear Structure," Ito International Center (IIRC) Symposium "Perspectives of the Physics of Nuclear Structure," Ito Hall, the University of Tokyo, November 2017.

T. Abe, "Recent advances in the no-core Monte Carlo shell model," Progress in Ab Initio Techniques in Nuclear Physics, TRIUMF, Canada, March 2018.

Y. Tsunoda, "Monte Carlo shell model calculations for structure of nuclei around Z = 28," IVth Topical Workshop on Modern Aspects in Nuclear Structure, Bormio, Italy, February 2018.

Y. Tsunoda, "Nuclear structure studied by Monte Carlo shell model calculations," NUSTAR Annual Meeting 2018, GSI, Darmstadt, Germany, March 2018.

N. Tsunoda, "Exotic neutron-rich medium-mass nuclei with realistic nuclear force," Keystone ARIS2017, May 2017.

N. Tsunoda, "Structure of exotic nuclei based on nuclear force," Perspective of physics of nuclear structure, Tokyo, Japan, November 2017.

N. Tsunoda, "Many body perturbation theory for the effective interaction for the shell model calculation and its application to island of inversion," Leuven-Tokyo mini workshop, Tokyo, Japan, March 2018.

J. Menéndez, "Nuclear matrix elements for double-beta decay: present and future," Solvay workshop "Beyond the Standard model with Neutrinos and Nuclear Physics", Brussels (Belgium), November 30, 2017.

J. Menéndez, "Nuclear Matrix Elements for Fundamental Symmetries," Perspective of the Physics of Nuclear Structure Conference, Tokyo (Japan), November 4, 2017.

J. Menéndez, "Double Gamow-Teller transition of ^{48}Ca and its relation to neutrinoless double-beta decay," Conference on Neutrino and Nuclear Physics (CNNP2017), Catania (Italy), October 17, 2017.

J. Menéndez, "The interplay of nuclear structure with β and double-β decays," International Symposium on Physics of Unstable Nuclei 2017 (ISPUN17), Halong City (Vietnam), September 26, 2017.

J. Menéndez, "Status of neutrinoless double-beta decay nuclear matrix elements," Recent developments in neutrino physics and astrophysics workshop, Gran Sasso (Italy), September 6, 2017.

J. Menéndez, "Which nuclear data and correlations can constrain neutrinoless double-beta decay matrix elements?" INT Program "Neutrinoless Double-beta Decay,'' Seattle (USA), June 21, 2017.

[Domestic Conference]

S. Hayashi, "J/psi production in heavy ion collisions," Heavy Ion Café, RIKEN, Wako, Japan, January 13, 2018.

S. Hayakawa,「CRIB での ^{7}Be ビームを用いたビッグバン元素合成反応の測定」, X 線天体と元素合成を中心とする宇宙核物理研究会, RIKEN, Wako, Japan, July 20–21, 2017.

H.Shimizu,「CRIBにおける ^{26}Al 核異性体の陽子弾性共鳴散乱実験」, X線天体と元素合成を中心とする宇宙核物理研究会, RIKEN, Wako, Japan, July 20–21, 2017.

山口英斉,「α 共鳴散乱による不安定核クラスター状態の研究」, RCNP 研究会「核子・ストレンジネス多体系におけるクラスター現象」大阪大学核物理研究センター, Aug 3−5, 2017.

S. Michimasa *et al*.,「LLFP 安定核種化・短寿命化のための核変換法の開発 (6) OEDO ビームラインの性能評価」, AESJ Fall meeting, Hokkaido University, Sapporo, Hokkaido, Japan, Sept. 13–15.

S. OTA, "Matter dominant universe through nuclear physics,'' High school lecture for Fukuoka Prefectural Chikushigaoka High School, CNS Wako campus, Saitama, Japan, Aug. 1, 2017.

S. Michimasa,「SHARAQ スペクトロメータを用いた中性子過剰核の直接質量測定」, 第 7 回先導原子力研コロキウム, Tokyo Institute of Technology, Meguro, Tokyo, Japan, July 21, 2017.

S. Shimoura,「エキゾチック原子核の世界」, 集中講義, 立教大学, June 9, 16, 23, 2017.

N. Imai,「不安定核物理の将来,'' JPA Fall meeting, Utsunomiya University, Utsunomiya, Tochigi, Japan, Sept. 12−15, 2017.

T. Gunji,「高エネルギー重イオン衝突による物理の将来」, JPA Fall meeting, Utsunomiya University, Utsunomiya, Tochigi, Japan, Sept. 12–15, 2017.

S. Hayashi, "Inclusive J/psi measurement in *p*-Pb collisions with the ALICE detector," JPS Autumn Meeting 2017, Utsunomiya University, Utsunomiya, Japan, September 12–15, 2017.

Y. Sekiguchi for the ALICE collaboration, "Study of particle correlations in *p*-Pb collisions with ALICE detector," 日本物理学会 2017 年秋季大会, 宇都宮大学, 峰キャンパス, 2017 年 9 月 12–15 日.

H. Murakami for the ALICE collaboration, "Status of direct photon measurement in small systems with ALICE," 日本物理学会 2017 年秋季大会 宇都宮大学, 2017 年 9 月 12–15 日.

早川勢也 (oral),「トロイの木馬法による ^{7}Be+n ビッグバン元素合成反応の測定 II」, 日本物理学会 2017 年秋季大会, 宇都宮大学, 2017 年 9 月 12–15 日.

N. Kitamura *et al*.,「TRIUMF におけるトリチウム標的の評価」, JPS Fall meeting, Utsunomiya University, Utsunomiya, Tochigi, Japan, Sept. 12–15, 2017.

K. Kawata *et al*.,「^{58}Ni の入射核破砕反応による高スピンアイソマービームの生成」, JPS Fall meeting, Utsunomiya University, Utsunomiya, Tochigi, Japan, Sept. 12–15, 2017.

C. Iwamoto *et al*.,「ガスアクティブ標的CATの大型化に向けた二重増幅率抑制型多層THGEMの開発」, JPS Fall meeting, Utsunomiya University, Utsunomiya, Tochigi, Japan, Sept. 12–15, 2017.

S. Michimasa *et al*.,「低速 RI ビームを用いた LLFP 核の核反応断面積測定」, AESJ Spring meeting, Osaka University, Osaka, Japan, Mar. 26–28.

M. Dozono *et al*., 「低速 RI ビームを用いた ^{107}Pd, ^{93}Zr の陽子および重陽子誘起反応測定」, AESJ Spring meeting, Osaka University, Osaka, Japan, Mar. 26–28.

大塚孝治,「核力と原子核の基本的性質」,「原子核多体問題の進展と展望」, 軽井沢, 2017 年 6 月.

清水則孝,「ベイズ統計による殻模型計算の解析」, 素粒子・原子核・宇宙「京からポスト京に向けて」シンポジウム, 筑波大学文京校舎, 2017 年 12 月.

清水則孝,「殻模型計算による核準位密度の微視的記述」, 2017 年度核データ研究会, 茨城県東海村, 東海駅前・アイヴィル, 2017 年 11 月.

清水則孝,「ボゴリューボフ準粒子基底によるモンテカルロ殻模型」, 日本物理学会 2017 年秋季大会（宇都宮大学峰キャンパス）, 2017 年 9 月.

宮城宇志,「3 体力効果を取り込んだ UMOA 計算」, 日本物理学会 2017 年秋季大会, 宇都宮大学, 峰キャンパス, 2017 年 9 月.

宮城宇志,「中重核における 3 体力の効果」, RIBF 理論若手放談会：エキゾチック核物理の広がり, 理化学研究所, 神戸キャンパス, 2017 年 8 月.

角田佑介,「モンテカルロ殻模型による原子核形状の研究」, RIBF 理論若手放談会：エキゾチック核物理の広がり, 理化学研究所神戸キャンパス, 2017 年 7 月.

角田佑介,「モンテカルロ殻模型による Sm 同位体の形状変化の研究」, 日本物理学会 2017 年秋季大会, 宇都宮大学峰キャンパス, 2017 年 9 月.

角田佑介,「中重核・重い原子核の形状のモンテカルロ殻模型による研究」, 素粒子・原子核・宇宙「京からポスト京に向けて」シンポジウム, 筑波大学東京キャンパス文京校舎, 2017 年 12 月.

角田佑介,「Sm 同位体の形状変化のモンテカルロ殻模型による研究」, 日本物理学会第 73 回年次大会, 東京理科大学野田キャンパス, 2018 年 3 月.

角田佑介,「量子自己組織化と原子核の集団性」, 研究会「量子クラスターで読み解く物質の階層構造」, 東京工業大学大岡山キャンパス, 2018 年 3 月.

角田直文,「Medium-mass nuclei from nuclear force」, 京都大学 基研研究会「核力に基づく核構造・核反応物理の展開」, 2017 年 3 月.

角田直文,「核力と中性子過剰核の構造」, 理研神戸・融合連携イノベーション推進棟 RIBF 若手放談会「エキゾチック核物理の広がり」, 2017 年 7−8 月.

角田直文,「中性子過剰な Mg 同位体の新たな様相」, 宇都宮大学 日本物理学会 2017 年秋季大会, 2017 年 9 月.

角田直文,「原子核殻模型における統計力学的考察」, 宇都宮大学 日本物理学会 2017 年秋季大会, 2017 年 9 月.

角田直文,「現実的核力に基づく多殻有効相互作用の構築と中性子過剰核への適用」, 東京理科大学 日本物理学会第 73 回年次大会, 2018 年 3 月.

富樫智章,「Zr 同位体近傍における形の量子相転移のモンテカルロ殻模型による研究」, 宇都宮大学, 日本物理学会 2017 年秋季大会, 2017 年 9 月.

富樫智章,「大規模殻模型計算による中性子過剰 N=82 近傍の半減期の計算」, 宇都宮大学, 日本物理学会 2017 年秋季大会, 2017 年 9 月.

富樫智章,「モンテカルロ殻模型による Sn 同位体の系統的研究」, 東京理科大学, 日本物理学会第 73 回年次大会, 2018 年 3 月.

小高康照他,「空間電荷効果を導入した理研 AVF サイクロトロン入射軌道解析」, 第 14 回日本加速器学会年会, 北海道札幌市, 北海道大学,

2016 年 8 月 1–3 日.

大城幸光(oral),「CNS イオン源の現状」，第 14 回 AVF 合同打合せ，福島県立医科大学，2017 年 6 月 29−30 日.

小高康照(oral),「4 次元エミッタンス測定値を用いた AVF 入射軌道解析(2)」，第 14 回 AVF 合同打合せ，福島県立医科大学，2017 年 6 月 29–30 日.

大城幸光(oral),「CNS イオン源の現状」，第 15 回 AVF 合同打合せ，大阪大学 RCNP，2018 年 2 月 26–27 日.

小高康照(oral),「AVF 入射軌道解析の現状」，第 15 回 AVF 合同打合せ，大阪大学 RCNP，2018 年 2 月 26–27 日.

Poster Presentations

[International Conference etc.]

T. Miyagi, "Nuclear ab initio calculations with the unitary-model-operator approach," Perspective of the physics of the nuclear structure, Tokyo, Japan, November 2017.

Y. Tsunoda, "Shapes of medium and heavy nuclei studied by Monte Carlo shell model calculations," Ito International Research Center (IIRC) symposium "Perspectives of the physics of nuclear structure," Tokyo, Japan, November 2017.

H. Shimizu: "^{26m}Al beam production and decay measurement at CRIB, " The 14th international symposium on Origin of Matter and Evolution of Galaxies (OMEG2017), Jun. 27–30, 2017, Daejeon, Korea.

Partner Institution
Center for Radioactive Ion Beam Sciences
Institute of Natural Science and Technology, Niigata University

1. Abstract

The Center for Radioactive Ion Beam Sciences, Niigata University, aims at uncovering the properties of atomic nuclei and heavy elements and their roles in the synthesis of elements, with use of the advanced techniques of heavy ion and radioactive ion beam experiments as well as the theoretical methods. Main research subjects include the measurements of various reaction cross sections and moments of neutron- or proton-rich nuclei, synthesis of super-heavy elements and radio-chemical studies of heavy nuclei, and theoretical studies of exotic nuclei based on quantum many-body methods and various nuclear models. In addition, we promote interdisciplinary researches related to the radioactive ion beam sciences, such as applications of radioactive isotopes and radiation techniques to material sciences, nuclear engineering and medicine. Many of them are performed in collaboration with RIKEN Nishina Center and with use of the RIBF facilities. The center emphasizes also its function of graduate education in corporation with the Graduate School of Science and Technology, Niigata University, which invites three researchers in RIKEN Nishina Center as visiting professors.

2. Major Research Subjects

(1) Reaction cross section and radii of neutron-rich nuclei
(2) Production of superheavy nuclei and radiochemistry of heavy elements
(3) Nuclear theory

3. Summary of Research Activity

(1) Measurements of matter and charge radii of exotic nuclei

The experimental nuclear physics group has studied the nuclear structures of exotic nuclei through the measurements of nuclear matter radii. The nuclear matter radii can be determined from interaction cross sections with the use of nuclear reaction model. At RIBF, RIKEN, we have performed experiments to measure interaction cross sections of F, Ne, Na, Mg, and Al isotopes and clarified the halo structure of ^{31}Ne, and also the development of strong deformation in those isotopes, $^{28-32}$Ne, $^{32-38}$Mg, which are located around and beyond the "island of inversion" region. Recently our new project to explore the equation of state (EOS) of nuclear matter has been started. For the understanding of the EOS of asymmetric nuclear matter, either highly proton deficient or neutron deficient, the investigation of the development of neutron skin thickness in the exotic nuclei give the crucial information. We have measured interaction cross sections and charge changing cross sections for $^{58-78}$Ni using BigRIPS fragments separator at RIBF in FY2016. While nuclear matter radii can be determined from interaction cross sections, the proton distribution radii will be determined from charge-changing cross sections, thus neutron skin thickness will be obtained. The data analysis are in progress.

(2) Production of superheavy nuclei and radiochemistry of heavy elements

The nuclear chemistry group has been investigating decay properties of super-heavy nuclei, measured the excitation functions of rutherfordium isotopes, and clarified the ambiguity of the assignment of a few-second spontaneously fissioning isotope of ^{261}Rf. The new equipment designed for measurement of short-lived alpha emitters is under development.

For the chemistry research of super-heavy elements, preparatory experiments, such as solvent extraction for the group 4, 5, and 6th elements and gaseous phase chemistry for group-4 elements, have been performed using radioisotopes of corresponding homolog elements.

(4) Nuclear theory

One of the main activities of the nuclear theory group concerns with developments of the nuclear density functional theory and exploration of novel correlations and excitations in exotic nuclei. A fully selfconsistent scheme of the (quasiparticle) random phase approximation (QRPA) on top of the Skyrme-Hartree-Fock-Bogoliubov mean-field has been applied not only for spherical nuclei but also for deformed nuclei. The model is used to study the low-lying dipole excitation in neutron-rich nuclei in order to investigate the relation between the low-lying strength and the equation of state (EOS) of asymmetric nuclear matter. The QRPA in the density functional framework has been developed in various directions. The continuum QRPA, which describes not only collective correlations but also coupling to unbound continuum states of nucleons, has been applied to describe the direct neutron capture reaction in the r-process nucleosynthesis. The QRPA is recently applied to describe collective excitation in inner crust of neutron stars. The continuum quasiparticle states are also analyzed to study possible pairing effects on low-lying p-wave resonances and s-wave scattering states in unbound odd-N nuclei. Cluster structure and the ab initio studies of light nuclei are also important research subjects of the theory group. A new direction of theoretical study is initiated in this fiscal year toward a fully microscopic description of low-energy heavy ion dynamics using the time-dependent Hartree-Fock theory. The model has been applied to describe multi-nucleon transfer reaction to form heavy neutron-rich nuclei, and fusion process to form superheavy nuclei.

Members

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List of Publications & Presentations

Publications
[Journal]

(Original Papers) *Subject to Peer Review

J. Goto, M. Oshima, M. Sugawara, Y. Yamaguchi, C. Bi, S. Bamba, T. Morimoto, "Introduction of multiple γ-ray detection to charged particle activation analysis", J. Radioanal. Nucl. Chem. **314**, 1707–1714 (2017).*

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Partner Institution
Wako Nuclear Science Center, IPNS (Institute of Particle and Nuclear Studies) KEK (High Energy Accelerator Research Organization)

1. Abstract

The KEK Isotope Separation System (KISS) has been constructed to experimentally study the β-decay properties of unknown neutron-rich nuclei near the neutron magic number $N = 126$, which are of interest in astrophysics. A new rotating target system was introduced and higher yields and more stable operational conditions were achieved. Resonance ionization spectroscopy for the hyperfine structure of ^{199}Pt was performed at KISS. An international collaboration with the Institute of Basic Science (IBS), Korea, has been organized. As part of this collaboration, an array of super-clover germanium detectors was installed. A new project for comprehensive mass measurements with MRTOF mass spectrograph at KISS and other devices has started in collaboration with the RIKEN SLOWRI team.

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 spectrograph for short-lived heavy nuclei.
(5) Development of RNB probes for materials science applications.

3. Summary of Research Activity

KISS is an element-selective isotope separator, combining the use of a magnetic mass separator with in-gas-cell resonant laser ionization. The gas cell, filled with argon gas at 75 kPa, is a central component of KISS, from which only the elements of interest are extracted as an ion beam for subsequent mass separation. In the cell, nuclei primarily produced by low-energy heavy-ion reactions are stopped (thermalization and neutralization), transported by a buffer gas (gas flow of ~75 kPa argon in the present case), and then re-ionized by laser irradiation just before the exit. The gas cell was fabricated to efficiently collect the reaction products produced by multi-nucleon transfer (MNT) reactions in the ^{136}Xe + ^{198}Pt system. For the first extraction of the reaction products, the ^{136}Xe beam energy and ^{198}Pt target thickness were set at 10.8 MeV/nucleon and 6 mg/cm^2, respectively. In FY2014, the half-life of ^{199}Pt was measured with β-ray telescopes and a tape transport system located at the focal point of KISS. The β-ray telescopes were composed of three double-layered thin plastic scintillators; the thicknesses of the first and second layers were 0.5 mm and 1 mm, respectively. In order to reduce the background, low-activity lead blocks and a veto counter system consisting of plastic scintillator bars surrounded the telescopes. The background rate of these β-ray telescopes was measured to be 0.7 counts per second. For further reduction of the background rate to as low as 0.1 counts per hour, a gas counter-based beta-ray telescope system was installed in FY2016. An array of germanium detectors consisting of four super-clover germanium crystals was also brought into operation in FY2016. Using these setups, new isomeric state in ^{195}Os were discovered and the half-lives of ^{197}Os and ^{198}Os, respectively, were revised and determined for the first time.

For higher primary beam intensities and a higher extraction efficiency, a doughnut-shaped gas cell with a rotating target wheel setup has been developed for KISS. Using this setup, resonance ionization spectroscopy of the ground-state hyperfine structure of Pt and Ir was performed. The nuclear g-factor and charge radius of the ground state and an isomeric state of ^{199}Pt were deduced from the experimental results. For further improvement of spectral resolution of the hyperfine structure measurements, an in-gas-jet laser ionization setup utilizing an S-shaped RF ion guide and a new laser system consisting of a 10 kHz Nd:YAG pump laser and a dye amplifier seeded by a narrow-band diode laser have been installed.

Cross-section measurements were performed at GANIL in 2012 to investigate the feasibility of using MNT in the reaction system of ^{136}Xe on ^{198}Pt to produce heavy neutron-rich isotopes around a mass number of 200 with the neutron magic number 126; the analysis of the data has been completed. The cross sections of target-like fragments around N=126 were comparable to those estimated using the GRAZING code, and their main contributions appear to be from the reactions having a low total energy loss with weak N/Z equilibration and particle evaporation. This suggests the use of the MNT reactions with a heavy projectile at energies above the Coulomb barrier could be a promising means for the production of neutron-rich isotopes around $N = 126$.

The multi-reflection time-of-flight mass spectrograph (MRTOF-MS) has been developed for direct mass measurements of short-lived heavy nuclei at KISS and other facilities. In FY2016, mass measurements of more than 80 nuclides, including short-lived ($T_{1/2}$ = 10 ms) isotopes of Ra and several isotopes of the trans-uranium elements Es and Md were performed at GARIS-II in collaboration with the SLOWRI team and the Super Heavy Element Synthesis team of RIKEN. The highest precisions, achieved for Ga isotopes, reached a level of 0.03 ppm. For most of the well-known nuclides, agreement with the literature mass values was found. However, discrepancies were found in some literature values derived from pre-1980 indirect measurements. This suggests that such indirect measurements must be revised with comprehensive direct mass measurements. The masses of four isotopes of Es and Md were measured for the first time, allowing for confirmation of the $N = 152$ shell closure in Md. Using these new mass data as anchor points, the masses of seven isotopes of super-heavy elements up to Mt were indirectly determined and comparisons with various nuclear mass models were performed.

The diffusion coefficient of lithium in solid materials used in secondary Li-ion batteries is one of the key parameters that determine how fast a battery can be charged. The reported Li diffusion coefficients in solid battery materials scatter over several orders of magnitude. An in-situ nanoscale diffusion measurement method using α-emitting radioactive ^{8}Li as a tracer has been developed. In this method, while implanting a pulsed 8 keV beam of ^{8}Li, the α-particles emitted at small angles (θ = 10 ± 1◦) relative to the sample surface were detected as a function of time. The Li diffusion coefficient could then be determined from the time-dependent yields of the α particles, the energy loss of which can be converted to nanometer-scale position information of diffused ^{8}Li. The method has been successfully applied to measure the lithium diffusion coefficients for amorphous Li_4SiO_4-Li_3VO_4 (LVSO) which was used as a solid electrolyte in a solid-state Li thin-film battery, well demonstrating that the present method is sensitive to diffusion coefficients down to the level of 10^{-12} cm^2/s, which corresponds with nanoscale Li diffusion. In FY2016, this method was used to determine Li diffusion coefficients in a spinel-type Li compound $LiMn_2O_4$ (LMO), which is used as the anode of Li batteries in electric vehicles. A significant change in the time dependent yields of the α particles was observed at a sample temperature of approximately 623 K and the measurements will be continued in order to obtain the temperature dependence of Li diffusion coefficients in LMO.

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List of Publications & Presentations

Publications
[Journal]

(Original Papers) *Subject to Peer Review

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

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Oral Presentations

[International Conference etc.]

M. Wada, "High Precision Spectroscopy of low-energy short-lived nuclei," Turkish Physical Society 33rd International Physics Congress; TPS33, Bodrum, Turkey, Sept. 9, 2017.

Y. Watanabe, "Production of neutron-rich nuclei by multinucleon transfer reactions at KISS project," 3rd International Symposium on Super-Heavy Elements (SHE 2017), Kazimierz Dolny, Poland, Sept. 11, 2017.

H. Miyatake, "Present status of the KISS project," RCNP International workshop on Physics Opportunities using CAGRA and RCNP tracking Ge detector (CAGRA17), Osaka, Japan, Oct. 10, 2017.

H. Miyatake, "Recent KISS activities and future's plan," Workshop for Einsteinium Campaign, Tokai, Japan, Nov. 7, 2017.

Y. Watanabe, "Nuclear production by multinucleon transfer reactions with neutron-rich heavy ion beams," Workshop for Einsteinium Campaign, Tokai, Japan, Nov. 7, 2017.

M. Wada, "Toward mass measurement of super-heavy nuclei using MRTOF," Workshop for Einsteinium Campaign, Tokai, Japan, Nov. 7, 2017.

M. Wada, "Mass measurements of short-lived nuclei with a multi-reflection time-of-flight mass spectrograph −recent results and future plans−," The 10th International Conference on Nuclear Physics at Storage Rings(STORI'17), Kanazawa, Japan, Dec. 5, 2017.

S. Kimura, "High precision mass measurements of intermediate-mass neutron-deficient nuclei via MRTOF-MS," The 10th International Conference on Nuclear Physics at Storage Rings (STORI'17), Kanazawa, Japan, Nov. 15, 2017.

H. Miyatake, "Present status of the KISS project," BUAA Workshop "Impact of Exotic Nuclear Structure on Explosive Nucleosynthesis," Beijing, China, Nov. 23, 2017.

M. Wada, "Precision mass measurements of short-lived heavy nuclei, present and future toward comprehensive measurement," International Symposium on RI beam Physics in the 21st Century: 10th Anniversary of RIBF, Wako, Japan, Dec. 5 2017.

Y. Hirayama, "Nuclear spectroscopy of r-process nuclei around $N \approx 126$ by using KISS," International Symposium on RI beam Physics in the 21st Century: 10th Anniversary of RIBF, Wako, Japan, Dec. 5, 2017.

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M. Wada, "KEK MRTOF Efforts," KEK-TRIUMF Scientific Symposium, Vancouver, Canada, Dec. 14–15, 2017.

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[Domestic Conference]

Y.X. Watanabe, "Multinucleon transfer reactions with low-energy neutron-rich heavy ion beams," ImPACT-OEDO Workshop, Wako, Jul. 13–14, 2017.

Y. Hirayama,「KISS I: ^{199}Pt のレーザー共鳴イオン化核分光」, 日本物理学会, Utsunomiya, Sep. 10–14, 2017.

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M. Wada,「MRTOF 質量分光器を用いた重元素の網羅的高精度質量測定」, 2017 年度核データ研究会, 東海村, Nov. 17, 2017.

H. Miyatake,「KISS、超微細構造測定と質量測定の現状」,平成 29 年度 KUR 専門研究会 短寿命 RI を用いた核分光と核物性研究 IV, Kumatori, Dec. 20–21, 2017.

Events (April 2017—March 2018)

RNC

Apr. 22	Wako Open Campus
Jun. 15	The 23rd RBRC Management Steering Committee (MSC)
Jul. 3	The 14th Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)
Jul.24–Aug.4	Nishina School
Aug. 4	Review of the Safety Management Group
Oct. 30	Review of the Accelerator Applications Research Group
Nov. 2	Review of the Instrumentation Development Group, the Research Instruments Group and the User Liaison and Industrial Cooperation Group
Dec. 7–9	The 18th Program Advisory Committee for Nuclear Physics Experiments at RI Beam Factory (NP-PAC)
Jan. 11–12	The 15th Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)
Jan. 19	The 7th Industrial Program Advisory Committee (In-PAC)

CNS

Aug. 23–29	16th CNS International Summer School CNSSS17 https://indico2.cns.s.u-tokyo.ac.jp/event/8/
Dec. 19	Completion Ceremony for the Construction of OEDO（OEDO 完成記念式典）

Niigata Univ.

Sep. 4–5	3rd Workshop on Many-body Correlations in Microscopic Nuclear Model

KEK

	not held in FY2017

Press Releases (April 2017−March 2018)

RNC

May. 17	Gamma decay of unbound neutron-hole states in ^{133}Sn	P. Doornenbal, H. Sakurai, Radioactive Isotope Physics Laboratory
May. 19	Auroral brightening at Jupiter observed by the Hisaki satellite and Hubble Space Telescope during approaching phase of the Juno spacecraft	T. Kimura, High Energy Astrophysics Laboratory
Jun. 13	Shapes evolution in neutron-rich krypton isotopes beyond $N = 60$: First spectroscopy of $^{98, 100}$kr	The SEASTAR collaboration group
Jun. 28	First elastic electron scattering from ^{132}Xe at the SCRIT facility	M. Wakasugi, SCRIT Team
Jul. 18	Success in producing and accelerating high intensity vanadium beam	T. Nakagawa, Y. Higurashi, Ion Source Team
Jul. 18	Decay measurement of ^{283}Cn produced in the ^{238}U(^{48}Ca, ^{3}n) reaction using GARIS-Ⅱ	D. Kaji, K. Morimoto, Superheavy Element Research Device Development Team
Nov. 1	Discovery of ^{72}Rb: A nuclear sandbank beyond the proton drip-line	H. Suzuki, BigRIPS Team, S. Nishimura, H. Sakurai, Radioactive Isotope Physics Laboratory
Dec. 21	Identification of new neutron-rich isotopes in the rare-earth region produced by 345 MeV/nucleon ^{238}U	N. Fukuda, K. Yoshida, BigRIPS Team
Jan. 5	Nuclear dependence of transverse single spin asymmetry for forward neutron production in polarized $p +$ A collisions at $\sqrt{s_{NN}}$ = 200 GeV	Y. Akiba, Experimental Group, I. Nakagawa, Radiation Laboratory

WNSC

Mar. 29	First direct mass measurements of 6 nuclides of trans-uranium elements nuclides, Md and Es	M. Wada, P. Schury, Y. Ito, D. Kaji