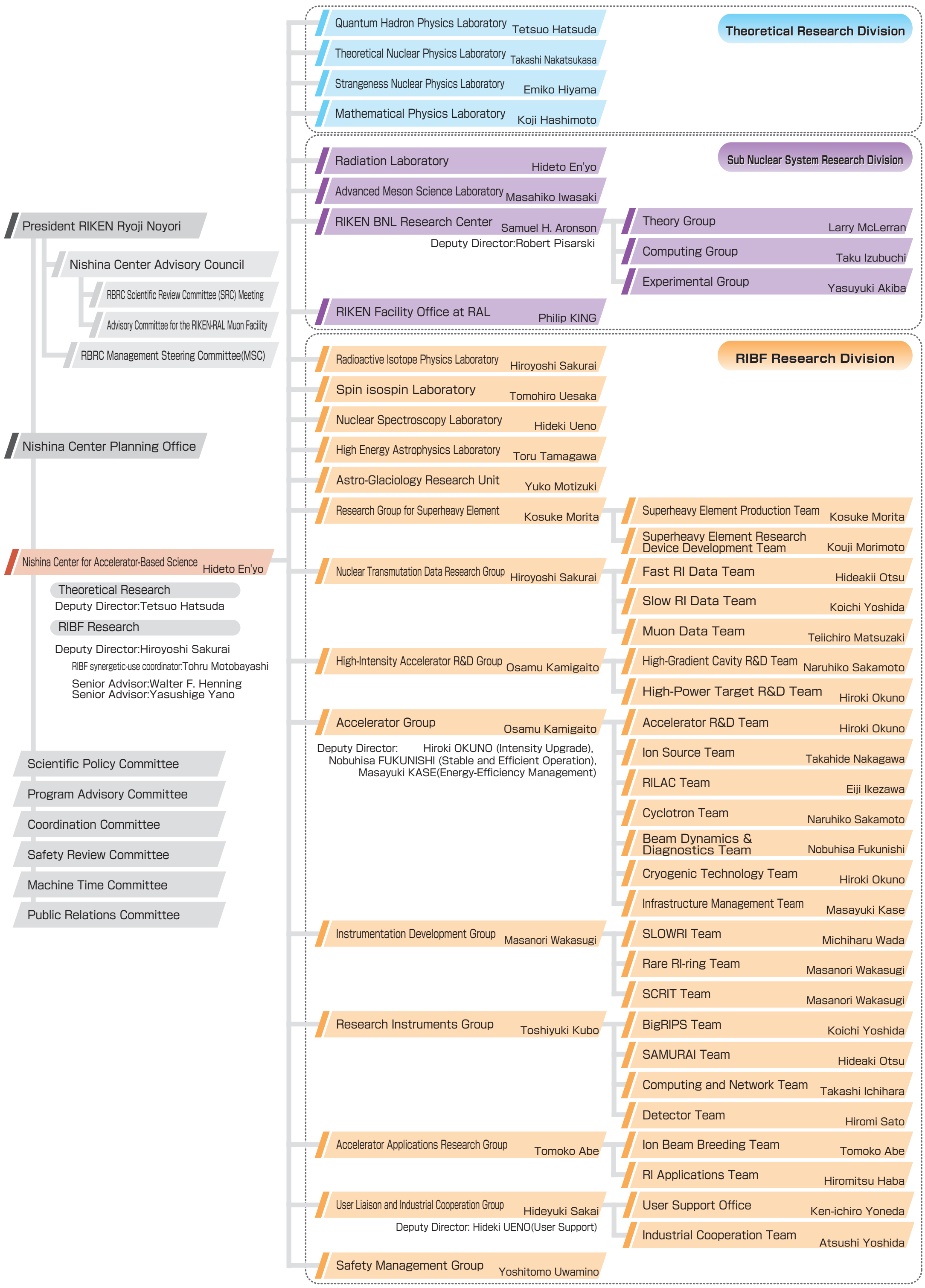
1. Organization

1.1 Organization Chart as of March 31, 2015



1.2 Topics in FY2014

In fiscal year 2014, RNC launched several interdisciplinary innovation programs as yet another new challenge for its researchers. One such example is RNC's participation in the ImPACT program which aims to significantly reduce and resource recycle high-level radioactive waste. To achieve this goal, the organizational structure required to develop key technology for effective nuclear transmutation has been revised so that the nuclear reaction data of the long-life fission products can be obtained. RNC also participates in the Strategic Innovation Program (SIP) in cooperation with eighteen other institutes in Japan to undertake the task of building a system for strategic omics breeding technology.

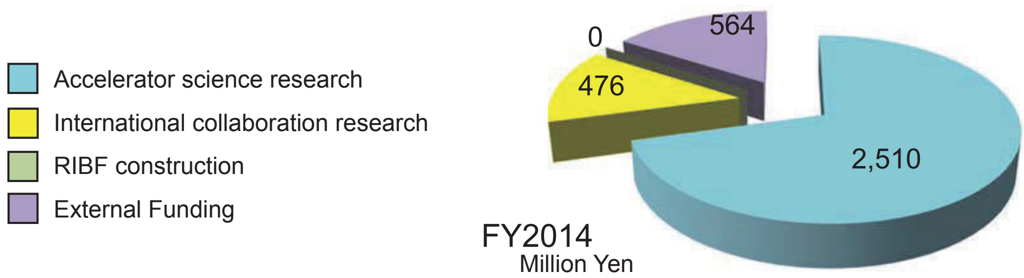
With President's Discretionary Fund providing the financial support of 450 million yen for international research collaboration, RNC was able to execute approximately five months of RIBF operation in total. Accordingly, user time also reached its record-high 2597 hours.

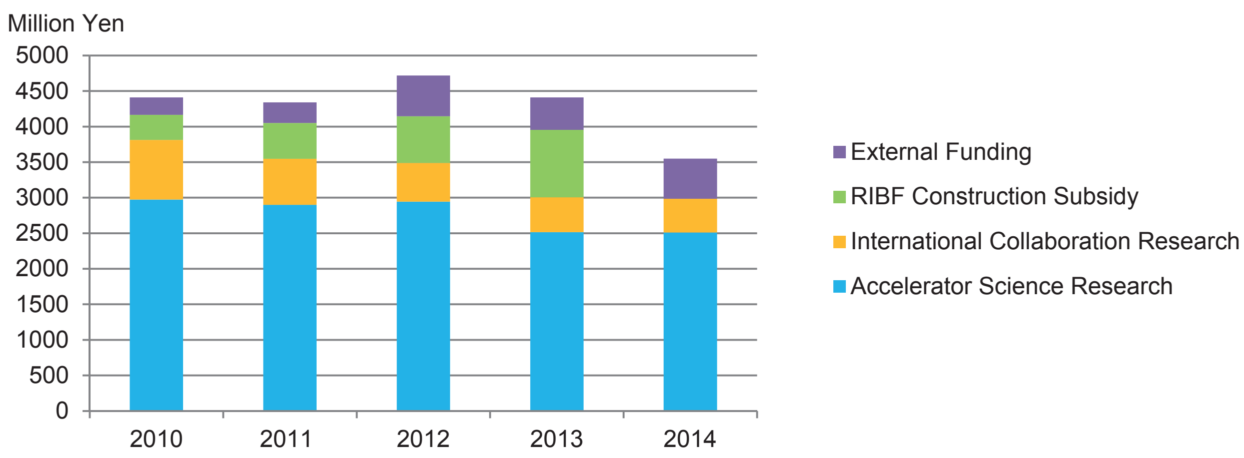
Oct. 1, 2014	Start of Nuclear Transmutation Data Research Group associated with following three teams Fast RI Data Team Slow RI Data Team Muon Data Team
	Start of High-Intensity Accelerator R&D Group associated with following two teams High-Gradient Cavity R&D Team High-Power Target R&D Team
Mar. 31, 2015	End of Mathematical Physics Laboratory

2. Finances

As mentioned in "1. Administrative Topic in FY2014", RNC executed approximately five months of RIBF operation. Breakdown expenses of the RNC FY2014 budget and a transition for the past five years are shown in following graphs.

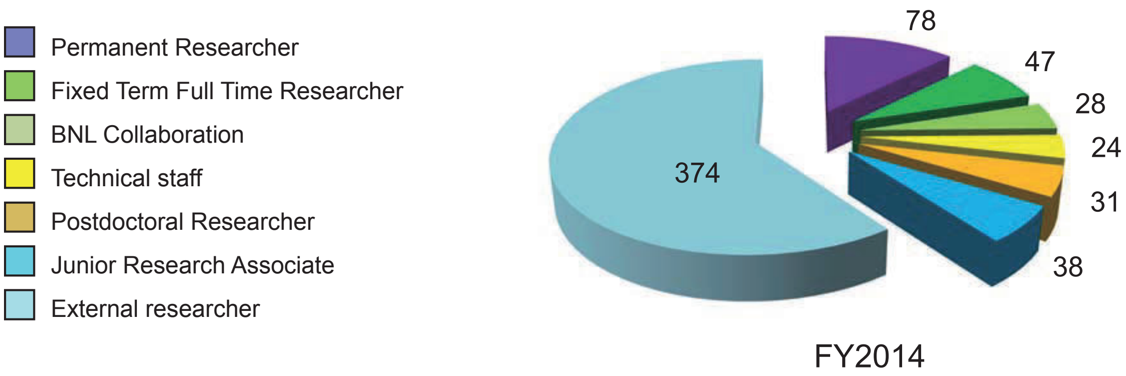
[Correction: In the 2013 edition, the FY2014 budget was shown erroneously instead of that of FY2013. The budget of FY 2014 has been reprinted with the revised external funding.].

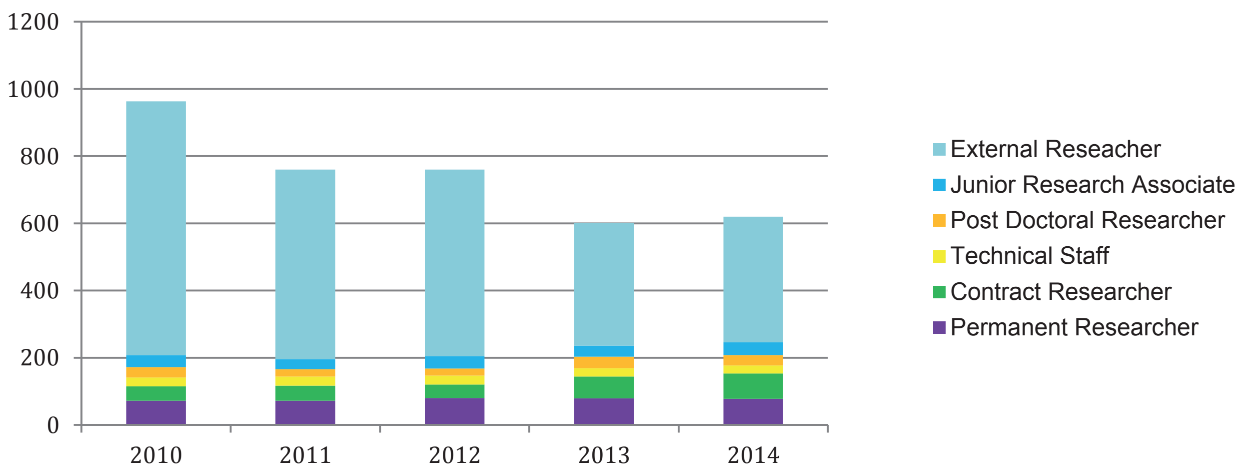




3. Staffing

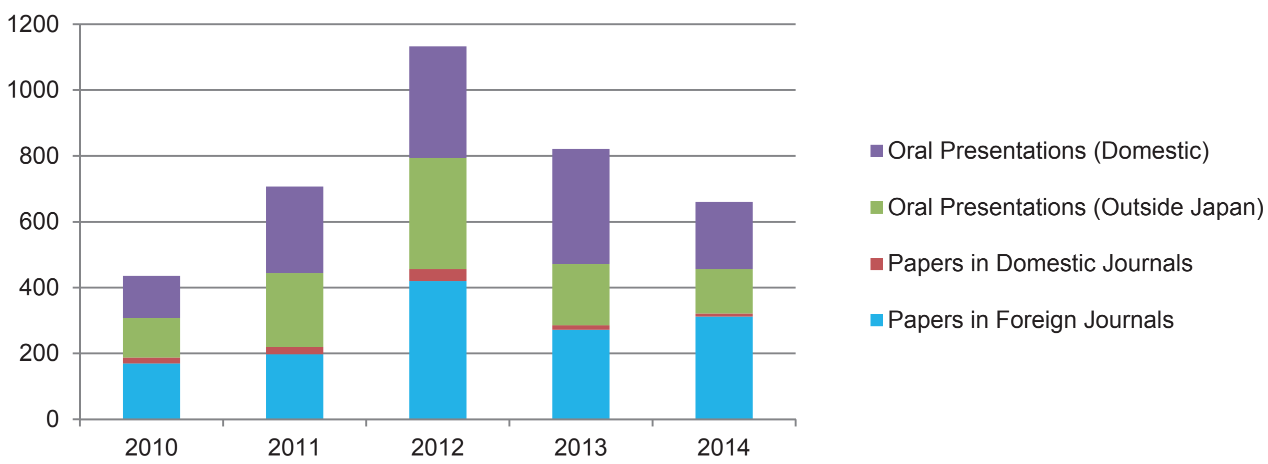
At the start of FY 2014, April 1 2014, there were 246 personnel affiliated with RNC and 347 researchers visiting RNC for research purpose. The following graphs show a breakdown of personnel into seven categories as of April 2014, and a transition of the number of each category. In the transition graph, researchers associated with the BNL collaboration in 2014 are counted as Contract Researcher.





4. Research publication

Research results published in 2014 are roughly split into two categories, i.e., papers published in journals and oral presentations. A transition of the number of the past five years is shown in the following graph.



5. Management

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

10 Laboratories
1 Research unit
9 Groups with 25 Teams
2 overseas research center with 3 Groups

as of the latter half of FY2014. 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
Safety Review Committee
RIBF Machine Time Committee
Public Relations Committee

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

RBRC Management Steering Committee (MSC) and Nishina Center Advisory Council with two subcommittees,

RBRC Management Steering Committee (MSC) and
Nishina Center Advisory Council with two subcommittees,
RBRC Scientific Review Committee (SRC) and
Advisory Committee for the RIKEN-RAL Muon Facility

Nishina Center for Accelerator-based Science

Executive Members (as of March 31, 2015)

Hideto EN'YO	Director RNC; Chief Scientist, Director of Radiation Laboratory
Tetsuo HATSUDA	Deputy Director (Theoretical Research), RNC; Chief Scientist, Director of Quantum Hadron Physics Laboratory
Hiroyoshi SAKURAI	Deputy Director (RIBF Research), RNC; Chief Scientist, Director of Radioactive Isotope Physics Laboratory; Group Director, Nuclear Transmutation Data Research Group
Tohru MOTOBAYASHI	RIBF Synergetic-Use Coordinator
Walter F. HENNING	Senior Advisor
Yasushige YANO	Senior Advisor
Minami IMANISHI	Assistant

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, 2015)

Hideto EN'YO	Director, RNC; Chief Scientist, Director of Radiation Laboratory
Hiroyoshi SAKURAI	Deputy Director, RNC; Chief Scientist, Director of Radioactive Isotope Physics Laboratory; Group Director, Nuclear Transmutation Data Research Group
Tetsuo HATSUDA	Deputy Director, RNC; Chief Scientist, Director of Quantum Hadron Physics Laboratory
Tohru MOTOBAYASHI	RIBF Synergetic-Use Coordinator
Walter F. HENNING	Senior Advisor
Yasushige YANO	Senior Advisor
Masahiko IWASAKI	Chief Scientist, Director of Advanced Meson Science Laboratory
Tomohiro UESAKA	Chief Scientist, Director of Spin isospin Laboratory
Hideki UENO	Chief Scientist, Director of Nuclear Spectroscopy Laboratory; Deputy Group Director, User Liaison and Industrial Cooperation Group
Toru TAMAGAWA	Associate Chief Scientist, Director of High Energy Astrophysics Laboratory
Takashi NAKATSUKASA	Associate Chief Scientist, Director of Theoretical Nuclear Physics Laboratory
Emiko HIYAMA	Associate Chief Scientist, Director of Strangeness Nuclear Physics Laboratory
Koji HASHIMOTO	Associate Chief Scientist, Director of Mathematical 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 E&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, Radiation Biology Team
Yoshitomo UWAMINO	Group Director, Safety Management Group
Toshiyuki KUBO	Group Director, Research Instruments Group; Team Leader, Detector Team
Masanori WAKASUGI	Group Director, Instrumentation Development Group; Team Leader, Rare RI-ring Team; Team Leader, SCRIT Team
Eiji IKEZAWA	Team Leader, RILAC Team
Takashi ICHIHARA	Team Leader, Computing and Network Team
Naruhiko SAKAMOTO	Team Leader, Cyclotron Team; Team Leader, High-Gradient Cavity R&D Team
Hiromi SATO	Team Leader, Detector Team
Takahide NAKAGAWA	Team Leader, Ion Source Team
Hiromitsu HABA	Team Leader, RI Applications Team
Koji MORIMOTO	Team Leader, Superheavy Element Device Development Team
Atsushi YOSHIDA	Team Leader, Industrial Cooperation Team
Koichi YOSHIDA	Team Leader, BigRIPS Team; Team Leader, Slow RI Data Team
Ken-ichiro YONEDA	Team Leader, User Support Office
Michiharu WADA	Team Leader, SLOWRI Team
Hideaki OTSU	Team Leader, SAMURAI Team; Team Leader, Fast RI Data Team
Teiichiro MATSUZAKI	Team Leader, Muon Data Team
Yasuyuki AKIBA	Vice Chief Scientist; 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
Yuko MOTIZUKI	Research Unit Leader, Astro-Glaciology Research Unit
Mitsuru KISHIMOTO	Deputy Director, Nishina Center Planning Office

Nishina Center Planning Office

The Nishina Center Planning Office is responsible for the following:

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, 2015)

Hiroshi TSUBOI	Executive Director; Director, Head of Nishina Center Planning Office
Mitsuru KISHIMOTO	Deputy Director, Nishina Center Planning Office; Administration Manager, RBRC; Administration Manager, RIKEN Facility Office at RAL
Kazunori MABUCHI	Deputy Manager, Nishina Center Planning Office
Yasutaka AKAI	Administrative Officer of Nishina Center Planning Office; Deputy Administration Manager, RBRC
Yukari ONISHI	Chief, Nishina Center Planning Office
Kumiko SUGITA	Special Administrative Employee
Yuko OKADA	Task-Specific Employee
Yukiko SATO	Task-Specific Employee
Kyoji YAMADA	Special Temporary Employee
Yoshio OKUIZUMI	Temporary Employee
Masatoshi MORIYAMA	Consultant for Advisory Committee, Research Review, etc.
Rie KUWANA	Temporary Staff

Scientific Policy Committee

The Scientific Policy Committee deliberates on the following:

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 FY2014.

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.

(1) Nuclear Physics Experiments at RIBF (NP-PAC): academic research in nuclear physics

(2) Materials and Life Science Researches at RNC (ML-PAC): academic research in materials science and life science
(3) Industrial Program Advisory Committee (In-PAC): non-academic research

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

Members (as of March 31, 2015)

Muhsin N. HARAKEH (Chair)	Prof., KVI (Kernfysisch Versneller Instituut), University of Groningen, Netherlands
Yanlin YE	Prof., State Key Lab. of Nucl. Phys. and Tech., School of Physics, Peking University, China
Christoph SCHEIDENBERGER	Head, NuSTAR/ENNA Department, GSI, Germany
Friedrich-K. THIELEMANN	Prof., Department of Physics, University of Basel, Switzerland
Rick F. CASTEN	Prof., Department of Physics, Yale University, USA
Christopher J. (KIM) LISTER	Prof., Department of Physics and Applied Physics, University of Massachusetts, Lowell, USA
Hans EMLING	Prof. Dr., GSI, Germany
Hironori IWASAKI	Assistant Prof., National Superconducting Cyclotron Laboratory, Michigan State University, USA
Walter D. LOVELAND	Full Prof., Department of Chemistry, Oregon State University, USA
Thomas NILSSON	Prof., Chalmers Univ. of Technology, Sweden; Chair of BFC (Board of FAIR Collaborations)
Bradley. M.SHERRILL	FRIB Associate Laboratory Director for Users, Michigan State University, USA
Olivier SORLIN	GANIL (Grand Accélérateur National d'Ions Lourds), France
Satoshi N. NAKAMURA	Prof. Nuclear Experiment Group, Faculty of Science, Tohoku University, Japan
Atsushi TAMII	Associate Prof., Research Center for Nuclear Physics, Osaka University, Japan
Yutaka UTSUNO	Senior Scientist, Advanced Science Research Center, JAEA, Japan
Masanobu YAHIRO	Prof., Faculty of Sciences, Kyushu University, Japan
Takashi NAKATSUKASA	Associate Chief Scientist, Theoretical Nuclear Physics Laboratory, RNC, Japan

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

Members (as of March 31, 2015)

Jean-Michel POUTISSOU (Chair)	Senior research scientist Emeritus, TRIUMF, Canada
Alex AMATO	Bulk μSR Group Head, GPS Scientist, Laboratory for Muon Spin Spectroscopy, PSI, Switzerland
Douglas E. MACLAUGHLIN	Prof., Emeritus, University of California, Riverside, USA
Sadamichi MAEKAWA	Director General, Advanced Science Research Center, JAEA, Japan
Kenya KUBO	Prof., Department of Material Science, International Christian University, Japan
Adrian HILLIER	ISIS, RAL, UK
Philippe MENDELS	Prof., Laboratorie de Physique des Solides, Universite Paris-SUD, France
Xu-Guang ZHENG	Prof., Department of Physics Faculty of Science and Engineering, Saga University, Japan
Hiroyuki YAMASE	Senior Researcher, National Institute for Materials Science, Japan
Ryosuke KADONO	Prof., Division Head, Muon Science Laboratory, Institute of Materials Structure Science, KEK, Japan
Norimichi KOJIMA	Prof., Department of Basic Science, Graduate School of Arts and Sciences, University of Tokyo, Japan
Toshiyuki AZUMA	Chief Scientist, Atomic, Molecular & Optical Physics Laboratory, RIKEN, Japan
Atsushi KAWAMOTO	Prof., Graduate School of Science, Hokkaido University, JAPAN
Shigeo YOSHIDA	Research Consultant, RIKEN Center for Sustainable Resource Science, RIKEN, Japan

Industrial Program Advisory Committee (In-PAC)

Members (as of March 31, 2015)

Akihiro IWASE (Chair)	Prof., Graduate School of Engineering, Osaka Prefecture University, Japan
Kenya KUBO	Prof., The College of Liberal Arts, International Christian University, Japan
Hitoshi NAKAGAWA	Auditor, Japan International Research Center for Agricultural Sciences, Japan
Nobuhiko NISHIDA	Full time research fellow, Toyota Physical and Chemical Research Institute, Japan
Toshinori MITSUMOTO	Chief Engineer, Quantum Equipment Division, Sumitomo Heavy Industries, Ltd, Japan
Toshiyuki AZUMA	Chief Scientist, Atomic, Molecular & Optical Physics Laboratory, RIKEN, Japan

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 RNC Director from the spokesperson of the approved experiment.

Safety Review Committee for Accelerator Experiments

Members (as of March 31, 2015)

Takashi KISHIDA (Chair)	Senior Research Scientist, Radioactive Isotope Physics Laboratory
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
Hiroshi WATANABE	Lecturer, Radioactive Nuclear Beam Group, IPNS, KEK

Hiromi SATO	Team Leader, Detector Team
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
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, 2015)

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

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, 2015)

Hideyuki SAKAI (Chair)	Group Director, User Liaison and Industrial Cooperation Group
Tomoko ABE	Group Director, Accelerator Applications Research Group
Nobuhisa FUKUNISHI	Deputy Group Director, Accelerator Group
Osamu KAMIGAITO	Group Director, Accelerator Group
Masayuki KASE	Deputy Group Director, Accelerator Group
Toshiyuki KUBO	Group Director, Research Instruments Group
Kouji MORIMOTO	Team Leader, Superheavy Element Research Device Development Team
Hiroki OKUNO	Deputy Group Director, Accelerator Group
Hiroyoshi SAKURAI	Chief Scientist, Radioactive Isotope Physics Laboratory
Hideki UENO	Chief Scientist, Nuclear Spectroscopy Laboratory
Tomohiro UESAKA	Chief Scientist, Spin isospin Laboratory
Yoshitomo UWAMINO	Group Director, Safety Management Group
Masanori WAKASUGI	Group Director, Instrumentation Development Group
Ken-ichiro YONEDA	Team Leader, User Support Office
Susumu SHIMOURA	Professor, Center for Nuclear Study, University of Tokyo
Hidetoshi YAMAGUCHI	Lecturer, Center for Nuclear Study, University of Tokyo
Hiroari MIYATAKE	Professor, Radioactive Nuclear Beam Group, IPNS, KEK

Observers (as of March 31, 2015)

Hideto EN'YO	Director, RNC
Nobuaki IMAI	Chair, RIBF-UEC, Associate Prof. Center for Nuclear Study, University of Tokyo
Hiromitsu HABA	Team Leader, RI Applications Team
Kosuke MORITA	Group Director, Research Group for Superheavy Element
Tohru MOTOBAYASHI	RIBF Synergetic-Use Coordinator
Koichi YOSHIDA	Team Leader, BigRIPS Team; Team Leader, Slow RI Data Team
Kanenobu TANAKA	Deputy Group Director, Safety Management Group
Mitsuru KISHIMOTO	Deputy Director, Nishina Center Planning Office

Public Relations Committee

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

(1) Creating public relations system for the RNC
(2) Prioritization of the public relations activities for the RNC
(3) Other general and important matters concerning the public relations of RNC

Members (as of March 31, 2015)

Hiroshi TSUBOI	Executive Director; Director, Head of Nishina Center Planning Office
Hiroyoshi SAKURAI	Deputy Director, RNC; Chief Scientist, Radioactive Isotope Physics Laboratory
Tetsuo HATSUDA	Deputy Director, RNC; Chief Scientist, Quantum Hadron Physics Laboratory
Tohru MOTOBAYASHI	RIBF synergetic-use coordinator
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
Toru TAMAGAWA	Associate Chief Scientist, High Energy Astrophysics Laboratory
Takashi NAKATSUKASA	Associate Chief Scientist, Theoretical Nuclear Physics Laboratory
Emiko HIYAMA	Associate Chief Scientist, Strangeness Nuclear Physics Laboratory
Koji HASHIMOTO	Associate Chief Scientist, Mathematical 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).

Members (as of March 31, 2015)

Maki KAWAI	Executive Director, RIKEN
Shoji NAGAMIYA	Science Advisor, RIKEN
Hideto EN'YO	Director, RNC
Berndt MUELLER	Associate Laboratory Director for Nuclear and Particle Physics, BNL
David LISSAUER	Deputy Chair, Physics Department, BNL
Satoshi OZAKI	Senior Advisor, BNL

Nishina Center Advisory Council

The agenda to be deliberated by NCAC are set by the Terms of Reference presented by the RNC Director on the fundamental issues regarding research activities and administrative matters. NCAC submits its report to the President of RIKEN, and to the Director of Nishina Center if necessary. The members of NCAC are recommended by the Director of the Nishina Center to the President of RIKEN and selected from among highly knowledgeable individuals and experts worldwide. NCAC has two sub-councils for the RBRC and the RAL Muon Facility, respectively.

Members (as of March 31, 2015)

Robert TRIBBLE (Chair)	Deputy Director for Science and Technology, BNL, USA
Hirokazu TAMURA	Prof., Department of Physics, Graduate School of Science, Tohoku University, Japan
Muhsin N. HARAKEH	Prof., Emeritus, KVI (Kernfysisch Versneller Instituut), University of Groningen, Netherlands; *Chair, NP-PAC*
Jean-Michel POUTISSOU	Senior research scientist Emeritus, TRIUMF, Canada; *Chair, ML-PAC*
Richard MILNER	Prof., Director, Laboratory for Nuclear Science, MIT, USA; *Chair, RBRC-SRC*
Andrew TAYLOR	Executive Director, STFC National Laboratories, UK; *Chair, RAL-IAC*
Juha ÄYSTÖ	Director of Helsinki Institute of Physics, Finland
Angela BRACCO	Prof., Department of Physics, the University of Milan, Italy
Masaki FUKUSHIMA	Prof., Institute for Cosmic Ray Research, University of Tokyo, Japan
Ken'ichi IMAI	Group Leader, Research Group for Hadron Physics, Advanced Science Research Center, JAEA, Japan
Marek LEWITOWICZ	Deputy Director, GANIL (Grand Accélérateur National d'Ions Lourds), France
Lia MERMINGA	Head, Accelerator Division, TRIUMF, Canada
Witold NAZAREWICZ	Prof., Department of Physics and Astronomy, the University of Tennessee, USA
Susumu SHIMOURA	Prof., Center for Nuclear Study (CNS), University of Tokyo, Japan
Matthias SCHÄDEL	Group Leader, Research Group for Superheavy Elements, Advanced Science Research Center, JAEA. , Japan
Jun SUGIYAMA	Principal Research Scientist, Toyota Central R&D Labs., INC, Japan
Wolfram WEISE	Director, European Center for Theoretical Studies in Nuclear Physic and Related Areas, Italy
GuoQing XIAO	Director, Institute of Modern Physics, Chinese Academy of Sciences, China
Akira YAMAMOTO	Head, Linear Collider Project Office, Department of Advanced Accelerator Technologies, KEK, Japan

RBRC Scientific Review Committee (SRC)

Members (as of March 31, 2015)

Richard MILNER (Chair)	Prof., Director, Laboratory for Nuclear Science, MIT, USA
Shinya AOKI	Prof., Yukawa Institute for Theoretical Physics, Kyoto University, Japan
Ken'ich IMAI	Group Leader, Research Group for Hadron Physics, Advanced Science Research Center, JAEA, Japan
Tetsuo MATSUI	Prof., Department of Basic Science, Graduate School of Arts and Sciences, Komaba, University of Tokyo, Japan
Alfred MUELLER	Prof., Department of Physics, Columbia University, USA
Peter Braun-MUNZINGER	Prof., Dr. GSI Helmholtzzentrum für Schwerionenforschung, Germany
Charles PRESCOTT	Prof., Stanford Linear Accelerator Center, USA
Akira UKAWA	Prof., Graduate School of Pure and Applied Science, University of Tsukuba, Japan

Advisory Committee for the RIKEN-RAL Muon Facility

Members (as of March 31, 2015)

Andrew D TAYLOR (Chair)	Executive Director, STFC National Laboratories, UK
Jean-Michel POUTISSOU	Senior research scientist Emeritus, TRIUMF, Canada
Klaus P. JUNGMANN	Prof., University of Groningen, Netherlands
Roberto De RENZI	Prof., Department of Physics and Earth Sciences, University of Parma, Italy
Yasuyuki MATSUDA	Assoc. Prof., Graduate School of Arts and Sciences, the University of Tokyo, Japan
Jun SUGIYAMA	Principal Research Scientist, Toyota Central R&D Labs., INC, Japan

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, Director of Advanced Meson Science Laboratory
Belgium	Katholieke Universiteit te Leuven	Framework	Michiharu WADA, Team Leader, SLOWRI Team
Bulgaria	The Institute for Nuclear Research and Nuclear Energy (INRNE)	Framework	Hedeki UENO, Chief Scientist, Nuclear Spectroscopy Laboratory
Canada	TRIUMF	Accelerator-based Science	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
China	China Nuclear Physics Society	Creation of the council for China -Japan research collaboration on nuclear physics	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
	Peking University	Nuclear Science	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
		Strategic cooperation (Nishina School)	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
	Shanghai Jiao Tong University	International Joint Graduate School Program	Takashi NAKATSUKASA, Associate chief scientist, Theoretical Nuclear Physics Laboratory
	ZHEJIANG University	International Joint Graduate School Program	Isao WATANABE, Advanced Meson Science Laboratoy
	Institute of Modern Physics, Chinese Academy of Science	Physics of heavy ions	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
	School of Nuclear Science and Technology, Lanzhou University	Framework	Yue MA, Advanced Meson Science Laboratory
	School of Physics, Nanjing University	Framework	Emiko HIYAMA, Associate chief scientist, Strangeness Nuclear Physics Laboratory
EU	European Gamma-Ray Spectroscopy Pool Owners Committee	The use of Euroball ditector at RIKEN	Shunji NISHIMURA, Radioactive Isotope Physics Laboratory
	European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*)	Theoretical physics	Tetsuo HATSUDA, Deputy Director, Chief Scientist, Quantum Hadron Physics Laboratory
	CERN	Framework	Satoshi YOKKAICHI, Senior Research Scientist, Radiation Laboratory
		RD-51:R&D programme for micro-pattern gas detectors (MPGD)	Satoshi YOKKAICHI, Senior Research Scientist, Radiation Laboratory
	ALICE Collaboration	Development of Gas Electron Multiplier, Silicon Detectors, etc.	Satoshi YOKKAICHI, Senior Research Scientist, Radiation Laboratory
	GSI & Reaction with Relativistic Radioactive Beams (R3B) Collaboration	To unravel structure of nuclei in the vicinity of and beyond the neutron dripline through experiments with the NeuLAND detector combined with the SAMURAI magnetic spectrometer at the RIBF	Tomohiro UESAKA, Chief Scientist, Spin Isospin 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, RIBF synergetic-use coordinator
	CNRS, CEA,GANIL, Université Paris Sud, etc.	Creation of an International Associated Laboratory (LIA) French-Japanese International Associated Laboratory for Nuclear Structure Problems	Tohru MOTOBAYASHI, RIBF synergetic-use coordinator
	IRFU CEA-Saclay DSM/IRFU, IPNO CNRS IN2P3, GANIL	The preparation and realization for the MUST2 campaign of experiments at RIKEN	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics 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	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	Université de Caen Basse Normandie	International Joint Graduate School Program	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory

Country	Partner Institute	Objects	RNC contact person
Germany	Technische Universität München	Nuclear physics, hadron physics, nuclear astrophysics	Emiko HIYAMA, Associate chief scientist, Strangeness Nuclear Physics Laboratory
	Max-Planck Gesellschaft	Comprehensive agreement	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
	GSI	Physics of heavey ions and accelerator	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope 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	Material science using muons at the RIKEN-RAL muon facility	Isao WATANABE, Advanced Meson Science Laboratoy
	UNPAD	International Joint Graduate School Program	Isao WATANABE, Advanced Meson Science Laboratoy
	Institut Teknologi Bandung (ITB)	International Joint Graduate School Program	Isao WATANABE, 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	National Institute of Nuclear Physics (INFN)	Physics of heavy ions	Tohru MOTOBAYASHI, RIBF synergetic-use coordinator
	Applied Physics Division, National Institute for New Technologies, Energy and Environment (ENEA)	Framework	Tohru MOTOBAYASHI, RIBF synergetic-use coordinator
Korea	Seoul National University	Nishina School	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
		International Joint Graduate School Program	Itaru NAKAGAWA, Radiation Laboratory
	Institute of Basic Science, Rare Isotope Science Project	Rare ion accelerator and related fields	Hiroyoshi SAKURAI, Shunji NISHIMURA
	Department of Physics, Kyungpook National University	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	College of Natural Sciences of Kyungpook National University	International Joint Graduate School Program	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	College of Science, Yonsei University	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
	Department of Physics, Yonsei University	International Joint Graduate School Program	Yasuyuki AKIBA, Radiation Laboratory
	Department of Physics, Korea University	Framework	Yuji GOTO, Radiation Laboratory
	College of Natural Science, Ewha Women's University	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
Malaysia	Universiti Sains Malaysia	Framework on Muon Science	Isao WATANABE, Advanced Meson Science Laboratoy
Poland	the Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences(IFJ PAN)	Framework	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics 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, Chief Scientist, Accelerator Group
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 Liverpool	International Joint Graduate School Program	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
USA	BNL	The Spin Physics Program at the Relativistic Heavy Ion Collider(RHIC)	Hideto EN'YO, Director of RNC
	Columbia University	The development of QCDCQ	Taku IZUBUCHI, Group Leader, Computing Group, RBRC
	Michigan State University	Framework	Tomohiro UESAKA, Chief Scientist, Spin Isospin Laboratory
		TPC(Time Projection Chamber)	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory & Tadaaki ISOBE, Radioactive Isotope Physics Laboratory
Vietnam	Vietnam Atomic Energy Commission	Framework	Tohru MOTOBAYASHI, RIBF synergetic-use coordinator
	Hanoi University of Science	International Joint Graduate School Program	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory
	Institute of Physics, Vietnam Academy of Science and Technology	Framework	Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory

7. Awards

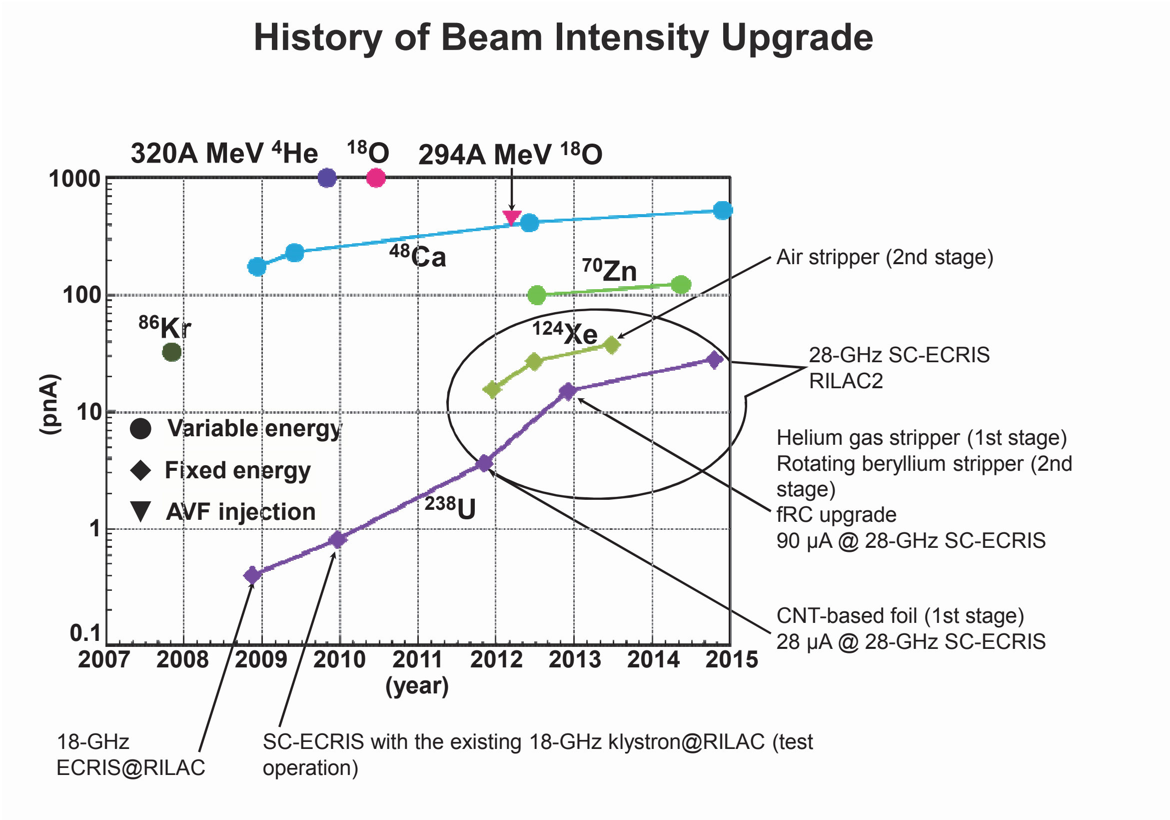
Awardee, Laboratory / Team	Award	Organization	Date
Tetsuo HATSUDA, Quantum Hadron Physics Laboratory Shinya AOKI (Visiting Scientist), Quantum Hadron Physics Laboratory Noriyoshi ISHII (Visiting Scientist), Radiation Laboratory	The Prizes for Science and Technology in Research Category, in the FY2015 Commendation for Science and Technology	The Minister of Education, culture, Sports, Science and Technology (MEXT)	Apr. 15
Tomonari HIRANO, Ion Beam Breeding Team Yusuke KAZAMA, Ion Beam Breeding Team Kotaro ISHII, Ion Beam Breeding Team Sumie OHBU, Ion Beam Breeding Team Yuki SHIRAKAWA, Ion Beam Breeding Team Tomoko ABE, Ion Beam Breeding Team	The Outstanding Presentation Award for their research at the 125th Meeting of the Japanese Society of Breeding	Japanese Society of Breeding	May 14
Maeyama TAKUYA, Beam Dynamics & Diagnostics Team	Young Scientist Award	The 5th Asia Pacific Symposium on Radiation Chemistry (APSRC2014)	Sep. 11
Yuko MOTIZUKI, the Astro-Glaciology Research Unit	NIceSTEP Award	National Institute of Science and Technology Policy	Dec. 19
Kimiko SEKIGUCHI (Visiting Scientist) , Spin Isospin Laboratory	The silver prize of the 2nd Yuasa Prize	Ochanomizu University	Dec. 24
Yoichi IKEDA, Quantum Hadron Physics Laboratory Toru SATO (Visiting Scientist), Strangeness Nuclear Physics Laboratory	The 20th Best Paper Award	The Physical Society of Japan	Mar. 23
Aiko TAKAMINE (Visiting Scientist) , SLOWRI Team	The 9th Young Scientist Award in the field of experimental nuclear physics	The Physical Society of Japan	Mar. 21
Abhay DESHPANDE, RBRC experimental group	Appointment as an APS Fellow	The American Physical Society	Mar. 13

8. Brief overview of the RI Beam Factory

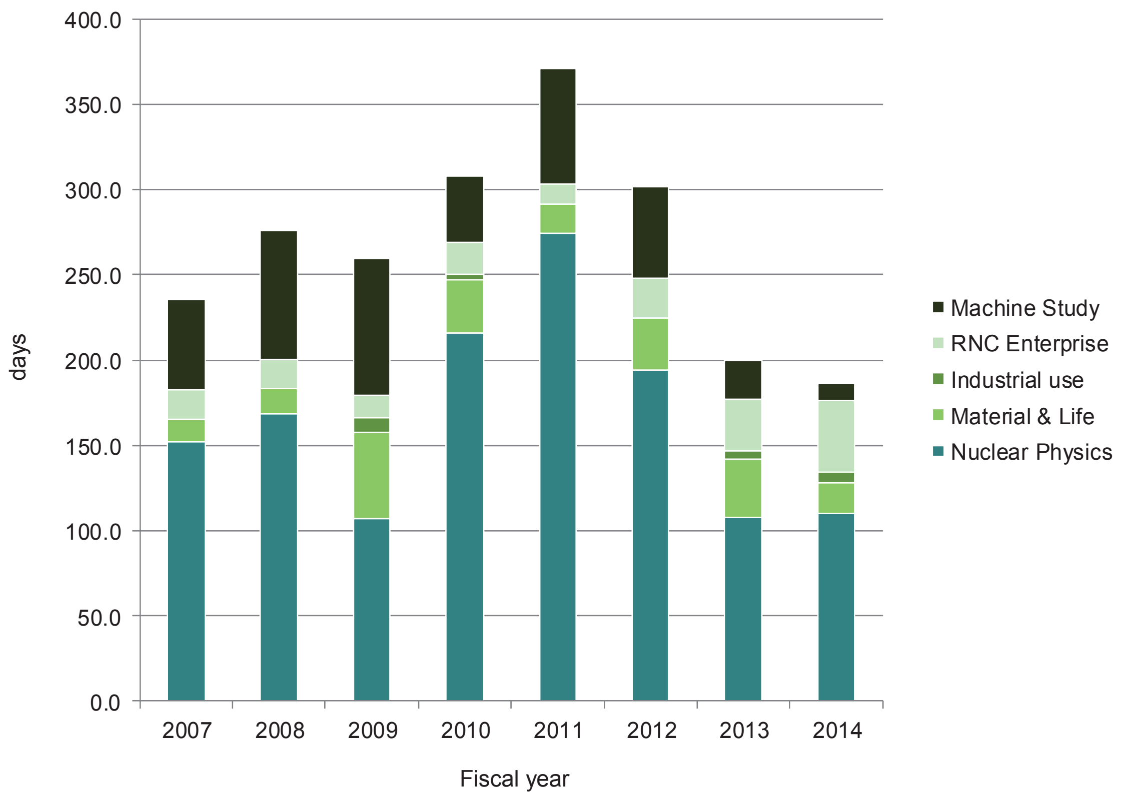
Intensity of Primary Beams

Achieved beam intensities (as of March 2015)

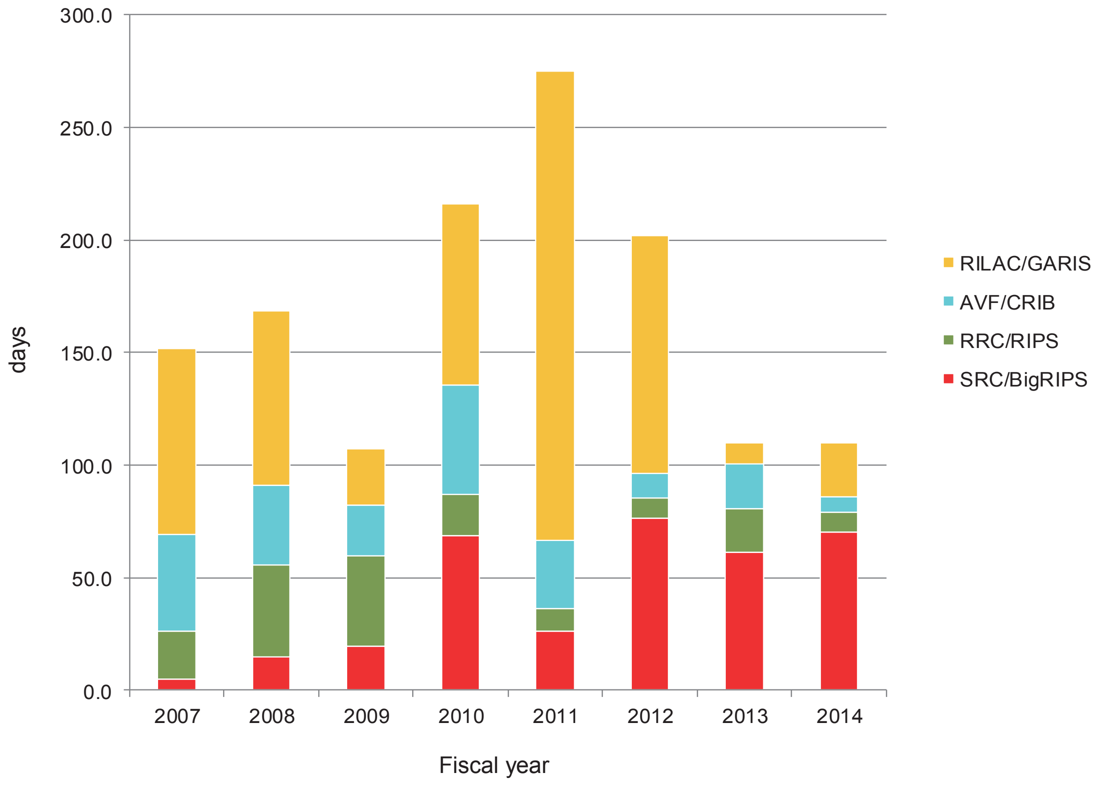
^{238}U	28 pnA	(345 MeV/u, Oct. 2014)
^{124}Xe	38 pnA	(345 MeV/u, Jun. 2013)
^{86}Kr	30 pnA	(345 MeV/u, Nov. 2007)
^{70}Zn	123 pnA	(345 MeV/u, Jun. 2014)
^{48}Ca	530 pnA	(345 MeV/u, Nov. 2014)
^{18}O	1,000 pnA	(345 MeV/u, Jun. 2010)
^{14}N	400 pnA	(250 MeV/u, Oct. 2010)
^{4}He	1,000 pnA	(250 MeV/u, Oct. 2009)
d	1,000 pnA	(250 MeV/u, Oct. 2010)
pol. d	1,000 pnA	(250 MeV/u, Apr. 2009)



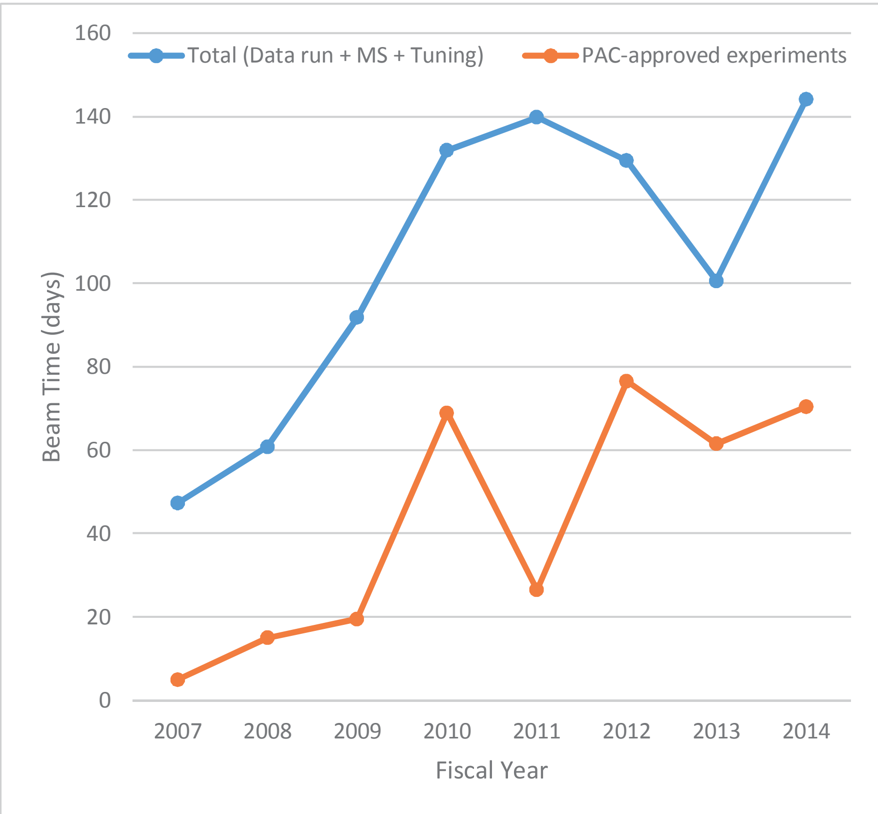
Total beam time for experiments



Breakdown of Nucl. Phys. Expts.



Total beam time allocated to BigRIPS experiments



Theoretical Research Division
Quantum Hadron Physics Laboratory

1. Abstract

Atomic nuclei are made of protons and neutrons bound by the exchange of Yukawa's 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) Improving the tenth-order QED contribution to the electron $g-2$
(2) Physics of particles with resonant interactions
(3) String duality and Sine-Square Deformation of Conformal Field Theory
(4) Theory of spontaneous symmetry breaking
(5) QCD under extreme conditions
(6) Lattice baryon forces

3. Summary of Research Activity

(1) Improving the tenth-order QED contribution to the electron $g-2$

The preliminary value of the tenth-order of the perturbation theory of QED contribution to the electron anomalous magnetic moment ($g-2$) was reported by us in 2012. Since then, we have been involved in improving and establishing its accuracy. To carry out it, we reevaluated the most difficult and large set of the Feynman diagrams by using the advanced technique of numerical calculation especially suitable to RIKEN's supercomputer. As a result, we have obtained more reliable and more precise values for the eighth- and tenth-order terms. Together with the Harvard experiment of the electron $g-2$, it leads to the world-best value of the fine-structure constant α that will be used to determine a next CODATA recommended value of α.

(2) Physics of particles with resonant interactions

Some particles, such as nucleons, can only weakly or nearly bind by pair. As a result, their pairwise interaction is resonant. Resonant interactions induce universal few-body phenomena, such as the Efimov effect. These phenomena lead to the existence of universal three-body bound states, that can be easily investigated with ultra-cold atoms. After analysing these experiments and clarifying these few-body phenomena for the past few years, we have now started to explore their consequences at the many-body level, by first looking at mixtures of resonantly interacting heavy and light particles. The near-resonant interaction induces a phase made of trimers of two heavy and one light particles. We have characterized this phase by carrying out for the first time a six-body calculation of the effective interaction between two universal trimers.

(3) String duality and Sine-Square Deformation of Conformal Field Theory

String duality is the concept that has been leading us to better understandings of the dynamics of string theory. One of such dualities is the open-closed duality, which suggests relation between gauge theories and the theory of gravity, thus could be behind another duality, AdS/CFT correspondence. Since the difference between open string and closed string is the difference of the boundary condition of the worldsheet of string, of particular interest is the recently found phenomenon called Sine-Square Deformation (SSD) in which certain quantum systems exhibit the change from the closed-boundary vacuums to open-boundary ones through the spatial modulation of the couplings. We investigated SSD in the context of Conformal Field Theory (CFT) in particular and found continuous Virasoro algebra, suggesting that CFT would acquire a continuous energy spectrum under SSD.

(4) Theory of spontaneous symmetry breaking

(4-1) Dispersion relations of Nambu-Goldstone modes at finite temperature and density

We discussed 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 (I) and type-B (II) 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 far away. We derived the gap formula for NG modes in the presence of a small explicit breaking term. We also discussed the gapped partners of type-B NG modes, when type-A and type-B NG modes coexisted.

(4-2) Effective field theory for spacetime symmetry breaking

We discussed 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 (an)isotropic Weyl symmetries as well as the internal symmetries including possible central extensions in nonrelativistic systems. Such a local picture distinguishes, e.g., whether the symmetry breaking condensations have spins and provides a correct identification of the physical NG fields, while the standard coset construction based on global symmetry breaking does not. We illustrated that the local picture becomes important in particular when we took into account massive modes associated with symmetry breaking, whose masses were not necessarily high. 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.

(5) QCD under extreme conditions

(5-1) Production and Elliptic Flow of Dileptons and Photons in the semi-Quark Gluon Plasma

We considered the thermal production of dileptons and photons at temperatures above the critical temperature in QCD. We used a model where color excitations are suppressed by a small value of the Polyakov loop, the semi Quark-Gluon Plasma (QGP). Comparing the semi-QGP to the perturbative QGP, we found a mild enhancement of thermal dileptons. In contrast, to leading logarithmic order in weak coupling there are far fewer hard photons from the semi-QGP than the usual QGP. To illustrate the possible effects on photon and dileptons production in heavy ion collisions, we integrated the rate with a realistic hydrodynamic simulation. Dileptons uniformly exhibit a small flow, but the strong suppression of photons in the semi-QGP tends to bias the elliptical flow of photons to that generated in the hadronic phase.

(5-2) Relativistic hydrodynamics from quantum field theory on the basis of the generalized Gibbs ensemble method

We derived relativistic hydrodynamics from quantum field theories by assuming that the density operator is given by a local Gibbs distribution at initial time. We decomposed the energy-momentum tensor and particle current into nondissipative and dissipative parts, and analyzed their time-evolution in detail. Performing the path-integral formulation of the local Gibbs distribution, we microscopically derived the generating functional for the nondissipative hydrodynamics. We also constructed a basis to study dissipative corrections. In particular, we derived the first-order dissipative hydrodynamic equations without choice of frame such as the Landau-Lifshitz or Eckart frame.

(6) Lattice baryon forces

One of the most important subjects in nuclear physics is to determine nuclear forces and hyperon forces, or generalized baryon forces, directly based on the fundamental theory, QCD. In HAL QCD Collaboration, we have been developing a novel lattice QCD formulation and performing first-principles numerical simulations to determine baryon forces. Spin-orbit forces have been calculated for the first time, and attraction in 3P2 channel is observed, which is related to the P-wave neutron pairing in neutron stars. The calculation of the N-Omega interaction shows that the system is bound in 5S2 channel. Three-nucleon forces have been calculated at several heavy quark masses, and quark mass dependence is found to be small. The lattice calculations are extended to the the exotic tetraquark systems as Tcc and Tcs, and the phenomenological diquark picture in these systems is studied as well. As an application, properties of medium-heavy nuclei have been calculated based on lattice nuclear forces, and so-called "mass-formula" is obtained.

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Part-time Workers

Yuki MINAMI (Oct. 1, 2014 – Mar. 31, 2015)
Kayo YAMAJI

Theoretical Research Division
Theoretical Nuclear Physics Laboratory

1. Abstract

Nuclei are finite many-particle systems composed of protons and neutrons. They are self-bound in femto-scale (10^{-15}m) by the strong interaction (nuclear force) whose study was pioneered by Hideki Yukawa. Uncommon properties of the nuclear force (repulsive core, spin-isospin dependence, tensor force, etc.) prevent complete microscopic studies of nuclear structure. There exist number of unsolved problems even at present. In addition, radioactive beam facilities reveal novel aspects of unstable nuclei. We are tackling these old problems and new issues in theoretical nuclear physics, developing new models and pursuing large-scale calculations of quantum many-body systems. We are also strongly involved in research on other quantum many-body systems, to resolve mysteries in the quantum physics.

2. Major Research Subjects

(1) Nuclear structure and quantum reaction theories
(2) First-principle calculations with the density functional theory for many Fermion systems
(3) Computational nuclear physics

3. Summary of Research Activity

(1) Systematic calculation of $T = 1$ triplets with proton-neutron-mixed energy density functionals

We have performed a systematic calculation for the $T = 1$ isobaric analog states (IASs) based on the Skyrme energy density functionals (EDFs) including protons-neutron (*p-n*) mixing. The IASs are calculated using the isocranking method. First we performed a systematic calculation for the energies of the $T = 1$ triplets in the $A = 10 \sim 66$ region with several Skyrme parameter sets. We used the isoscalar *p-n* mixed Skyrme EDFs, which are invariant under rotation in the isospin space, together with the Coulomb energy functional. The calculated results show a systematic underestimation from the experimental data, which may be related to violation of the charge symmetry and the charge independence of the nucleon-nucleon interaction and may imply that we need to further extend the energy functionals including isospin breaking terms. Recently, we have started a calculation including the isospin breaking interactions.

(2) Three dimensional mesh calculations for covariant density functional theory

The covariant density functional theory has some numerical difficulties, such as variational collapse and the fermion doubling. Because of these problems, the three-dimensional (3D) mesh calculation was impossible for a long time. In order to realize such calculations for the first time, we proposed in a novel and practical method to solve Dirac equations in the 3D coordinate space. The variational collapse is prevented by employing a method based on the variational principle for the inverse of a single-particle Hamiltonian, while for the fermion doubling, we have extended the method of Wilson fermion, which has been widely employed in lattice QCD calculations.

Using ^{16}O as an example, we have confirmed that our strategy provides accurate solutions for self-consistent mean-field calculations without the influence of the negative-energy spectrum and the spurious solutions of a discretized Dirac equation. We have also shown with ^{24}Mg and ^{28}Si that this method is applicable to deformed solutions in the (β, γ) deformation plane. This development enables us, e.g., i) to study any complicated structure of nuclei with a single numerical code, ii) to compare directly the results of the relativistic models to those of 3D mesh calculations with the non-relativistic models, and iii) to provide reliable theoretical predictions with the relativistic models for unknown nuclei allowing symmetry-breaking solutions. It also allows a straightforward extension of the finite amplitude method within the relativistic framework for a study of nuclear excitations in deformed nuclei.

(3) Microscopic description of fusion hindrance in heavy systems

We investigate fusion hindrance in heavy systems, where the fusion probability is strongly hindered compared with that in light- and medium-mass systems, to understand the origin of the fusion hindrance from a microscopic point of view. We employ microscopic time-dependent Hartree-Fock (TDHF) model for the analysis. In TDHF simulations, we reasonably reproduce the extra-push energies estimated from experimental data for heavy systems. Then, we extract nucleus-nucleus potential and energy dissipation by combining TDHF simulations for fusion reactions with Newton equation including a dissipation term. Extracted potentials in heavy systems show monotonic increase as the relative distance of two nuclei decreases and the disappearance of an ordinary barrier structure, which are different from lighter systems. Using these properties, we analyze the origin of the extra-push energy and find that the contribution to extra-push energy from the increase in potential is larger than that from dissipated energy in most systems. We conclude from our analysis that the main origin of the fusion hindrance is dynamical increase in potential.

(4) Hidden pseudo-spin and spin symmetries and their origins in atomic nuclei

Pseudo-spin symmetry (PSS) was introduced to explain the near degeneracy between pairs of nuclear single-particle states with the quantum numbers (n-1, l+2, j=l+3/2) and (n, l, j=l+1/2). We have written a review article [arXiv:1411.6774, *Phys. Rep.* in press], and intended to provide a comprehensive overview on the recent progress of pseudo-spin and spin symmetries in a systematic way. These symmetries were discussed in various systems and potentials: from stable nuclei to exotic nuclei, from non-confining to confining potentials, from local to non-local potentials, from central to tensor potentials, from bound states to resonant states, from nucleon spectra to anti-nucleon spectra, from nucleon spectra to hyperon spectra, from spherical nuclei to deformed nuclei.

Furthermore, three of the open issues in this field were selected and discussed in detail, i.e., the perturbative nature of PSS, the puzzle of intruder states, and the supersymmetric (SUSY) representation of PSS. For the perturbative nature of PSS, we emphasized that whether or not the symmetry breaking behaves perturbatively depends on whether an appropriate symmetry limit is chosen and an appropriate symmetry-breaking term is identified. As long as an appropriate symmetry limit is chosen, the nature of PSS is indeed perturbative. For the puzzle of intruder states, we showed several different features about this puzzle. By doing that a number of "contradicting" results in the literature for the spin (pseudo-spin) partners have been clarified in an explicit way. For the SUSY representation of PSS, we pointed out one of the promising ways for understanding the PSS and its symmetry breaking, by combining the similarity renormalization group, the SUSY quantum mechanics, and the perturbation theory. Meanwhile, how to apply the SUSY technique directly to the Dirac equations, which have non-trivial scalar and vector potentials, remains an interesting and open question.

(5) "Hybrid Kurotama model" for total reaction cross sections

We have developed a new general-purpose-total-reaction-cross-section model/subroutine called ``Hybrid Kurotama". The model has been tested and compared with available data for *p*+He, *p*+nucleus, and nucleus+nucleus total reaction cross sections. The overall agreement has been found better than former published models. This model is therefore very suitable to be used in any deterministic or Monte Carlo particle and heavy ion transport code.

(6) Improved parametrization of the transparency parameter in Kox and Shen models of total reaction cross sections

The total reaction cross section is an essential quantity in particle and heavy-ion transport codes when determining the mean-free path of a transported particle. Many transport codes determine the distance a particle is transported before it collides with the target or is stopped in the target material, with the Monte Carlo (MC) method using semiempirical parametrization models for the total reaction cross sections. In order to improve the well-known Kox and Shen models of total reaction cross sections and allow the models to be used at energies below 30 MeV/nucleon, we have proposed a modified parametrization of the transparency parameter. We have also reported that the Kox and Shen models have a projectile-target asymmetry and should be used so that the lighter nucleus is always treated as the projectile.

(7) Energy and mass number dependence of total reaction cross sections of nuclei

We have systematically analyzed nuclear reaction data that are sensitive to nuclear size, namely, proton-nucleus total reaction cross sections and differential elastic cross sections, using a phenomenological black-sphere approximation of nuclei that we are developing. In this framework, the radius of the black sphere is found to be a useful length scale that simultaneously accounts for the observed proton-nucleus total reaction cross section and first diffraction peak in the proton elastic differential cross section. This framework is expected to be applicable to any kind of projectile that is strongly attenuated in the nucleus. On the basis of a cross-section formula constructed within this framework, we find that a less familiar $A^{1/6}$ dependence plays a crucial role in describing the energy dependence of proton-nucleus total reaction cross sections.

(8) Probing the critical behavior in the evolution of GDR width at very low temperatures in A ~ 100 mass region

The influence of giant dipole resonance (GDR) induced quadrupole moment on GDR width at low temperatures is investigated experimentally by measuring the GDR width systematically in the unexplored temperature range T = 0.8-1.5 MeV, for the first time, in A ~ 100 mass region. The measured GDR width, using alpha induced fusion reaction, for ^{97}Tc confirms that the GDR width remains constant at the ground state value up to a critical temperature and increases sharply thereafter with the increase in T. The data have been compared with the adiabatic thermal shape fluctuation model (TSFM), phenomenological critical temperature fluctuation model (CTFM) and microscopic phonon damping model (PDM). Interestingly, the CTFM and PDM give the similar results and agree with the data, whereas the TSFM differs significantly even after incorporating the shell effects indicating towards the inclusion of GDR-GQR coupling in the TSFM.

(9) Giant dipole resonance in highly excited nuclei

The evolution of the giant dipole resonance's (GDR) width and shape at finite temperature T and angular momentum J is described within the framework of the phonon damping model (PDM). The PDM description is compared with the established experimental systematics obtained from heavy-ion fusion and inelastic scattering of light particles on heavy target nuclei, as well as with predictions by other theoretical approaches. Extended to include the effect of angular momentum J, its strength functions have been averaged over the probability distributions of T and J for the heavy-ion fusion evaporation reaction, which forms the compound nucleus ^{88}Mo at high T and J. The results of theoretical predictions are found in excellent agreement with the experimental data. The predictions by PDM and the heavy-ion fusion data are also employed to predict the viscosity of hot medium and heavy nuclei.

We also explore an approach that includes temperature-dependent shell effects and fluctuations of the pairing field in the thermal shape fluctuation model (TSFM). We apply this approach to study the width of GDR in ^{120}Sn, ^{179}Au and ^{208}Pb. Our results demonstrate that the TSFM that includes pairing fluctuations can explain the recently observed quenching in the GDR width.

(10) Reentrance phenomenon of superfluid pairing in hot rotating nuclei

When a nucleus rotates (total angular momentum J and/or rotational frequency ω are not zero), the nucleon (proton and neutron) pairs located around the Fermi surface will scatter to the empty levels nearby and lead to the decreasing of pairing correlation. When the J or ω is sufficiently high, i.e., equal to the critical value J_c or ω_c, the scattered nucleons completely block the single-particle levels around the Fermi surface. Consequently, pairing correlation disappears. However, when J is slightly higher than J_c (or $\omega > \omega_c$), the increase of temperature T will relax the particles scattered around the Fermi surface and causes some levels become partially unoccupied, making them available for scattered pairs. As a result, the pairing correlation reappears at some critical value T_1. As T goes higher, e.g., at $T_2 > T_1$, the newly created pairs will be eventually broken down again. This phenomenon is called the pairing reentrance. The recently developed

FTBCS1 theory that includes the effect due to quasiparticle-number fluctuations in the pairing field and angular momentum *z* projection at $T \neq 0$ has predicted the pairing reentrance effect in some realistic nuclei. The shell-model Monte Carlo calculations have suggested that the pairing reentrance effect can be observed in the nuclear level density in a form of a local maximum at low T (or excitation energy E^*) and high J (or ω). Recently, an enhancement of level density of ^{104}Pd at low E^* and high J has been experimentally reported. This work demonstrates that the enhancement observed in the extracted level density of ^{104}Pd is the first evidence of pairing reentrance phenomenon in atomic nuclei.

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Theoretical Research Division
Strangeness Nuclear Physics Laboratory

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) Baryon-baryon interaction based on lattice QCD
(4) Structure of three- and four-body ^{4}He atom systems

3. Summary of Research Activity

(1) Recently, we observed of neutron-rich system nnΛ as a bound state. To investigate this system, we performed nnΛ+NnΣ three-body coupled channel calculation. Using YN interaction to reproduce observed binding energies for $^4{}_\Lambda$H, $^4{}_\Lambda$He, and $^3{}_\Lambda$H, we do not find any bound state for nnΛ system which is inconsistent with the data. Now, we propose the experimentalists to perform a search experiment of nnΛ system again.
(2) It is interesting to study the structure of Ar isotope, since we have some superdeformed states (SD) in this Isotope. Within the framework of AMD method, we investigate the structure of SD states. In addition, we study the structure of Ar Λ hypernuclei. Then, we found that Λ-separation energy was dependent on the degree of deformation of core nuclei.
(3) Using several realistic ^{4}He atomic potential, we calculate Efimov spectra of trimer and tetramer systems of 4He. Our result shows an extension of the universality in Efimov trimers that the appearance of the repulsive barrier at the three-body hyperradius $R_3 \approx 2\ W_{rvd}$ makes the critical scattering lengths independent of the short-range details of the interactions as reported in the literature and also in the present work for the 4He trimer with the realistic potentials.

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Theoretical Research Division
Mathematical Physics Laboratory

1. Abstract

The aim of mathematical physics laboratory is to apply mathematical scheme to resolve long-standing issues in various subjects of physics. Mathematics, in particular that originates in superstring theory, has universal feature which is common to wide range of physics. This covers elementary particle physics, hadron physics, nuclear physics, cosmology, general relativity and condensed matter physics. We apply mathematical scheme such as superstring theory, D-branes, AdS/CFT correspondence, solitons, statistical mechanics and integrable systems. Topics which the laboratory covers currently include non-perturbative analysis of quantum chromo-dynamics, superstrings, and models beyond the standard model of particle physics, and soliton physics.

2. Major Research Subjects

(1) Application of Superstring Theory
(2) Non-perturbative analyses of strongly-coupled gauge theories
(3) Physics of Black Holes and Cosmology
(4) Solitons physics
(5) Mathematical physics
(6) Lattice gauge theory

3. Summary of Research Activity

Interplay between mathematics and physics is indispensable, as any physics law is described in terms of mathematics. However, the present status of various theoretical physics does not fully appreciate the usefulness of mathematics, as each topics goes into details and has less interaction with other subjects even nearby. We integrate various subjects of physics, by applying recent development of mathematics and mathematical physics, to solve long-standing issues in physics. In particular, mathematical methods in superstring theory has been developed and is mature enough to be applied to other physics. We put efforts on the application as described below, in addition to some other mathematical techniques such as numerical simulations, solitons and integrable systems.

(1) Application of superstring theory

1) Magnetic instability in AdS/CFT : Schwinger effect and Euler-Heisenberg Lagrangian of Super- symmetric QCD

To reveal the Schwinger effect for quarks, i.e., pair creation process of quarks and antiquarks, we derive the vacuum decay rate at strong coupling using AdS/CFT correspondence. Magnetic fields, in addition to the electric field responsible for the pair creation, causes prominent effects on the rate, and is important also in experiments such as RHIC/LHC heavy ion collisions. In this paper, through the gravity dual we obtain the full Euler-Heisenberg Lagrangian of N=2 supersymmetric QCD and study the Schwinger mechanism with not only a constant electric field but also a constant magnetic field as external fields. We determine the quark mass and temperature dependence of the Lagrangian. In sharp contrast with the zero magnetic field case, we find that the imaginary part, and thus the vacuum decay rate, diverges in the massless zero-temperature limit. This may be related to a strong instability of the QCD vacuum in strong magnetic fields. The real part of the Lagrangian serves as a generating function for non-linear electro-magnetic responses, and is found such that the Cotton-Mouton effect vanishes. Interestingly, our results of the Schwinger / Cotton-Mouton effects coincide precisely with those of N=2 supersymmetric QED.

2) Electric Field Quench in AdS/CFT

An electric field quench, a suddenly applied electric field, can induce nontrivial dynamics in confining systems which may lead to thermalization as well as a deconfinement transition. In order to analyze this nonequilibrium transitions,we use the AdS/CFT correspondence for N=2 supersymmetric QCD that has a confining meson sector. We find that the electric field quench causes the deconfinement transition even when the magnitude of the applied electric field is smaller than the critical value for the static case (which is the QCD Schwinger limit for quark-antiquark pair creation). The time dependence is crucial for this phenomenon, and the gravity dual explains it as an oscillation of a D-brane in the bulk AdS spacetime. Interestingly, the deconfinement time takes only discrete values as a function of the magnitude of the electric field. We advocate that the new deconfinement phenomenon is analogous to the exciton Mott transition.

3) Entropic destruction of heavy quarkonium in non-Abelian plasma from holography

Lattice QCD indicates a large amount of entropy associated with the heavy quark-antiquark pair immersed in the quark-gluon plasma. This entropy grows as a function of the inter-quark distance giving rise to an entropic force that can be very effective in dissociating the bound quarkonium states. In addition, the lattice data show a very sharp peak in the heavy quark-antiquark en- tropy at the deconfinement transition. Since the quark-gluon plasma around the deconfinement transition is strongly coupled, we employ the holographic correspondence to study the entropy as- sociated with the heavy quark-antiquark pair in two theories: i) N=4 supersymmetric Yang-Mills and ii) a confining Yang-Mills theory obtained by compactification on a Kaluza-Klein circle. In both cases we find the entropy growing with the inter-quark distance and evaluate the effect of the corresponding entropic forces. In the case ii), we find a sharp peak in the entropy near the de- confinement transition, in agreement with the lattice QCD results. This peak in our holographic description arises because the heavy quark pair acts as an eyewitness of the black hole formation in the bulk ? the process that describes the deconfinement transition. In terms of the boundary theory, this entropy likely emerges from the entanglement of a ”long string” connecting the quark and antiquark with the rest of the system.

(2) Cosmology

1) Dynamical breaking of shift-symmetry in supergravity-based inflation

Shift-symmetry is essential to protect the flatness of the potential, even beyond the super- Planckian vacuum expectation value (VEV) for an inflaton field. The breaking of the shift- symmetry can yield potentials suitable for super-Planckian excursion of the inflaton. The aim of this paper is to illustrate that it is indeed possible to break the shift-symmetry dynamically within 4 dimensional supergravity prior to a long phase of inflation. Thanks to the shift-symmetry, the leading contribu- tion to the inflaton potential is free from the dangerous exponential factor even after its breaking, which is the main obstacle to realizing the super-Planckian inflation in super- gravity. But, in our simple model, the resulting inflaton potential is a cosine type potential rather than the power-law one and it is difficult to realize a super-Planckian breaking scale unfortunately.

2) Effective gravitational interactions of dark matter axions

We investigate the structure of gravitational self-interactions of coherently oscillating axions in the general relativistic framework. A generic action for a massive scalar field in the Friedmann- Robertson-Walker background is first introduced based on the effective field theory approach to cosmological perturbations. Using the obtained setup, we evaluate the effective gravitational inter- action of the massive scalar field, i.e. scalar quartic interactions mediated by metric perturbations. Applying the results to the system of dark matter axions, we estimate their self-interaction rate and discuss its implications for the axion Bose-Einstein condensate dark matter scenario. Leading contributions for the gravitational interactions of axions are given by the process mediated by the dynamical graviton field, which is essentially the Newtonian potential induced by fluctuations of the background fluids. We find that it leads to the same order of magnitude for the interaction rate of dark matter axions in the condensed regime, compared with the results of previous studies using the Newtonian approximation.

(3) Condensed matter physics

1) Current Reflection and Transmission at Conformal Defects: Applying BCFT to Transport Process

We study reflection/transmission process at conformal defects by introducing new transport co- efficients for conserved currents. These coefficients are defined by using BCFT techniques thanks to the folding trick, which turns the conformal defect into the boundary. With this definition, exact computations are demonstrated to describe reflection/transmission process for a class of conformal defects. We also compute the boundary entropy based on the boundary state.

2) Bulk angular momentum and Hall viscosity in chiral superconductors

We establish the Berry-phase formulas for the angular momentum (AM) and the Hall viscosity (HV) to investigate chiral superconductors (SCs) in two and three dimensions. The AM is defined by the temporal integral of the anti-symmetric momentum current induced by an adiabatic defor- mation, while the HV is defined by the symmetric momentum current induced by the symmetric torsional electric field. Without suffering from the system size or geometry, we obtain the macro- scopic AM Lz = (h/2pi) m N0/2 at zero temperature in full-gap chiral SCs, where m is the magnetic quantum number and N0 is the total number of electrons. We also find that the HV is equal to half the AM at zero temperature not only in full-gap chiral SCs as is well-known but also in nodal ones, but its behavior at finite temperature is different in the two cases.

(4) Mathematical physics

1) Duality and integrability of supermatrix model with external source

We study the Hermitian supermatrix model involving an external source. We derive the deter- minantal formula for the supermatrix partition function, and also for the expectation value of the characteristic polynomial ratio, which yields the duality between the characteristic polyno- mial and the external source with an arbitrary matrix potential function. We also show that the supermatrix integral satisfies the one and two dimensional Toda lattice equations as well as the ordinary matrix model.

2) Laplace operators on Sasaki-Einstein manifold

We decompose the de Rham Laplacian on Sasaki-Einstein manifolds as a sum over mostly positive definite terms. An immediate consequence are lower bounds on its spectrum. These bounds constitute a supergravity equivalent of the unitarity bounds in dual superconformal field theories. The proof uses a generalization of Kahler identities to the Sasaki-Einstein case.

3) Non-Lagrangian Theories from Brane Junctions

We use 5-brane junctions to study the 5D TN SCFTs corresponding to the 5D N=1 uplift of the 4D N=2 strongly coupled gauge theories, which are obtained by compactifying N M5 branes on a sphere with three full punctures. Even though these theories have no Lagrangian description, by using the 5-brane junctions proposed by Benini, Benvenuti and Tachikawa, we are able to derive their Seiberg-Witten curves and Nekrasov partition functions. We cross-check our results with the 5D superconformal index proposed by Kim, Kim and Lee. Through the AGTW correspondence, we discuss the relations between 5D superconformal indices and n-point functions of the q-deformed WN Toda theories.

4) From the Berkovits formulation to the Witten formulation in open superstring field theory

The Berkovits formulation of open superstring field theory is based on the large Hilbert space of the superconformal ghost sector. We discuss its relation to the Witten formulation based on the small Hilbert space. We introduce a one-parameter family of conditions for partial gauge fixing of the Berkovits formulation such that the cubic interaction of the theory under the partial gauge fixing reduces to that of the Witten formulation in a singular limit. The local picture-changing operator at the open-string midpoint in the Witten formulation is regularized in our approach, and the divergence in on-shell four-point amplitudes coming from collision of picture-changing operators is resolved. The quartic interaction inherited from the Berkovits formulation plays a role of adjusting different behaviors of the picture-changing operators in the s channel and in the t channel of Feynman diagrams with two cubic vertices, and correct amplitudes in the world-sheet theory are reproduced. While gauge invariance at the second order in the coupling constant is obscured in the Witten formulation by collision of picture-changing operators, it is well defined in our approach and is recovered by including the quartic interaction inherited from the Berkovits formulation.

5) Duality of topological branes

We show a duality of branes in the topological B-model by inserting two kinds of the non-compact branes simultaneously. We explicitly derive the integral formula for the matrix model partition function describing this situation, which correspondingly includes both of the characteristic poly- nomial and the external source. We show that these two descriptions are dual to each other through the Fourier transformation, and the brane partition function satisfies integrable equa- tions in one and two dimensions.

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Sub Nuclear System Research Division
Radiation Laboratory

1. Abstract

Nucleons, such as protons and neutrons, are a bound state of constituent quarks glued together with gluons. The detail structure of nucleons, however, is not well understood yet. Especially the mechanism to build up the spin of proton, which is 1/2, is a major problem in physics of the strong force. The research goal of Radiation Laboratory is to solve this fundamental question using the world first polarized-proton collider, realized at RHIC in Brookhaven National Laboratory (BNL) in USA. RHIC stands for Relativistic Heavy Ion Collider, aiming also to create Quark Gluon Plasma, the state of Universe just after the Big Bang. RIKEN-BNL Research Center (RBRC) directed by S. Aronson carries our core team at BNL for those exciting researches using the PHENIX detector. We have found that the proton spin carried by gluons is indeed small. 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 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]

In 2014 we have reached a major milestone in determining the gluon spin contribution to the total spin of the nucleon. After initially measuring small asymmetries statistically consistent with zero, we have succeeded to determine non-zero gluon polarization in the recent high statistics runs at 510 GeV. 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. While orbital angular momentum cannot be directly accessed at RHIC, several transverse spin phenomena are being accumulated to study the orbital angular momentum and the overall three-dimensional structure of the nucleon.

To further investigate these effects the PHENIX experiment proposes substantial detector upgrades to go along the expected accelerator improvements. The proposed upgrade replaces the present magnet with a solenoid, so that we are considering to build an open-geometry forward spectrometer which can measure hadrons, photons, electrons, muons and jets in the forward rapidity region. Especially the Drell-Yan (quark-antiquark annihilation into lepton pairs) transverse single spin asymmetries are the main goal of these upgrades. As a pilot measurement, some of us are participating in the Fermilab SeaQuest experiment which has been collecting muon pairs using a 120-GeV unpolarized proton at Fermilab. By measuring the unpolarized Drell-Yan process, we can study quark spin-orbit effects which supplement what can be learned in the polarized Drell-Yan process.

(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 Tc~170MeV, from hadronic phase to quark-gluon plasma. This work was rewarded by Nishina Memorial Prize in 2011. Using the same "virtual photon" method used in the thermal photon measurement, we measured direct photons in d+Au collisions. The results show that there is little cold nuclear effects in direct photons. This supports that the large enhancement of direct photons observed in Au+Au is indeed due to hot quark-gluon plasma formed in Au+Au collisions.

We also measured the elliptic flow strength, v2, of direct photons in Au+Au collisions. The results show surprisingly large v2, which means the source of those photons expands elliptically. This is one of the most interesting results from RHIC in the last three years. One of the JRA students of Radiation Laboratory led this important analysis. Also, the most recent measurements of high p_T π^0 suppression in Au+Au collisions show that the suppression reduces at very high pT (pT~20GeV).

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 first preliminary results from the 2011 Au+Au run and 2012 p+p run was reported in the Quark Matter 2012 conference. We are now finalizing the results for publication. Analysis of the 2014 Au+Au run is also in progress and we expect the first preliminary results from the 2014 run in this year (2015).

In Wako we are operating a cluster computer system 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 the jobs are assigned to the nodes 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.

We have about 1.7 PB of data produced by the PHENIX experiment. They are stored in the archive system (HPSS) operated by the Advanced Center for Computing and Communication (ACCC). Since ACCC decided to replace HPSS, we have started to transfer the data into the new archive system.

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

Preparation of the experiment E16 at J-PARC 50-GeV PS is underway with the Grant-in-Aid for Scientific Research on Innovative Areas (MEXT). This experiment aims to perform a systematic study of the mass modification of low-mass vector mesons in nuclei to explore the chiral symmetry breaking in dense nuclear matter, namely, the mechanism proposed by Nambu to generate the major part of hadron mass.

Gas Electron Multiplier (GEM) technology is adopted for the two key detectors, GEM Tracker (GTR) and Hadron-blind Cherenkov detector (HBD). With a cooperation with Japanese industries, GEM foils with a world-largest size (30cm x 30cm) are newly developed. Through the beam tests at ELPH, J-PARC, LEPS, and RIKEN RIBF, the followings are achieved and proven; 1) required position resolution of 0.1 mm, and 2) stable operation under the hadron-background environment, typically 30 times higher rate than that expected in the J-PARC experimental area. The design parameters of the GTR and HBD were finalized and the mass-production of GTR GEM started. HBD GEM is under the final tuning to achieve the required stability, efficiency and pion-rejection power.

For the readout electronics of GEM, a preamp using the APV25 ASIC chip is developed and tested. For the digitization and the data transfer, the SRS system developed by CERN is also tested and adopted. Another preamp-ASIC for the trigger signal from GEM foils is also developed and tested. Trigger logic boards, which are developed by Belle II, are tested with the firmware customized for this experiment.

The development phase of the detectors is just over and we are moving to the production phase. For the readout electronics, the mass production will start in a year after some remained tests. The construction of the beam line is finally funded in KEK and started at J-PARC in 2013. It will be completed by March 2016. The spectrometer construction at the beam line is planned to start in March 2015 and the commissioning with a primary beam will be performed in early 2016.

(4) Detector development for PHENIX experiment

After 7 years of hard work, we installed the silicon vertex tracker (VTX) into the PHENIX detector at RHIC in December 2010. VTX is a 4-layer silicon tracker to measure heavy quark (charm and bottom) production in p+p and heavy ion collisions at RHIC. The detector was funded by RIKEN and the US DOE. We and RIKEN BNL Research Center are responsible for construction and operation of the inner two pixel detectors. The VTX was successfully commissioned during the 500 GeV p+p run in 2011. Subsequently, we collected 5 billion Au+Au events in the 2011 run, 11/pb of p+p data at 510 GeV, 3/pb of p+p data at 200 GeV, 110/μb of U+U data at 193 GeV, and 2.9/nb of Cu+Au at 200 GeV. We are now analyzing those datasets to study the interaction between heavy quarks and the quark-gluon plasma.

During the 2011 run, part of the pixel detector was damaged due to thermal stress on the detector. We repaired the damaged pixel detectors in 2012 to 2013, and the tracker was re-installed in PHENIX before the 2014 run and has been successfully re-commissioned. The 2014 run is a major heavy quark run of RHIC and the VTX detector worked very well during the run. PHENIX recorded about 20 billion Au+Au collision events with VTX. This dataset is effectively more than 10 times of that of 2011 data. We expect definitive results on heavy quark measurements from the 2014 run.

Sea quark polarization measurement via W-boson production is one of the highlight of PHENIX spin program. In order to detect high momentum muons from W-decay, we developed the momentum-sensitive trigger system for the PHENIX forward muon arms with collaborators from KEK, Kyoto and Rikkyo University. Together with new hadron absorber, W-boson measurement was successfully carried out using the new high momentum trigger. We accumulated high-integrated luminosity of about $250pb^{-1}$ in Run13 and almost achieved our goal. The intensive analysis is underway towards the publication. Preliminary results were released in October 2014 and the analysis is at the final stage towards the publication. Besides W detection, the trigger system has been also operated for heavy flavor meson detection in conjunction with a forward vertex (FVTX) detector.

(5) Development of beam source

Under the collaboration with Brookhaven National Laboratory, we are developing various techniques for a laser ion source (LIS) to provide high quality heavy-ion beams to the accelerators at present or in the future. In 2014, we installed a new LIS which provides various species of singly charged ions to the RHIC-AGS complex. The commissioning was very successful and we have delivered C, Al, Ti, Si, Ta and Au ions. We also demonstrated fast switching of ion species within one second. At this moment, we are upgrading this LIS to provide gold beam and other lighter ion beams simultaneously. Once this upgrade is completed, all the ion beams except proton and uranium will be supplied by the LIS at the RHIC-AGS complex with much enhanced versatility. Besides, we are studying the highly charged ionization and magnetic field confinement of laser ablation plasma, and testing a linear accelerator model which selectively accelerates charge states.

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Ryoji AKIMOTO (Univ. of Tokyo, – Mar. 31, 2014)
Takeru IGURI (Rikkyo Univ., – Mar. 31, 2014)
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Assistants

Keiko SUZUKI
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Sub Nuclear System Research Division
Advanced Meson Science Laboratory

1. Abstract

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

Kaon is the second lightest meson having "strange"-quark as a constituent quark, which also does not exist in natural nuclei. 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) to study physics beyond the standard model.

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 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 at precise determination of the $K^{bar}N$ interaction, and clarify the nature of kaon in nuclei and the nature of Λ(1405), which could be K^-p bound state. At Spring-8 and at GSI, we are also aiming to study omega and η' nuclei. By these experiments, we aim to be a world-leading scientific research group using these light meta-stable particles.

(1-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 $K^{bar}N$ 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 $^3He(K^-, n)$ 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 $6x10^9$ kaons on ^3He target, corresponding to a ~1% of the approved proposal. We successfully obtained semi-inclusive $^3He(K^-, n)$ 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 $^3He(K^-, \Lambda p)$ n events. To derive more information on the $K^{bar}N$ interaction by the exclusive measurement, we are planning to perform the second physics-run, in which 10 times more data will be accumulated.

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

Simultaneously, with the above experiment (1), we have performed an X-ray spectroscopy of atomic $3d \to 2p$ transition of negatively charged K mesons captured by helium atoms (J-PARC E17). 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. Very recently, we have performed a proof-of-principle experiment by measuring pionic-atom X rays with a TES array at the PiM1 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, we are preparing for the kaonic-atom experiment at J-PARC.

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 $K^{bar}N$ interaction. We can resolve isospin dependence of the strong interaction by the measurement. We submitted a proposal to J-PARC PAC to measure kaonic deuteron X-ray and got stage-one approval.

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

We have been working on precision spectroscopy of pionic atoms systematically, that leads to understanding of the origin of hadron mass. The precision data set stringent constraints on the chiral condensate at nuclear medium. We are presently preparing for the precision measurement at RIBF. The first measurement is aiming at ^{121}Sn as the first step for the systematic spectroscopy. A pilot experiment was performed in 2010, and showed a very good performance of the system. We have been analyzing the data to improve experimental setup of the pionic atom spectroscopy at the RIBF in RIKEN. We expect to achieve better experimental resolution with much reduced systematic errors.

We are also working on spectroscopy of η' mesic 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'-mesic nuclei). From this measurement, we can access information about partial restoration of chiral symmetry in nuclear media via the binding energy and decay width of η'-nuclear bound state.

(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 x 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 advantage 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 installed in November 2013. Engineering run for the first experiment was performed in December 2013 to confirm performance of our detector system. Full set of the detector will be installed by mid April 2014 and we are planning to perform first physics data taking run starting from mid April 2014 to end of July 2014.

(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

We have opened the new μSR spectrometer named CHRONUS to collaborative experiments from the May-June cycle in 2014. To have higher affinity on μSR studies with the ISIS muon facility, common data acquisition (DAQ) system with the ISIS standard DAQ (DAEIII) and the front-end control system (SECI) have been installed and optimized along with other equipment in Port-4. The same DAQ and control systems will be installed in Port-2 as well. Thus, we can perform two independent μSR experiments in Port-2 and 4 at the same time, switching double-pulse to share beam between the two.

Among our scientific activities on μSR studies from year 2012 to 2014, following five subjects of material sciences are most important achievements at the RIKEN-RAL muon facility:

1) A static ordering of small Ir moments in the pyrochlore iridate, $Nd_2Ir_2O_7$, was examined. We found that this system is located close to the quantum critical point.
2) A static ordering of Yb moment in pyrochlore structure of $Yb_2Ti_2O_7$ crystal has been confirmed. This ordering can be explained by the Higgs mechanism.
3) Spontaneous small static internal fields in the superconducting state of URu_2Si_2 have been measured. From the data and its crystal structure, we obtained a scenario to explain superconducting mechanism of this system.
4) The universality class of the Mott transition in $EtMe_3P[Pd(dmit)_2]_2$ has been confirmed by pressure dependences of transportation properties.
5) A novel coexisting state between Fe spin-glass and Cu stripe ordered states have been found in the doverdoped regime of $La_{2-x}Sr_xCu_{1-y}Fe_yO_4$.

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

If we can improve muon beam-emittance, beam-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 be stopped in thin foil, multi-layered materials and artificial lattices and we 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 had been working on the "ultra-slow muon" generation based on the following technique, namely, positive muon beam with thermal energy has been produced by laser ionization of muoniums in vacuum (bound system of μ^+ and electron) emitted from the hot tungsten surface by stopping "surface muon beam" at Port-3. However, the muon yield and obtained emittance was far from satisfactory, and remained to be far from any kind of realistic application.

Therefore, in this mid-term, we are developing two key components first, 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. In 2013, we demonstrated 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-α laser in collaboration with laser group at RIKEN. In this laser development, we succeeded to synthesize novel laser crystal Nd:YGAG, which has an ideal wave-length property for laser amplification to generate Lyman-α by four wave mixing in Kr gas cell. The developed new laser will ionize muoniums 100 times more efficiently for slow muon beam generation. In order to fully apply these new developments to slow muon generation, we designed and manufactured a new beam line based on microscope optics. Its installation and beam test is planned in the first half of 2015.

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 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.

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Mitsue YAMAMOTO (May 1, 2014-)
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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 succeed by BNL Distinguished Scientist, N. P. Samios, who served until 2013. The current director is Dr. S. H. Aronson. Support for RBRC was initially for five years and has been renewed three times, and presently extends to 2018. The Center is located in the 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 the DOE RHIC Spin Group, the RIKEN Spin Group at BNL, and the PHENIX heavy ion groups. BNL provides office space, management, and administrative support. In addition, the Computer Science Center (CS) and Information Technology Division (ITD) at BNL provides 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). L. McLerran (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) PHENIX detector upgrades

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

Samuel H. ARONSON

Deputy Director

Robert PISARSKI

Administrative Staff

Mituru KISHIMOTO (Administration Manager, Nishina Center Planning Office)
Kazunori MABUCHI (Deputy Administration Manager, Nishina Center Planning Office, – Dec. 31, 2014)
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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. 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.

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

2. Major Research Subjects

(1) Heavy Ion Collision
(2) Perturbative QCD
(3) Phenomenological QCD

3. Summary of Research Activity

(1) Spin Physics

The experimental program at RBRC is strongly focused on determining the origin of spin in the proton and neutron. To extract the spin content of nucleon requires both precise data and precise computation. Dr. Jianwei Qiu of the Nuclear Theory group is one of the world's leading theorists in perturbative QCD, and leading the effort at BNL in spin physics. Their effort will continue to concentrate on computing perturbative QCD effects to sufficient precision that one can reliably extract information from the evolving experimental program. In addition they are developing ideas which might be tested in an electron-hadron collider, such as the one proposed to be built by adding an electron ring to RHIC.

(2) Matter at High Energy Density

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.

Matter at high temperature has been studied by a variety of techniques involving both numerical and analytic methods. Much of the high precision work on numerical simulations of lattice QCD at nonzero temperature and density such matter have been done by members of the Lattice Gauge Theory Group at BNL, including Frithjof Karsch, Peter Petreczsky, Swagato Mukherjee, and postdoctoral assistants. These groups, along with collaborators at Columbia University, the University of Bielefeld, and other groups, have computed numerous properties of QCD in thermodynamic equilibrium. This includes the equation of state for physical quark masses, susceptibilies with respect to quark chemical potentials, and transport coefficients.

Phenomenological theories of the Quark-Gluon Plasma, based upon results from lattice simulations, have been developed by R. Pisarski of the Nuclear Theory Group, in collaboration with Dr. Y. Hidaka (previously of RBRC/BNL, and now a permanent member at RIKEN in Waco), Shu Lin, Daisuke Sato, and other postdoctoral research assistants at RBRC/BNL.

The theory of the Color Glass Condensate and Glasma was largely developed by RBRC scientists. This theory has been successfully applied to a wide variety of experimental results involving high energy collisions of hadrons, electrons and nuclei. There is recent data on heavy ion collisions that are naturally explained by such matter, including data on proton (or deuteron) nucleus collisions. Much of the effort here will be aimed towards excluding or verifying the Color Glass Condensate and Glasma hypothesis in RHIC and LHC experiments.

Thermal matter at high temperature and baryon density has been traditionally conjectured to be of two phases: confined and deconfined, with a direct correlation between deconfinement and the restoration of chiral symmetry. RBRC scientists have recently conjectured a third phase, of quarkyonic matter. This is baryonic matter at energy densities very high compared to the QCD scale. It has a pressure and energy density typical of quarks, yet it is confined. The name arises because it shares properties of confined baryonic matter with unconfined quark matter. This hypothesis is new and predicts new classes of phenomena that might be observed in collisions of nuclei of relatively low energy at RHIC. There are a number of first principle theoretical issues also to be understood.

Efforts on RHIC phenomenology proceed on a broad front. Recent efforts include improving hydrodynamic computations using state of the art equations of state derived from lattice gauge theory. Understanding the nature of matter at high baryon number density has generated the idea of Quarkyonic Matter, that may have implications for an upcoming low energy run at RHIC and eventual experiments in the future at FAIR and NICA. An issue being studied is the nature of mass generation and the breaking of translational invariance. A central focus of work at RBRC, the Color Glass Condensate and the Glasma, matter that controls the high energy limit of QCD, is being realized in experiments at RHIC. Much activity focuses on the relation between observations at LHC and the implications made at RHIC.

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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 using the 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 pertrubative 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 calaution for $K\to\pi\pi$ decay, ε'/ε, or hadronic contributions go muon’s anomalous magnetic moment, or Nucleon’s shape and structures.

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).
(2) Dynamics of QCD and related theories, including study for the structures of nucleons
(3) Theoretical and algorithmic development for lattice field theories, QCD machine design

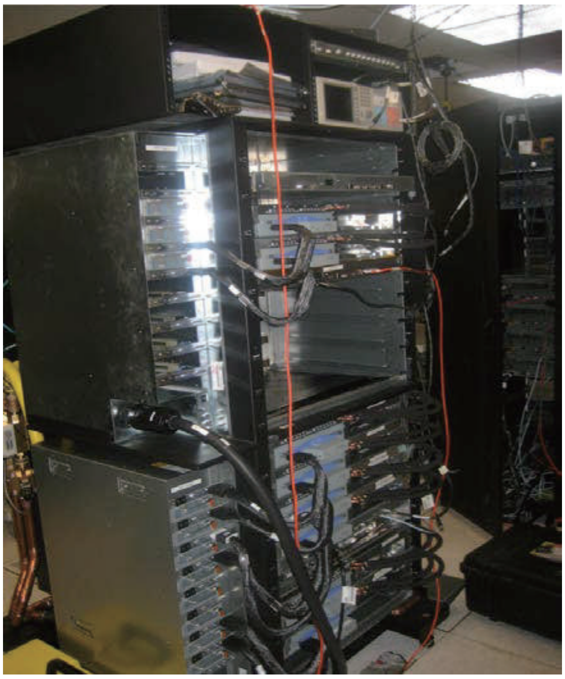
3. Summary of Research Activity

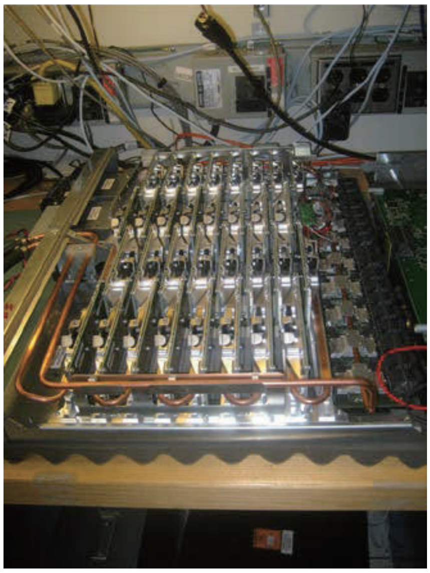
In 2011, QCD with Chiral Quarks (QCDCQ), a third-generation lattice QCD computer that is a pre-commercial version of IBM’s Blue Gene/Q, was installed as an in-house computing resource at the RBRC. The computer was developed by collaboration among RBRC, Columbia University, the University of Edinburgh, 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 RICC, the cluster computers at RIKEN (Japan), Fermi National Accelerator Laboratory, the Jefferson Lab, and others.

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. Several projects are ongoing: flavor physics in the framework of the CKM theory for kaons and B mesons; the electromagnetic properties of hadrons; hadronic contributions to the muon’s anomalous magnetic moment; the proton’s and neutron’s electric dipole moments; proton decay; nucleon form factors, which are related to the proton spin problem; and QCD thermodynamics in finite temperature/density systems such as those produced in heavy-ion collisions at the Relativistic Heavy Ion Collider. Major breakthroughs on important problems such as the direct CP violation process ($K \to \pi\pi$, ε'/ε) will be attempted using this computer.

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 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 group also delivers an algorithmic breakthrough, which speed up generic lattice gauge theory computation typically by a factor of 20 or more. In this novel technique called All Mode Averaging (AMA), the whole calculation is divided into frequent approximated calculations, and infrequent expensive and accurate calculation using lattice symmetries.





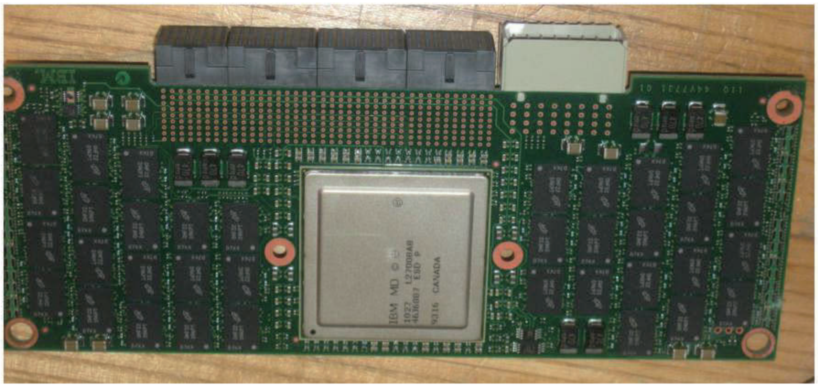


Fig. The rack, motherboard, and chips of QCDCQ

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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. Our recent data analysis has shown that the proton spin carried by the gluons is small, which is a very striking finding beyond our expectations. 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 have 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. VTX detector was installed in PHENIX in 2011 and we are taking data since then. Muon trigger was complete and it was essential for W→μ measurement in 2013.

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 publication from 2006 run has shown that the gluon polarization in the proton is small and only about half of proton spin can be accounted by gluon spin in the measured region of gluon momentum in proton. Figure 1 shows our most recent results of π^0 ALL measurement, which has just submitted to Physical Review D. The figure shows the combined results of RUN5, RUN6, and RUN9. The new data give even stronger constraint on the gluon spin. RBRC exp. G led the gluon spin analysis in PHENIX. K. Bolye, a fellow of RBRC experimental group has a major role in this paper.

RHIC achieved polarized p+p collisions at 500 GeV in 2009. The collision energy increased to 510 GeV in 2012 and 2013. We have recorded The main goal of these high energy p+p run is to measure anti-quark polarization via single spin asymmetry AL of the W boson production. We have published the first results on W→e measurement at mid-rapidty from 2009 dataset in 2011. We upgraded the muon trigger system to measure W→m decays in the forward direction. With the measurement of W→ e and W→μ, 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. Combined with the datasets in 2009 (8.6/pb), 2011(18/pb), and 2012(~30/pb), we will have a definite measurement of anti-quark spin.

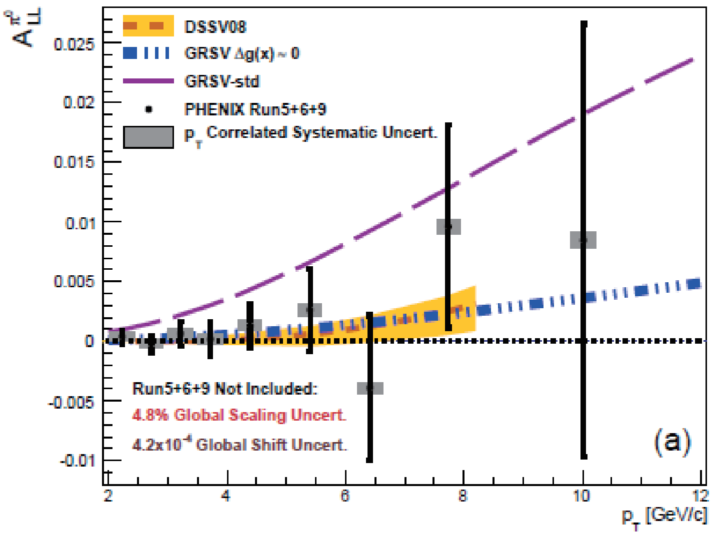

Figure 1 Double spin asymmetry ALL in π^0 production as function of transverse momentum pT compared with expectations for different gluon polarization ΔG(x). Published in Physical Review D90,012007 (2014)

(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 over 1900 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/Psi 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 Tinit = 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) PHENIX detector upgrade

The group has 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 are measuring heavy quark (charm and bottom) production in p+p, A+A collisions to study the properties of quark-gluon plasma. We have recorded 20 billion Au+Au collisions in the 2014 run. The large dataset will produce definitive results on heavy quark production at RHIC.

Muon trigger upgrades are needed for W→μ measurement at 500 GeV. New trigger electronics (Muon Trigger FEE) and new Muon trigger detectors using RPC technology were installed in PHENIX muon arms. Additional hadron absorbers were installed in front of the muon arms to reduce the background. These upgrades were essential for the high statistic W→μ measurement in 2013 run. Over 150/pb of data was recorded in the run. I. Nakagawa is the leading person of the installation of the Muon Trigger FEE, and R. Seidl have major role in the RPC project. He is also leading the W→μ analysis.

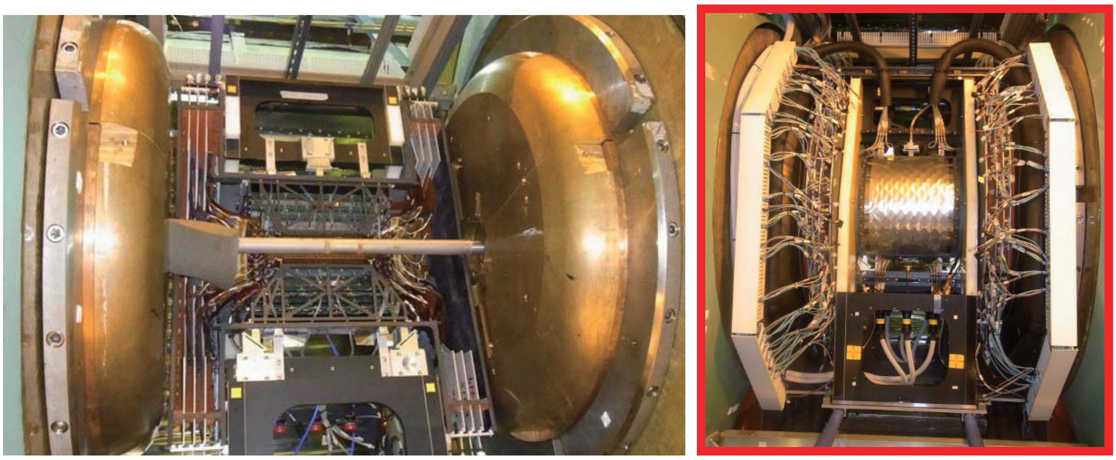

Figure 2 Left: a picture of West half of VTX detector installed in PHENIX experiment. The interior of the detector can be seen. Right: The VTX detector completed with all cables, cooling tubes and dry gas connections.

(4) Other data analysis in PHENIX

PHENIX experiment has a very good capability of low mass electron pair measurement. Recently we used this capability for search for "dark photon", a hypothetical particle in Beyond Standard Model theories. Many experiments looked for this particle since it can provide a simultaneous explanation of the 3.6σ deviation of the measured value of muon anomalous magnetic moment (g-2) from its theoretically calculated value and the positron excess observed by PAMELLA, FERMI, and AMS-2 experiments. If dark photon exists, it decays into an electron-positron pair, and thus it can be observed as a narrow peak in e^+e^- mass spectrum. We looked for this signal of dark photon in a large sample of electron pairs measured by PHENIX experiment. We observed no significant signal of dark photon and then set the upper limit of the dark photon – ordinary photon mixing parameter as function of mass. The result is shown in Fig. 3 below. Combined with other experimental limits, the parameter space of dark photon as the explanation of muon g-2 anomaly was almost completely ruled out.

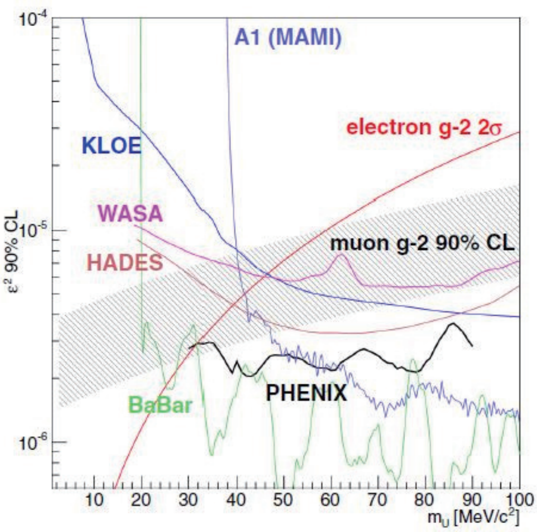

Figure 3 90% CL limit of photon-dark photon mixing parameter as a function of mass. The shaded band show the parameter space favored by the muon g-2 anomaly. Accepted in Physical Review C.

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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 very precisely local magnetic fields and their fluctuations at muon stopping sites. The method to study characteristic 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 studies of electro-magnetic properties of insulating, metallic, magnetic, superconducting systems. Muons reveal static and dynamic properties of electronic state of materials in the zero-field condition, which is the ideal magnetic condition for researches on the magnetism. μSR is applied to those systems. As one example of those researches, we have carried out μSR investigations on frustrated pyrochlore systems, which have variety of exotic ground state of magnetic spins. We are approaching to achieve the first evidence of the appearance of a quasi-monopole state in the pyrochlore system.

We have been working on producing ultra-slow muon beam, which has a momentum spread as small as thermal energy. Our method of the beam generation is based on the laser ionization of muoniums (bound system of μ^+ and electron), which emitted from hot tungsten surface by stopping low-momentum muon beam at Port-3. The ultra-slow muon beam can be stopped in thin foils, multi-layered materials and artificial lattices and we 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/EDM measurement. We have been developing muonium generators to create more muoniums in vacuum even at room temperature. Very recently, we demonstrated 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 muoniums 100 times more efficiently for slow muon beam generation.

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 with their own spin polarization enable us to conduct (1) material studies under external zero-field condition, (2) magnetism studies with samples without nuclear spins, and (3) measurements of muon spin relaxation changes at wide temperature range with same detection sensitivity. The detection time range of local field fluctuations by μSR is 10^{-6} to 10^{-11} second, which is an intermediate region between neutron scattering method (10^{-10}-10^{-12} second) and Nuclear Magnetic Resonance (NMR) (longer than 10^{-6} second). At Port-2 and 4 of the RIKEN-RAL Muon Facility, we have been performing μSR researches on newly fabricated strong correlated-electron systems, organic molecules and biological samples to study electron structures, superconductivity, magnetism, molecular structures and crystal structures.

In the period from 2012 to 2014, we have obtained excellent results, and the highlights are listed in the following,

1) A static ordering of small Ir moments in the pyrochlore iridate; $Nd_2Ir_2O_7$ is close to a quantum critical point.
2) A static ordering of Yb moment on the corner of the pyrochlore structure of $Yb_2Ti_2O_7$ can be explained by the Higgs mechanism.
3) Spontaneous formation of small static internal fields in the superconducting state of URu_2Si_2 was observed, which indicate appearance of an exotic superconducting state in this material.
4) Universality class of the Mott transition is confirmed in $EtMe_3P[Pd(dmit)_2]_2$.
5) Finding new muon sites in La_2CuO_4, which can only be explained by taking into account the spatial distribution of Cu spin.
6) A novel coexisting state between Fe spin-glass and Cu stripe ordered states in the over-doped regime of $La_{2-x}Sr_xCu_{1-y}Fe_yO_4$.
7) International collaborations to organize new μSR experiments and to develop a group to work on muon-site calculations by using computational technique.

Solid observations of a static magnetically ordered state of corner-shared magnetic moments on pyrochlore systems gave us new interpretation to understand exotic phenomena, like the quantum criticality of magnetic moments and a quasi-magnetic monopole state (result-1 and 2). We measured an increase of static internal fields at the muon site in the zero-field condition just below the superconducting transition temperature of URu_2Si_2. This could shed a light on the mechanism of the superconductivity, which has been a long-standing problem of this system (result-3). We have been developing gas-pressurized high-pressure apparatus, which can be used not only for μSR but also for other purposes. We have applied this pressure system to $EtMe_3P[Pd(dmit)_2]_2$ and have found that pressure dependent resistivity and thermoelectric coefficient measurements have shown that the Mott transition belongs to the Ising universality class even in two-dimensional states (result-4). Well-known and deeply investigated La_2CuO_4 has opened a new scheme of the Cu spin. Taking into account the effect of the spatial distribution of Cu spin, we have succeeded to explain newly found muon sites and hyperfine fields at those sites (result-5). Fe spins form a spin glass state through the RKKY interaction in the over-doped regime in $La_{2-x}Sr_xCu_{1-y}Fe_yO_4$. This spin glass state is expected to co-exist with the stripe ordered state at lower temperatures (result-6).

We have been very keen to develop muon activities in Asian countries. We have formed MOU with Universiti Sains Malaysia (USM) in order to develop activities on the muon-site calculation. We have newly started to collaborate in μSR experiments on strongly correlated systems with researchers from Taiwan and Korea including graduate students (result-7).

A new μSR spectrometer "Chronus" which has finely multi-segmented forward and backward μ-e counter arrays (304 counters each) is now used for real μSR experiments in Port-4 in parallel with ARGUS in Port-2. Software systems, which control the data acquisition and experimental conditions, are renewed based on the ISIS frontend so as to have common data format with the other ISIS muon facilities (DAE with SECI), so as to have more affinity with the ISIS facility and its analysis platform.

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

We are performing R&D to realize efficient generation of ultra-slow muon beam having energy dispersion below thermal energy utilizing laser ionization of muoniums at Port-3. To study magnetism at surface and interface, and to realize new high-precision muon g-2/EDM measurement, it is essential to increase the slow muon beam production efficiency by more than 100 times. 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.

In the period from 2011 to 2014, we developed a high power Lyman-alpha laser in collaboration with the Advanced Photonics group at RIKEN. The new laser will ionize muoniums 100 times more efficiently for slow muon beam generation. 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". This Grant-in-Aid research group is a complex of research institutions from universities together with J-PARC muon group and RIKEN. The new laser system was installed to J-PARC slow muon beam line and is being tested. In this development, we succeeded to synthesize novel ceramic-based Nd:YGAG crystal, and 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 based on the experiences.

Another plan in 2011-2014 was 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 tremendous increase of the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. The measurement was carried out at TRIUMF in collaboration with J-PARC muon g-2/EDM group. We believe that the better efficiency and beam quality can be achieved in ultra-slow muon generation by using this new muonium source.

Based on these two new key components, we are planning to feed these new techniques to RIKEN-RAL ultra-slow muon beam line to realize further development of ultra-slow muon technology. The present muonium production target section, which had been designed with hot tungsten, was rebuilt to use advantage of the new room temperature target, such as no need of thermal shielding etc. Also, we adopted an all-cylindrical beam-transport design, because of its simpler optics and better manufacture precision, which will contribute to the ultimate cold muon source required for muon g-2/EDM. We plan the testing with the muon beam to be started in middle 2015.

(3) Other topics

Muon catalyzed fusion has been one of the main subject of studies since the start of the RIKEN-RAL Muon Facility. It has produced many new results by using the advantage of the high-intensity pulsed muon beam and the advanced tritium handling facility as was reported in previous RIKEN-RAL IACs. Even though, huge increase of the catalysis rate that is enough for energy production is yet difficult to achieve. Considering the limited budget and human resources maintaining the tritium facility, we had discussions with RAL on the safe closure of the tritium facility. The decommissioning was completed in March 2015.

New demand is emerging on utilizing the muon beam for electronics chips radiation effect studies. Recent progress of semiconductor devices has produced electronics chips with very fine structure. It is concerned that the single memory upset by the ionization effect of single muon may result in malfunction or errors of advanced electronics. Muon is the main component of the cosmic ray in our ordinal life and difficult to be removed. We have started measurement at RIKEN-RAL in 2013 to measure such an error rate and observed an effect that is correlated with the muon energy deposit rate. Further measurements were performed in 2014.

A new proposal was submitted to measure the proton radius by using the hyperfine splitting of the 1S states of muonic hydrogen. This is in contrast to the recent measurement at PSI using energy splitting between 2S-2P levels. The hyperfine transition measurement needs a high intensity laser so it needs to be matched with pulsed muon beam. A new laser system was designed in collaboration with RIKEN's advanced photonics group based on their experience on the commissioning of a laser of similar type. We are also preparing the target chamber and detectors for this measurement.

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RIBF Research Division
Radioactive Isotope Physics Laboratory

1. Abstract

This 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 RI beams to discover new phenomena and properties in exotic nuclei. Another important subject is the equation-of-state in asymmetric nuclear matter, and its association with the origin of elements and with neutron stars. For instance, we are making attempts to the better understand underlying mechanism for exotic stability-enhancements of very neutron-rich fluorine isotopes, the large deformation of the nucleus Mg-34 with N=22 in spite of its vicinity to the N=20 magic neutron number and anomalous collectivity in C-16. We are further extending these studies to medium- and heavy-mass regions by developing facilities, detectors and unique methods at RIBF, thereby leading on the challenging task to find new exotic phenomena. We also perform numerical simulations of nucleosynthesis under the environment of core-collapse supernovae, and moreover quest for footprints of supernovae and solar activities in the past, embedded in Antarctic ice core.

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~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.

Concerning a next generation detector, a construction proposal of a LaBr3 array "SHOGUN", was submitted to the PAC 2009, and an international workshop was organized in Feb. 2011 to form the SHOGUN collaboration. A technical development with small sized crystals is now in progress.

(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~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, 10 papers including 7 PRL'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.

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 will be coupled with the AIDA silicon strip system. A construction proposal was approved at the PAC 2013 and two physics proposals have been approved at PAC 2014.

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. Physics runs are scheduled in 2016.

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

(4) Nucleon correlation and cluster in nuclei

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

In 2013, two programs were conducted at the SAMURAI spectrometer. One is related to proton-neutron correlation in the C-12 nucleus via p-n knockout reaction with a carbon target. The other is to search for a cluster state in C-16, which was populated via inelastic alpha scattering. The data is being analyzed.

(5) Nuclear data for nuclear waste of long-lived fission products

The nuclear waste problem is an inevitable subject in nuclear physics and nuclear engineering communities. Since the Chicago Pile was established in 1942, nuclear energy has become one of major sources of energy. However, nowadays the nuclear waste produced at nuclear power plants has caused social problems. Minor actinide components of the waste have been studied well as a fuel in fast breeder reactors or ADS. Long-lived fission products in waste, on the other hand, have not been studied extensively. A deep geological disposal has been a policy of several governments, but it is difficult to find out location of the disposal station in terms of security, sociology and politics. To solve the social problem, a scientific effort is necessary for nuclear physics community to find out efficient methods for reduction of nuclear waste radioactivity.

In 2013, we have started up a new project to take nuclear data for transmutation of long-lived fission products to obtain cross section data needed for designing a nuclear waste treatment system. In 2014, we made the first attempt to obtain fragmentation reaction data with Cs-137 and Sr-90 beams at 200A MeV.

Since 2014, this activity has been intensively organized as one of the ImPACT projects by the Nuclear Transmutation Data Research Group.

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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. 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. One of our goals is to elucidate a variety of nuclear phenomena in terms of interplay of spin and isospin.

Establishment of storage-ring science in Japan is another big goal of our laboratory. We are leading, in collaboration with the Wakasugi group, the Rare RI Ring project to achieve precision mass measurement of r-process nuclei.

2. Major Research Subjects

(1) Direct reaction studies of neutron-matter equation of state
(2) Study of spin-isospin responses with RI-beams
(3) Production of spin polarized protons and its application to RI-beam experiments
(4) R-process nucleosynthesis study with heavy-ion storage ring
(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 is planned to be performed in 2015. Prior to the ^{132}Sn experiment, we have applied the ESPRI setup that consists of a solid hydrogen target and recoil proton detectors to ^{16}C in 2012.

(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 will be applied to a ^{132}Sn experiment in 2015.

(1-c) Multi-neutron andα-cluster correlations at low densities

Occurrences of multi-neutron andα-cluster correlations are other interesting aspects of nuclear matter and define its low-density behavior. The multi-neutron andα-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,2p)-delayed fission experiments at the SAMURAI to determine the fission barrier heights in neutron-rich nuclei in Pb region.

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

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

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

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

(3) Production of spin-polarized protons and its application to 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.

In exploring the spin effects in exotic nuclei, scattering with polarized protons should be a powerful tool. We have constructed a novel polarized proton solid target aiming to shed light of polarization on the physics of exotic nuclei. A distinguished feature of the target system is that it works under a low magnetic field of 0.1 T and temperature higher than 100 K, which exhibits a striking contrast to standard DNP targets working in extreme conditions of several Tesla and sub-Kelvin. 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.

The polarized proton target was applied, for the first time, to measurement of vector analyzing power in the proton elastic scattering of neutron-rich ^{6,8}He nuclei at 71 MeV/nucleon at RIPS, RIKEN. At RI Beam Factory, a hole-state spectroscopy via the (p, 2p) knockout reaction from unstable oxygen isotopes was performed with the polarized target.

(4) 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 in 2015. A series of experiments will start with nuclei in the A=80 region and will be extended to heavier region.

(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
b) Thin solid hydrogen target
c) MINOS (developed at Saclay and hosted by the Spin Isospin Laboratory)

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Nuclear Spectroscopy Laboratory

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 aim 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 stopped/slowed-down RI beams
(2) R&D studies on the production of spin-oriented RI beam
(3) Application of RI probes
(4) Fundamental physics: Study of symmetry

3. Summary of Research Activity

(1) Nuclear spectroscopy with stopped/slowed-down 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, a new method has been developed based on the laser spectroscopy which makes use of characteristic atomic properties of RIs surrounded by liquid helium.

(2) R&D studies on the production of spin-oriented RI beams

A new method has been developed for controlling spin in a system of rare RIs, taking advantage of the mechanism of the two-step projectile fragmentation reaction combined with the momentum-dispersion matching technique. This success allows us to utilize spin-controlled world's highest intensity rare RIBs delivered from BigRIPS for researches on the nuclear structure of species situated outside the traditional region of the nuclear chart. In parallel with this work, the 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.

(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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RIBF Research Division
High Energy Astrophysics Laboratory

1. Abstract
In the immediate aftermath of the Big Bang, the beginning of our universe, only hydrogen and helium existed. However, nuclear fusion in the interior of stars and the explosion of supernovae in the universe over 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 through the use of an accelerator.

2. Major Research Subjects
(1) Nucleosynthesis in Stars and Supernovae
(2) Particle Acceleration Mechanism in Astronomical Objects
(3) Physics in Extremely Strong Magnetism and Gravity
(4) Research and Development of Innovative X-ray and Gamma-ray detectors

3. Summary of Research Activity
High Energy Astrophysics Laboratory started on April 2010. The goal of our research is to reveal the mechanism of nucleosynthesis in the universe, and to observe exotic physical phenomena in extremely strong magnetic and/or gravitational field. We have observed supernova remnants, strongly magnetized neutron stars, pulsars, black holes and galaxies with X-ray astronomical satellites.

We showed that the expansion of ejecta in Tycho's supernova remnant was consistent with a spherically symmetric shell, based on Suzaku (Japanese X-ray observatory) measurements of the Doppler broadened X-ray emission lines. This is the first direct measurement of the expansion velocity of the elements produced in the thermonuclear expansion supernova. This information tells us the stratified structure of the elements, implying that the heavier elements such as Fe are produced deeper interior of the explosion.

We discovered the emission line of aluminum in supernova remnant G344.7-0.1 for the first time. Aluminum is produced in the neutron rich environment of supernova explosions. We also found manganese, which is enriched in the environment of neutron excess, in some supernova remnants. A systematic study of those lines emitted from the neutron rich elements will be a good tool to explore the nucleosynthesis in the interior of star explosions.

High-energy X-rays from radioactive Ti-44, which is a direct tracer of the supernova blast, was first imaged with the focusing telescope, NuSTAR. The map of Ti-44 in Cassiopeia A does not show spherical or axial symmetry, but asymmetry, supporting a mildly asymmetric explosion model with low-mode convection. This is the first astronomical image with nuclear gamma-rays and new observational evidence to understand the mechanism of supernova explosion and nucleosynthesis.

Gamma-ray emission up to 10 MeV was detected from thundercloud, suggesting that the detected gamma-rays were produced by relativistic electrons via bremsstrahlung. Those relativistic electrons are probably accelerated through an electrical potential difference in the thundercloud. This observation gives us a hint of the particle acceleration probably occurred near the neutron stars.

We continue to construct the Gravity and Extreme Magnetism Small Explorer (GEMS) under the collaboration with NASA Goddard Space Flight Center (USA). GEMS is the first dedicated satellite for the X-ray polarimetry, which is opening a new field in Astrophysics and Astronomy. The construction of an engineering model and basic performance studies of an X-ray polarimeter were carried out in FY2010, and the semiflight model of the detector was built in FY2012 and tested in FY2013. Unfortunately, NASA stops the GEMS project due to an expected cost overrun in 2012, but we will repropose the mission in 2014 with some modification. RIKEN will become a co-principal investigator institute and takes more responsibility on the X-ray polarimeter system and science.

Members

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RIBF Research Division
Astro-Glaciology Research Unit

Our Astro-Glaciology Research Unit promotes both theoretical and experimental studies to open up a new interdisciplinary research field between astrophysics and glaciology. On the theoretical side, we numerically simulate:

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

(2) The explosive nucleosynthesis, including the rapid neutron capture process (the r-process) for the creation of the elements heavier than iron, arising in the environment of core-collapse supernova explosions.

Subjects (1) and (2) themselves are very important in solar–terrestrial research and nuclear astrophysics, respectively; furthermore, the items (1) and (2) are intended to be coupled with experimental studies described below.

On the experimental side, we analyze ice cores drilled at the Dome Fuji station in Antarctica in collaboration with National Institute of Polar Research, Tokyo. These ice cores correspond to time capsules of the past. 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 the Dome Fuji ice cores may have an original advantage to study astronomical phenomena of the past, since gamma-rays and high-energy protons emitted from astronomical events affect the chemical and isotopic compositions in the stratosphere and not those in the troposphere. Accordingly, we measure:

(3) Variations in the nitrate ion (NO_3^-) concentrations in the ice cores, in order to seek the proxy of past solar activity and the footprints of supernovae in our galaxy,

(4) Variations in the water isotopes (^{18}O and ^{2}H) in the ice cores, in order to reconstruct past temperature changes on the earth, and

(5) Variations in the nitrate isotope (^{15}N) in the ice cores, in order to investigate the possibility of this isotope becoming a new and a more stable proxy for solar activity and/or galactic supernovae.

Items (3), (4), and (5) have been analyzed with Dome Fuji ice cores with a temporal resolution of about 1 year. By comparing the results for items (3) and (4), we aim to understand the correlation between solar activity and climate changes in the past on the millennium scale. The basis for item (4) is already established in glaciology. Item (5) will be the one of very first measurements taken in ice cores. The theoretical studies related to items (1) and (2) will provide a background for distinguishing the characteristics of the astronomical events from meteorological noise that usually appears in the ice core data. Finally, we note that the supernova rate in our galaxy is crucial to understand the r-process nucleosynthesis but yet remains unknown. Our item (3) is also intended to diagnose the galactic supernova rate ultimately.

Members

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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 (not yet named) 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.

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 will be ready for operation in fiscal year 2009 after some commissioning works.

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

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

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

We observed 5 isotopes in total which tentatively assigned to ^{293}Lv, and ^{292}Lv.

Members

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

For this year, see the section of Research Group for Superheavy Element.

Members

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RIBF Research Division
Research Group for Superheavy Element
Superheavy Element Research 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 rerated 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 asymmetric reaction such as hot-fusion reaction. New element $^{278}113$ were produced by ^{70}Zn + ^{209}Bi reaction using GARIS. Further the new element search Z > 118 are preparing by using GARIS-II.

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. It will be ready for operation in fiscal year 2014 after some commissioning works. We will also offer user-support if a researcher wishes to use the devices for his/her own research program.

Members

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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 of LLFP in inverse kinematics at RIBF. The third Team "Muon Data Team" is to obtain muon capture data of LLFP at muon facilities. All of the teams are focusing to obtain high-quality data which are essentially necessary to establish reliable reaction models. Each team has its own subjects and promotes LLFP reaction programs based on their large experiences, techniques and skills.

3. Summary of Research Activity

In 2014, all the teams polished up experimental strategies, formed collaboration and prepared experiments.

Members

Group Director

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

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 (Oct. 1, 2014−, concurrent: Team Leader, SAMURAI Team)

Technical Staff I

Nobuyuki CHIGA (Jan. 1, 2015−)

Student Trainees

Shouhei ARAKI (Kyushu Univ.)
Tatsuya YAMAMOTO (Miyazaki Univ.)

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 energy degradation and purification of RI beams are the main subjects of the team. Developments of devices used for the energy degradation of RI beams are also an important subject.

3. Summary of Research Activity

1) Study and development of the energy degradation methods for LLFP.
2) Development of the devices used for the energy degradation.
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
Koichi YOSHIDA (concurrent: BigRIPS Team)

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 belonging to electron group, and is 207 times as heavy as electron. The muon has positive or negative electric charge, and the lifetime is 2.2 μsec. The negative muon is caught by a nucleus (atomic number: Z) in materials to form a muonic atom, and is then captured by the nucleus. The negative muon is combined with a proton to form a neutron and a neutrino to create an excited state of the nucleus with the atomic number of Z-1, followed by emissions of neutrons and gamma rays. The muon nuclear capture reaction produces the isotopes of the (Z-1) nucleus. However, the reaction mechanism is not yet well clarified. The research team aims at obtaining the experimental data to understand the mechanism of muon nuclear capture reactions as well as at establishing the reaction theory.

2. Major Research Subjects
(1) Experimental clarification on reaction mechanism of nuclear muon-capture
(2) Establishment of reaction theory on nuclear muon-capture
(3) Interdisciplinary applications of nuclear muon-capture reactions

3. Summary of Research Activity

Members

Team Leader
Hiroyoshi SAKURAI (Oct. 1, 2014 – Nov. 30, 2014, concurrent: Chief Scientist, RI Physics Lab.)
Teiichiro MATSUZAKI (Dec. 1, 2014 –)

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

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RIBF Research Division
High-Intensity Accelerator R&D Group
High-Gradient Cavity R&D Team

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

Members

Team Leader

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

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 calcium beam reached 530 pnA at 345 MeV/u, which corresponds to 8.8 kW.
(2) The maximum intensity of the uranium beam reached 28 pnA at 345 MeV/u.
(3) The overall beam availability for the RIBF experiments in 2014 reached 92 %.
(4) The large infrastructure was properly maintained based on a well-organized cooperation among the related sections.
(5) An intensity-upgrade plan of the RIBF has been further investigated, mainly on the design of a new superconducting linac.

Members

Group Director
Osamu KAMIGAITO

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

Research Consultant
Tadashi FUJINAWA (– Mar. 31, 2015)

International Program Associate
Vasileios TZOGANIS (Univ. of Liverpool)

Visiting Researchers
Akira GOTO (Yamagata Univ.)
Toshiyuki HATTORI (Tokyo Tech.)

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)

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

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

(Ohnishi, J., Okuno, H.)

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

(Ohnishi, J., Okuno, H.)

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

Special Postdoctoral Researcher
Hironori KUBOKI (– Mar. 31, 2013)

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

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 uranium 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 uranium ion beams

3. Summary of Research Activity

(1) Operation and development of ECR ion sources
(T. Nakagawa, M. Kidera, Y. Higurashi, K. Ozeki, T. Nagatomo, H. Haba, and T. Kageyama)

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 uranium ion beam
(T. Nakagawa, J. Ohnishi, M. Kidera, Y. Higurashi, K. Ozeki and T. Nagatomo)

The RIBF is required to supply uranium ion beams with very high intensity so as to produce RI's. 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
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Nishina Center Research Scientists
Masanori KIDERA
Yoshihide HIGURASHI

Contract Researcher
Kazutaka OHZEKI (– Sept. 30, 2014)

Special Postdoctoral Researcher
Tatsuya URABE (Apr. 1, 2014 –)

Postdoctoral Researcher
Tatsuya URABE (– Mar. 31, 2014)

Research Consultant
Tadashi KAGEYAMA (Apr. 1, 2014 –)

Temporary Employee
Tadashi KAGEYAMA (– Mar. 31, 2014)

Part-time Worker
Yumi KURAMITSU

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
Toshiya CHIBA

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 OHZEKI (Technical Scientist)

Nishina Center Research Scientist
Kenji SUDA

Research Consultant
Yoshiaki CHIBA

Visiting Technician
Yan CONG (IMP, CAS)

RIBF Research Division
Accelerator Group
Beam Dynamics & Diagnostics Team

1. Abstract

The cascaded cyclotrons used in 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) Seeking the best operation method of the RIBF accelerator complex based on the beam dynamics study.
(2) Maintenance and development 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 power supplies.
(5) Developments of beam interlock system suited to high-power cyclotron complex.

3. Summary of Research Activity

(1) The world-first beam current monitor with a high-Tc current sensor and SQUID has been developed.
(2) 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 and contributes to stable and high-intensity operation of RIBF.
(3) An EPICS-based control system and a homemade beam interlock system have been stably working. Replacement 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.
(4) 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.
(5) 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)
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Shin-ichiro Hayashi (Hiroshima Int'l Univ.)
Hiromichi RYUTO (Kyoto Univ.)

Visiting Technician
Jun-ichi ODAGIRI (KEK)

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

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

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Temporary Employee
Kumio IKEGAMI (– Mar. 31, 2014)

Research Consultant
Kumio IKEGAMI (Apr. 1, 2014 –)

Part-time Worker
Shizuho TSURUMA

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)
Hideyuki YAMASAWA (Manager)

Temporary Employee
Tadashi FUJINAWA (– Mar. 31, 2014)

Research Consultant
Shin-ichi WATANABE

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. Experimental installations currently under setting up include common elements enabling multiple-use (SLOWRI), as well as others that are highly program specific (SCRIT and Rare-RI Ring). 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. 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 (Rare RI Ring). The technological knowhow accumulated in our projects will play a significant role in the next generation RIBF. Status and future plan for each project is described in subsections. SCRIT is now under finalizing the experimental setup for electron scattering off unstable nuclei, and the comprehensive test will be soon. The first experiment will be planed in 2015. Rare RI Ring construction has been almost completed. Test experiments using alpha particle for evaluating the ring performance were successfully performed, and the isochronism in the order of 10^{-5} was confirmed in ten-turns circulation. The first commissioning experiment is planed in June 2015. Construction of the SLOWRI system was completed in 2014, and it is now under setting up for the first commissioning in 2015.

Members

Group Director
Masanori WAKASUGI

Senior Visiting Scientist
Akira OZAWA (Univ. of Tsukuba)

Student Trainees
Mamoru TOGASAKI (Rikkyo Univ.)
Yohei SUMI (Rikkyo Univ.)
Saki MATSUO (Rikkyo Univ.)
Kohei YAMADA (Rikkyo Univ.)

RIBF Research Division
Instrumentation Development Group
SLOWRI Team

1. Abstract

Construction of a next-generation stopped and low-energy radioactive ion beam facility (SLOWRI) which will provide low-energy, high-purity and small emittance ion beams of all elements has been started in FY2013 as one of the principal facilities at the RIKEN RI-beam factory (RIBF). High-energy radioactive ion beams from the projectile fragment separator BigRIPS are thermalized in a large He gas catcher cell (RFC cell) or in a small Ar gas catcher cell (PALIS cell). In the RFC cell, thermalized ions in buffer gas are guided and extracted to a vacuum environment by a combination of dc electric fields and inhomogeneous rf fields (rf carpet ion guide). The PALIS cell will be placed in the vicinity of the second focal plane slits of BigRIPS and can be used continuously during other experiments. From these gas cells, the low-energy ion beams will be delivered via mass separators and switchyards to various devices: such as an ion trap, a collinear fast beam apparatus, and a multi-reflection time of flight mass spectrograph. In the R&D works at the present ring cyclotron facility, an extraction efficiency of 33% for a 100A MeV ^{8}Li ion beam from the projectile fragment separator RIPS was achieved and the dependence of the efficiency on the ion beam intensity was investigated.

First spectroscopy experiment at the prototype SLOWI was performed on Be isotopes. Energetic ions of ^{7,10,11}Be from the RIPS were trapped and laser cooled in a linear rf trap and precision spectroscopy was performed. The evaluated ion temperature of <10 mK demonstrates that a reduction of more than 15 orders of magnitude for the kinetic energy of radioactive Be was achieved online. The ground state hyperfine constants of all Be isotopes have been measured precisely by laser and microwave. These precision measurements will be used to confirm the anomalous mean radius of the valence neutron of the so called neutron halo nucleus. Other laser spectroscopy experiments using the slow RI-beams are also under progress in off-line setups. A collinear fast beam apparatus for nuclear charge-radii measurements was build and tested with stable Ar^{+} ion beams.

A multi-reflection time-of-flight mass spectrograph (MRTOF) has been developed and tested online for radioactive lithium isotope, ^{8}Li. A high mass resolving power of 170,000 has been obtained for an isobaric doublet of ^{40}K and ^{40}Ca with a very short flight time of 2 ms. This performance allowed accurate mass determination of $<10^{-7}$ accuracy by a single isobaric reference. Two mass measurement projects using MRTOF mass spectrographs have been started: one is for trans uranium elements at the GARIS facility and the other is for r-process nuclides at SLOWRI facility.

Resonance ionization spectroscopy has been tested during the offline development of PALIS gas cell. Stable isotopes of Co, Cu, Fe, Ni, Ti, Nb, Sn, In, and Pd were resonantly ionized by excimer pumped dye lasers or Nd:YAG laser pumped Ti:Sapphire lasers with the prototype gas cell setup. The resonance spectra are in many cases sufficient to resolve the hyperfine structures. Nuclear spins and magnetic moments will be determined for various isotopes obtained during other experiments.

2. Major Research Subjects

(1) Construction of 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 parasitic slow RI-beam production method using resonance laser ionization.
(5) Development of ion-surfing gas cell.

3. Summary of Research Activity

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

(WADA, Michiharu, SONODA, Tetsu, KATAYAMA, Ichiro, SCHURY, Peter, ITO, Yuta, ARAI, Fumiya, ARAI, Shigeaki, KUBO, Toshiyuki, KUSAKA, Kensuke, FUJINAWA Tadashi, MAIE Takeshi, YAMASAWA Hideyuki, WOLLNIK, Hermann,)

Installation of SLOWRI has been started in FY2013. It consists of two gas catchers (RF Carpet gas cell and PALIS gas cell), mass separators a 50-m beam transport line, a beam cooler-buncher, an isobar separator, and a laser system. The RFCarpet gas cell will be installed at the exit of the D5 dipole magnet of BigRIPS. The gas catcher contains a large cryogenic He gas cell with a large traveling wave rf-carpet. It will convert main beams of BigRIPS to low-energy, low-emittance beams without any restrictions on 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 those ions lost in the slits during other experiments. In this gas catcher, thermalized RI ions quickly become neutral and will be re-ionized by resonant laser radiations. These gas catchers will be tested off-line in FY2014. 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 (BPM). SD1 and SD2, located right 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 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, for compensation of ion optical aberrations. This multipole element can also produce dipole fields for steering and scanning the beam. The BPM 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 a very low-intensity RI-beams. Off- and on-line commissioning will take place in FY2014 and the low-energy RI-beams will be provided for users in FY2015.

(2) Laser spectroscopy of trapped radioactive beryllium isotope ions

(WADA, Michiharu, TAKAMINE, Aiko, SCHURY Peter, SONODA Tetsu, OKADA, Kunihiro, KANAI, Yasuyuki, YOSHIDA, Atsushi, KUBO, Toshiyuki, WOLLNIK, Hermann, SCHUESSLER, Hans, Shunsuke, KATAYAMA Ichiro)

As a first application of the prototype SLOWRI setup, we applied hyperfine structure spectroscopy to the 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 2s $^2S_{1/2}$ - 2p $^2P_{3/2}$ transition of ^{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 $^7Be^+$ ions using the laser-microwave double resonance spectroscopy were also performed and the magnetic hyperfine constants of $^7Be^+$ and $^{11}Be^+$ ions were determined with accuracies of better than10^{-7}.

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

(WADA, Michiharu, SCHURY Peter, ITO, Yuta, ARAI Fumiya, SONODA Tetsu, WOLLNIK, Hermann, MORIMOTO, Koji, KAJI, Daiya, HABA, Hiromitsu, KOURA, Hiroyuki)

The atomic mass is one of the most important quantities of a nucleus and has been studied in various methods since the early days of physics. Among many methods we chose a multi-reflection time-of-flight (MR-TOF) mass spectrometer. Slow RI beams extracted from the RF ion-guide are bunch 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 with a 2 ms flight time for 40K and 40Ca isobaric doublet. This mass-resolving power should allow us to determine ion masses with an accuracy of 10^{-7}. An online mass measurement for radioactive lithium isotope has been carried out at the prototype SLOWRI setup.

The MR-TOF mass spectrograph has been placed under the GARIS-II separator aiming at direct mass measurements of trans-uranium elements. A small cryogenic gas catcher cell will be placed at the focal plane box of GARIS-II and a bunched low-energy heavy ion beam can be transported to the trap of MR-TOF. An online commissioning experiment is planned in FY2014.

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

(WADA, Michiharu, SCHUESSLER, Hans, IIMURA, Hideki, SONODA, Tetsu, SCHURY, Peter, TAKAMINE, Aiko, OKADA, Kunihiro, WOLLNIK, Hermann)

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 alkaline, alkaline-earth, noble-gases and several other elements have been measured by collinear laser spectroscopy since these ions have all 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 beams. This should expand the range of applicable nuclides of laser spectroscopy. In the first years of the RIBF project, Ni and its vicinities, such as Ni, Co, Fe, Cr, Cu, Ga, 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 recycle transitions which enhance the detection probabilities noticeably. Also 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.

We have built an off-line mass separator and a collinear fast beam apparatus with a large solid-angle fluorescence detector. A 617 nm transition of the metastable Ar+ ion at 20 keV was measured with both collinear and anti-collinear geometry that allowed us to determine the absolute resonant frequency of the transition at rest with more than 10^{-8} accuracy. Such high accuracy measurements for Ti and Ni isotopes are in progress.

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

(SONODA Tetsu, IIMURA Hideki, WADA Michiharu, KATAYAMA Ichiou, ADACHI Yoshitaka, NOTO Takuma, TAKATSUKA Takaaki, TOMITA Hideki, WENDT Klaus, ARAI Fumiya, ITOU Yuta, SCHURY Peter, FUKUDA Naoki, INABE Naohito, KUBO Toshiyuki, KUSAKA Kensuke, TAKEDA Hiroyuki, SUZUKI H., WAKASUGI Masanori, YOSHIDA Koichi)

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, to rescue such dumped precious RI using a compact gas catcher cell and resonance laser ionization was proposed as a part of SLOWRI. The thermalized RI ions in a cell filled with Ar gas can be quickly neutralized and transported to the exit of the cell by gas flow. Irradiation of resonance lasers at the exit ionizes neutral RI atoms efficiently and selectively. The ionized RI ions can be further selected by a magnetic mass separator and transported to SLOWRI experimental area for various experiment. The resonance ionization scheme itself can also be a useful method to perform hyperfine structure spectroscopy of RI of many elements.

A prototype setup has been tested for resonance ionization scheme of several elements, extraction from the cell, and transport to a high vacuum chamber. An online setup, which will be placed at the second focal plane (F2) of BigRIPS, has been fabricated in FY2013 and commissioning is scheduled in FY2014.

Members

Team Leader
Michiharu WADA

Research & Technical Scientist
Hideyuki YAMASAWA (concurrent; Infrastructure Management Team)

Nishina Center Research Scientists
Tetsu SONODA
Kensuke KUSAKA (concurrent; BigRIPS Team)

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Yoshitaka ADACHI (Nagoya Univ.)
Takahide TAKAMATSU (Nagoya Univ.)

RIBF Research Division
Instrumentation Development Group
Rare RI-ring Team

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 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 end of 2013 and is now under preparation for the first commissioning experiment. Our target performance in the mass determination is to achieve accuracy of the order of 10^{-6} (~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. Design study for R3 has been continued from more than ten years ago, and it was constructed in 2012 and 2013. In 2014, we demonstrated the R3 performances in test experiments using alpha particle. We are now setting up and testing all equipments including the power supplies, the control system, the vacuum system, and so on, toward the first commissioning planed in 2015.

2. Major Research Subjects

Developments of isochronous storage ring to measure mass of rare RI.

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 200 MeV/u 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. Main coils of all the bending magnets are connected in series, and the current of 3000 A is required for rare-RIs, 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 an precise isochronous magnetic field. For $\Delta p=0$ particle, the circumference is 60.35 m and the betatron tunes are $\nu x=1.21$ and $\nu y=0.84$ in horizontal and vertical directions, respectively. The momentum acceptance is $\Delta p/p = \pm 0.5$ %, and the transverse acceptances are 20π mmmrad and 10π mmmrad in horizontal and vertical directions, respectively. Although the transverse acceptances of the R3 itself are actually larger than these values, they are limited by that of the injection beam line. Of special note is that the isochronism is precisely fulfilled in a wide range of momentum (full width 1 %) due to a cyclotron-motion based lattice design.

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 have 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. Development of an ultra-fast response kicker system is a key issue for establishing the individual injection scheme. Performances required for the kicker system are an ultra-fast response, a fast charging, and a full-time charging.

We provided ordinary beam diagnostic devices such as a screen monitor and a beam position monitor based on triangle pickup electrodes. Although five sets of these monitors distributed along the orbit in R3 are useful in a machine tuning process using a high-intensity primary beam. They, however, are incapable for rare-RIs because of the poor sensitivity. Therefore, we inserted high-sensitive monitors, which are applicable even for a single particle circulation. One of them is a cavity type of Schottky pick-up. A resonance frequency is designed to be 171 MHz, which corresponds to the harmonic number of 56, and a measured quality factor is about 1900 and shunt impedance is 170 kΩ. We can detect single ion circulation of $^{78}Ni^{28+}$ with only a few ms measurement. 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/u survives only for first 1000 turns because of an energy loss at the foil.

In test experiments using alpha particles emitted from an ^{241}Am source performed in 2014, we succeeded in the individual injection of the single particle, beam accumulation and the beam extraction. We successfully measured the TOF for 1~10 turns circulation of alpha particles, and the isochronism in R3 in the order of 10^{-5} was confirmed. R2 is now under preparation for the first commissioning experiment using heavy ion beam from accelerators.

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RIBF Research Division
Instrumentation Development Group
SCRIT Team

1. Abstract

The SCRIT Electron Scattering Facility is now under construction 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 technique has made 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 detector system for scattered electrons. Operation of accelerators, RTM and SR2, was started in 2010, performance test of the SCRIT system using stable isotopes, ^{133}Cs and ^{132}Xe, was successfully done in 2011 and 2012. Construction of ERIS was started in 2011 and it was commissioned in 2012. The first RI beams from ERIS were supplied in 2013, and the extraction efficiency was improved by a factor more than ten in 2014. The detector system consisting of a high-resolution magnetic spectrometer, drift chambers, trigger scintillators, and luminosity monitors were installed. The commissioning using tungsten wire target resulted the energy resolution of 10^{-3}. We are going to perform the first experiment of electron scattering from unstable nuclei within a fiscal year 2015.

2. Major Research Subjects

Development of SCRIT electron scattering technique and construction of the SCRIT electron scattering facility.

3. Summary of Research Activity

Development of an electron scattering experimental system for short-lived unstable nuclei using a novel internal target of unstable nuclei (SCRIT).

(Wakasugi, Ohnishi, Kurita, Suda, Tsukada, Tamae, Enokizono, Hori, Hara, Ichikawa)

SCRIT is novel technique to form internal target in an electron storage ring. Positive ions are confined in the electron beam axis by transverse focusing force given by the circulating electron beam. This is well known "ion trapping" phenomenon. The created ion cloud in which RI ions injected from outside are confined works as a target of electron scattering.

In 2010, we successfully commissioned electron accelerators RTM and SR2. Current of electron beams stored in SR2 and its storage lifetime have been reached to 300 mA and 2 hours, respectively, in the energy range of 150-300 MeV that is required in electron scattering experiments. In test experiments of the SCRIT system performed in 2011 and 2012, we used stable isotopes, ^{133}Cs and ^{132}Xe, and revealed many details of the SCRIT performance. The luminosity of 10^{27} /(cm^{2}s) was obtained in case of the number of injected ions of 10^8. The lifetime of the ion confinement was obtained to be over 1 s. They are performances satisfactory to the electron scattering experiment. In fact, we succeeded in measurements of angular distributions of scattered electrons from the target ions trapped in the SCRIT device.

Development of ERIS is one of the most important issue in the facility construction. RIs are generated by photo-fission process of ^{238}U, which is driven by the 150-MeVelectron beams from RTM. ERIS consists of a target ion source including UCx targets and a mass separation system. ERIS was constructed in 2011 and performances such as the extraction efficiency of 21 % and the mass resolving power of 1660 were obtained in the commissioning in 2011. We developed production method of UCx targets by ourselves. The first RI production was succeeded in last year, and $^{126-132}$Sn and $^{138-141}$Xe isotopes were extracted. The extraction efficiency was improved in 2014, and the overall efficiencies for ^{137}Xe and ^{132}Sn reached to 14% and 2%, respectively. The yield of ^{137}Xe isotopes exceeded 10^7 pps with 10-W driver power. A cooler buncher system based on a RFQ linear trap connected to the ERIS beam line is indispensable, because the continuous beam from ERIS has to be converted to pulsed beam for ion injection to the SCRIT device. The offline test experiments resulted more than 10% bunching efficiency for heavy ion beam, and the cooler buncher was installed in the ion beam line from ERIS.

The new detector system consists of a high-resolution magnetic spectrometer, a beam tracking system using drift chambers, trigger scintillators, and a luminosity monitor. This has a solid angle of 100 msr, energy resolution of 10^{-3}, and the scattering angle coverage of 30-60 degrees. A wide range of momentum transfer, 80-300 MeV/c, is covered by changing the electron beam energy from 150 to 300 MeV. In last year, the new detector system was successfully commissioned by means of electron scattering from a tungsten wire target.

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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 construction, operation and improvement of the core research instruments at RIBF, such as BigRIPS in-flight 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 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 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.

Members

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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. Help and management for SAMURAI-based research programs.

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"

Members

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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 600 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. We have added a 52 TB RAID for the data analysis in the autumn of 2014 and replaced the ssh login server (RIBF00) in the winter of 2015.

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

We are operating RIBF.RIKEN.JP server as a mail/NFS/NIS server. This server is a core server of RIBF Linux cluster system. Postfix has been used for mail transport software and dovecot has been used for imap and pop services. These software packages enable secure and reliable mail delivery. Sophos Email Security and Control (PMX) installed on the mail front-end servers tags spam mails and isolates virus-infected mails. The probability to identify the spam is approximately 95-99%. We are operating several information servers such as Web servers, Integrated Digital Conference (INDICO) server, Wiki servers, Groupware servers, Windows Media and Quick Time streaming servers, and an anonymous FTP server (FTP.RIKEN.JP). A new Web server has been installed in April 2014 as an official Web server of RNC to replace the old Web server installed in 2005. A new 72 TB RAID was installed to replace the old RAID to the anonymous FTP server in August 2014.

(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), and NeuLAND (GSI) cases, data taken by their DAQ systems are transferred to RIBFDAQ. For SPIRIT (RIKEN/GANIL/CEA Saclay/NSCL), RIBFDAQ data are sent to GET system that is a large-scale signal processing system for the time projection chamber. These cases, data are merged in online. On the other hand, EURICA (GSI) and BRIKEN (GSI/Univ. Liverpool/IFIC) 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 on GTO.

(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 60 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

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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 beam-line 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 research and development of new detectors that can be used for higher-intensity RI beams.

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).

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) Development of a high dynamic range preamplifier for silicon strip detectors

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RIBF Research Division
Accelerator Applications Research Group

1. Abstract
This group promotes various applications of ion beams from RI Beam Factory (RIBF). Radiation Biology Team studies various biological effects of fast heavy ions and develops new technology to breed plants and microbials 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) Development of heavy-ion breeding.
(3) Production and application of radioisotopes.
(4) Developments of trace elements analyses.
(5) Development of chemical materials for ECR ion sources of RIBF accelerators.

Members

Group Director
Tomoko ABE

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 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) Studies on ion-beam breeding and genome analysis
(3) Innovative application of heavy-ion beams

3. Summary of Research Activity

We study biological effects of fast heavy ions from the RIKEN Ring Cyclotron using 135A MeV C, N, Ne ions, 95A MeV Ar ions and 90A MeV Fe 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 LET. The peak of LET is achieved at the stopping point and known at the Bragg peak (BP). It is well know 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, 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 22.5 to 640 keV/μm, on mutation induction using the model plant *Arabidopsis thaliana*. The most effective LET (LETmax) was 30.0 keV/μm. 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 of ion beams seems to be an important factor affecting mutagenesis.

(2) Study on ion-beam breeding and genome analysis

In contrast to X rays and gamma rays, fast heavy ions are found to be useful for plant breeding since they only cause localized damage on DNA and can induce mutations more effectively with lower dosage. Our team utilizes beams of fast heavy ions from the RRC to develop heavy-ion breeding techniques. 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. Higher LET (> 290 keV/μm) was shown to efficiently generate large deletions ranging from several to several tens of kbp. Many genes in the *Arabidopsis* genome (> 10%) are composed of tandem duplicated genes that share functions. Previous studies demonstrated that large deletions were required to knockout tandem arrayed genes, and the appropriate deletion size was estimated to be approximately 5–10 kbp, based on gene density in *Arabidopsis*. 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 2014, it consisted of 168 groups from Japan and 18 from overseas. Breeding was performed previously using mainly flowers and ornamental plants. We have recently put a new Japanese barnyard millet cultivar with low amylose content and short culm, 'Nebarikko No. 2' 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. We also successfully isolated 4 salt-resistant lines of rice from 325 progeny lines. We collaborate with Miyagi prefecture and Tohoku University to breed salt-resistant lines in the more delicious commercial rice varieties, 'Hitomebore' and 'Manamusume', that will grow normally and retain their good taste in saline paddy fields affected by the recent tsunami. The target of heavy-ion breeding is extended from flowers to crops like grains so that it will contribute to solve the global problems of food and environment.

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Research & Technical Scientist

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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, 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 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 the RIBF accelerators.

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 using accelerator techniques and its applications to geoscience and environmental science
(4) Development of chemical materials for ECR ion sources of RIBF accelerators

3. Summary of Research Activity

RI Applications Team utilizes RIBF heavy-ion accelerators for following research subjects:

(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, medicine, engineering, and environmental sciences. We have been developing production technologies of useful radiotracers at RIBF and conducted 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 30 radiotracers from ^{7}Be to ^{206}Bi. 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. 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 2014, we developed production technologies of radioisotopes such as ^{28}Mg, ^{48,51}Cr, ^{67}Cu, ^{95m}Tc, ^{183,184m,184g}Re, and ^{191}Pt which were strongly demanded but lack supply sources in Japan. We also investigated the excitation functions for the ^{nat}Ti(α,x), ^{nat}Ge(α,x), ^{nat}Zr(α,x), ^{nat}Mo(d,x), ^{nat}Cd(α,x), ^{116}Cd(α,x), ^{nat}Sm(d,x), ^{nat}Ho(α,x), ^{nat}W(d,x), and ^{nat}Pt(d,x) reactions to produce useful RIs. We produced ^{65}Zn, ^{109}Cd, and ^{88}Y for our scientific researches on a regular schedule and supplied the surpluses through Japan Radioisotope Association to the general public. In 2014, we have accepted 5 orders of ^{65}Zn with a total activity of 33 MBq, 3 orders of ^{109}Cd with 21 MBq, and 2 orders of ^{88}Y with 2 MBq.

(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, long-lived ^{261}Rf (Z = 104), ^{262}Db (Z = 105), and ^{265}Sg (Z = 106) are produced in the ^{248}Cm(^{18}O,5n)^{261}Rf, ^{248}Cm(^{19}F,5n)^{262}Db, and ^{248}Cm(^{22}Ne,5n)^{265}Sg reactions, respectively, and their chemical properties are investigated.

We have been developing a gas-jet transport system at 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: (i) the background radioactivities of unwanted reaction products are strongly suppressed, (ii) the intense beam is absent in the gas-jet chamber and hence high gas-jet efficiency is achieved, and (iii) the beam-free condition also allows for investigations of new chemical systems. In 2014, the isotope of element 107 ^{266}Bh was produced in the ^{248}Cm(^{23}Na,5n)^{266}Bh reaction, and its decay properties were investigated using the rotating wheel apparatus MANON for α/SF spectrometry. Toward the SHE chemistry behind GARIS, we developed a gas-chromatograph apparatus directly coupled to GARIS, which enabled in-situ complexation and gas-chromatographic separation of a large variety of volatile compounds of SHEs. Toward aqueous chemistry of the heaviest elements such as Sg and Bh, we also started to develop a new rapid chemistry apparatus which consisted of a continuous dissolution apparatus Membrane DeGasser (MDG), a flow liquid-liquid extraction apparatus, and a flow liquid scintillation detector for α/SF-spectrometry.

At the AVF cyclotron, the distribution coefficients (K_d) of ^{261}Rf on the Aliquat 336 resin were measured in HCl with the AutoMated Batch-type solid-liquid Extraction apparatus for Repetitive experiments of transactinides (AMBER) in collaboration with Osaka Univ. The extraction behavior of ^{89m}Zr and ^{173}Hf in the Aliquat 336/HCl system was investigated for Rf chemistry with the flow-type liquid-liquid extraction apparatus. The reversed-phase TTA extraction chromatography of ^{261}Rf and its homologues ^{85}Zr and ^{169}Hf was conducted in HF/HNO_3 using the Automated Rapid Chemistry Apparatus (ARCA) in collaboration with Kanazawa Univ., Niigata Univ., and JAEA. The reversed-phase extraction chromatography of ^{90g}Nb and ^{178a}Ta in Aliquat 336/HF and the anion-exchange chromatography of ^{90g}Nb and ^{178a}Ta in HF/HNO_3 were also conducted with ARCA for chemical studies of Db. For Sg chemistry, we investigated the extraction behavior of ^{93m}Mo and ^{177,179m}W in H_2SO_4 and $H_2C_2O_4$ solutions with Aliquat 336.

(3) Development of trace element analysis using accelerator techniques and its application to geoscience and environmental science

We developed new mass spectrometry technologies for trace element analyses as an application of accelerator technology to various fields such as cosmochemistry, environmental science, and archaeology. ECRIS-AMS is a new type of accelerator mass spectrometry at RILAC equipped with an ECR ion source. This system is available for measuring trace elements (10^{-14}–10^{-15} level) and is expected to be especially effective for measurements of low-electron-affinity elements such as ^{26}Al, ^{41}Ca, and ^{53}Mn. In 2014, we have renovated the detection system and examined the sensitivity and mass resolution power. We also attempted to develop another technology by customizing a mass spectrometer equipped with a stand-alone ECR ion source for analyses of elemental and isotopic abundances. Especially, we equipped laser-ablation system with ion source to achieve high-resolution analysis. Furthermore, we analyzed sulfur and lead isotope ratios for cinnabar samples from ancient tombs in Japan to elucidate the origin of cinnabar. In 2014, we showed that the lead isotopes in cinnabar ore exhibited clear local characteristics and the origin of the cinnabar ore could be distinguished from the lead isotope compositions.

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

In 2014, we investigated production methods of $^{238}U(C_8H_8)_2$ and metallic ^{50}Ti powder for the ECR ion source of RIBF. We also prepared metallic ^{238}U and $^{238}UO_2$ on a regular schedule.

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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 User Support 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

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RIBF Research Division
User Liaison and Industrial Cooperation Group
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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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 handles fee-based distribution of radioisotopes Zn-65, Y-88 and Cd-109 from 2007, which are produced by the RI application team at the AVF cyclotron, to nonaffiliated users under a Material Transfer Agreement between Japan Radioisotope Association and RIKEN. In 2014, we delivered 3 shipments of Cd-109 with a total activity of 22 MBq, 7 shipments of Zn-65 with a total activity of 44 MBq and one shipment of Y-88 with an activity of 1 MBq. The final recipients of the RIs were five universities, one research institutes and two hospitals.

(2) Support of Industrial application using RIBF

In November 2009, RNC started a new project “Promotion of applications of high-energy heavy ions and RI beams” as a grant-in-aid program of MEXT “Sharing Advanced Facilities for Common Use Program”. In this project, RNC opens the old part of the RIBF facility, which includes the AVF cyclotron, RILAC, RIKEN Ring Cyclotron and experimental instruments like RIPS, to non-academic proposals from users including private companies. This MEXT program was terminated in September 2010, but RNC succeed and promote this facility sharing program after that. The proposals are reviewed by a program advisory committee, industrial PAC. The proposals which have been approved by the industrial PAC are allocated with beam times and the users pay RIKEN the beam time fee. The intellectual properties obtained by the use of RIBF belong to the users. In order to encourage the use of RIBF by those who are not familiar with utilization of ion beams, the first two beam times of each proposal can be assigned to trial uses which are free of beam time fee.

The fourth industrial PAC meeting held in August 2014 reviewed two fee-based proposals from private companies and approved them. The first proposal of fee-based utilization was performed in October with a 70-MeV/A 84Kr beam at the E5A beamline of the RIKEN Ring Cyclotron.

(3) Development of real-time wear diagnostics using RI beams

We are promoting a method for real-time wear diagnostics of industrial material using RI beams as tracers. For that purpose, very intense RI beams of 7Be (T1/2=52 days) at 4.1 MeV/u and 22Na (T1/2=2.6 years) at 3.7 MeV/u were produced via the (p,n) reaction at the CRIB separator using beams from the AVF cyclotron. As we can provide RI beams of different nuclides and control the implantation depth, we have developed a novel method of wear diagnostics.

Under a collaborative research agreement entitled “Development and application of wear diagnosis method with RI beams" between RIKEN, University of Tokyo and two private companies, we had two beam-times in February and in March 2014, at E7A beam-line of the AVF cyclotron. Beams of RI nuclei 7Be and 22Na were provided by CRIB and implanted near surface of metallic machine parts, whose wear-loss rate was evaluated through measurements of the radio-activities.

We are also developing a new method to determine the spatial distribution of positron-emitting RIs on periodically-moving objects in a closed system, which can be used for real-time evaluation of wear loss in a running machine. This is based on the same principle as the medical PET systems but is simpler and less expensive.

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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.

We revised the safety interlock system of RIBF building to prevent excess exposures due to unexpected high-intensity beam transport through the BigRIPS. When the primary beam is transported through BigRIPS, rooms adjacent to and in the vicinity of the room where the beam is transported are evacuated. If the magnetic fields of the two dipole magnets before and after the BigRIPS target position were set very closely, the interlock system recognizes the primary beam is transported through the BigRIPS. The primary beam mode can be also set manually. In the primary beam mode, some attenuators of accelerators cannot be taken out not to deliver a high-intensity beam to BigRIPS by human error.

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Partner Institution

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 of the University of Tokyo (CNS), Institute of Particle and Nuclear Studies of KEK (KEK), and Department of Physics, 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, 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 newly constructed isotope separator KISS will be available for the users in near future.

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. We started a new project OEDO for a new energy-degrading scheme, where a RF deflector system is introduced to obtain a good quality of low-energy beam. 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) Active Target Development

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. Development of ECR heavy ion sources is to provide new HI beams, higher and stable beams of metallic ions, and to improve the control system. The Hyper ECR and the Super ECR sources provide all the beams for the AVF cyclotron and support not only CRIB experiments but also a large number of RIBF experiments. Injection beam monitoring and control are being developed and studied. Detailed study of the optics from the ion sources are expected to improve transmission and qualities of beams for the RIBF facility.

(2) Nuclear Astrophysics

The nuclear astrophysics group in CNS is working for experimental researches using the low-energy RI beam separator CRIB.
The call for proposals for the NP-PAC now includes proposals for CRIB again, and 3 new proposals have been approved in the NP-PAC meetings in the fiscal year 2014. In May 2014, a measurement of the elastic scattering of ^{8}B+Pb was performed in collaboration with INFN-LNL (Padova). It was made possible by the special development of intense and energy-enhanced ^{6}Li beam. A unique beam of ^{8}B at 50 MeV and 10^4 pps was produced, and the measurement was successfully completed.

(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 2014, the following progress has been made.

Experimental data taken in 2013 under the EURICA collaboration are being analyzed for studying octupole deformation in neutron-rich nuclei. Gamow-Teller transitions of ^{8}He were studied by the (p,n) reaction in inverse kinematics, where a prominent sharp peak at Ex~8 MeV was found to be the Gamow-Teller resonance. Exothemic charge exchange reactions (^{8}He,^{8}Li*(1+)) on ^{4}He are being analyzed for studying spin-dipole response of few-body system on the photon line. The tetra-neutron system was studied by the ^{4}He(^{8}He,^{8}Be)4n reaction, which shows a candidate of the ground state of the tetra neutrons just above the 4n threshold as well as continuum at higher excitation energy.

The readout system of 14 detectors of the CNS GRAPE was upgraded, where digital pulse data taken by sampling ADCs are analyzed by FPGAs on boards.

(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 PHENIX, the group has been concentrating on the physics analysis involving leptons and photons; dielectron measurement in Au+Au collisions, dark photon searches in low mass Dalitz decays, and J/ψ production in ultra-peripheral Au+Au collisions.

As for ALICE, the group has involved in the data analyses, which include the neutral pion production in Pb+Pb collisions, and measurement of low-mass lepton pairs in Pb+Pb and p+Pb collisions. The group has involved in the ALICE-TPC upgrade using a Gas Electron Multiplier (GEM). Performance evaluation of the MicroMegas + GEM systems for the upgrade is performed.

R&D of GEM and related techniques has been continuing. Development of Teflon GEM has been progressing in collaboration with the Tamagawa group of RIKEN.

(5) Nuclear Theory

The nuclear theory group has been promoting the CNS-RIKEN collaboration project on large-scale nuclear structure calculations since 2001 and maintaining its PC cluster. In order to review and promote this collaboration further, an international workshop "Progress in nuclear shell-model calculations in CNS-RIKEN collaboration" was held on Nov. 26-28, 2014.
This group has revealed that the 4^+_1 of ^{44}S is high-K isomer, and discussed the deformation properties of the high-spin states of neutron-rich Cr and Fe isotopes utilizing shell-model calculations. A memorandum of understanding on this collaboration has been made between CNS and RIKEN in March 2014. In parallel, this group participated in activities of HPCI Strategic Programs for Innovative Research (SPIRE) Field 5 "The origin of matter and universe" since 2011.

(6) OEDO/SHARAQ project

The OEDO/SHARAQ group promoted high-resolution experimental studies of RI beams by using the high-resolution beamline and SHARAQ spectrometer. The mass measurement by TOF-Bρ technique was performed for very neutron-rich calcium isotopes around N=34. For the experiment, we introduced new detector devices into the experiment. Diamond detectors, which were developed as timing counters with extreme resolution, were installed for measuring time of flight at the first and final foci of the beam line. Clover-type Ge detectors were installed at the final focal plane of the SHARAQ spectrometer for the first time, enabling particle identification of RI beams by probing delayed gamma rays from known isomeric states of specific nuclei.

We have started ion optical development for achievement of high-quality RI beams with energies lower than 100 MeV/u. This project was named OEDO (Optimized Energy-Degrading Optics for RI beam) and the basic magnet arrangement and ion optics was discussed based on the existing high-resolution beamline and SHARAQ spectrometer.

(7) Exotic Nuclear Reaction

The Exotic Nuclear Reaction group studies various exotic reactions induced by beams of unstable nuclei.
In 2014, a parity transfer probe of the (^{16}O, ^{16}F(g.s)) reaction was demonstrated on ^{12}C at SHARAQ. The proton from the subsequent instant decay of ^{16}F(g.s.) $\rightarrow$ ^{15}F+p was detected by a MWDC newly introduced. The kinematical reconstruction of ^{16}F was successful. At SAMURAI, a measurement of knockout reactions from Borromean nuclei, ^{11}Li and ^{14}Be was performed to study the two-neutron correlation. Analysis of the ^{22,24}O(p,2p) reaction data obtained in 2012 was almost finished and the spin-orbit splitting of proton 0p orbitals in ^{22}O was derived.

(8) Active Target Development

In a project of active target development launched as an intergroup collaboration in 2009, two types of active target, called GEM-MSTPC and CAT, respectively, have been developed. The (α,p) reactions on ^{18}Ne, ^{22}Mg and ^{30}S, and the alpha emission following the beta decay of ^{16}N have been measured using GEM-MSTPC and data analyses are on going. The deuteron inelastic scattering off ^{132}Xe was measured by using the CAT with 10^6-particles-per-spill ^{132}Xe beam at HIMAC accelerator facility in Chiba.

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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) Reaction cross section and radii of neutron-rich nuclei

The experimental nuclear physics group has studied nuclear structure with the RI beam. One of our main interests is the interaction/reaction cross section measurements. They are good probes to investigate nuclear matter radii and nuclear matter distributions including halo or skin structure. Recently we have measured the interaction sections of Ne, Na, Mg and Al isotopes from stable region to neutron drip line with BigRIPS in RIBF. We found a large enhancement of cross section at ^{31}Ne. It suggests that ^{31}Ne nucleus has a neutron halo. It is consistent with the soft E1 excitation measurement. We also found an enhancement at ^{37}Mg. For odd-Z nuclei, Na and Al, we did not find such a large enhancement from neighbor isotopes. The systematics of observed interaction/reaction cross sections shows the changing of nuclear structure from stable region to neutron drip line via island of inversion.

(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 for deformed nuclei has been developed in the group. The versatility of this method to describe the deformation splitting of the giant resonances associated with the onset of deformation has been demonstrated for the first time by the intensive numerical calculation performed for Nd and Sm isotopes. The same method is further extended to describe the spin-isospin modes of excitation in deformed neutron-rich nuclei. A successful description of the Gamov-Teller beta-decay transition rate in the neutron-rich Zr isotopes is achieved with this method. Another correlation of interest in neutron-rich nuclei is the pair correlation, for which the spatial di-neutron correlation has been a key topic. Applying the continuum QRPA to the pairing modes of excitation in neutron-rich Sn isotopes, we predict the emergence of an anomalous pair vibration for isotopes with A>132. Furthermore the new mode is predicted to exhibits the di-neutron character. In addition to these studies, activities related to the proton-neutron pairing, the di-neutron correlation in the asymptotic tail in drip-line nuclei, the quasiparticle resonances in unbound odd-N nuclei are under way. Cluster structure and the ab initio studies of light nuclei are also important research subjects of the theory group.

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1. Abstract

The KEK Isotope Separation System (KISS) has been constructed to experimentally study the β-decay properties of unknown neutron-rich nuclei with around neutron magic numbers N = 126 for astrophysical interest. In FY2014, first radioactive nuclear beam of ^{199}Pt, which was produced by ^{136}Xe + ^{198}Pt reaction, collected by an Ar gas cell, selectively ionized by a resonant ionization technique and mass-separated, has been successfully extracted from KISS. The measured half-life of extracted ^{199}Pt was good agreement with the reported value.

2. Major Research Subjects

(1) Radioactive isotope beam production and manipulation for nuclear experiments.
(2) Explosive nucleosyhnthesis (r- and rp-process).
(3) Heavy ion reaction mechanism for producing heavy neutron-rich nuclei.
(4) Single particle states of neutron-rich nuclei by isobaric analog resonances.
(5) Development of RNB probes for materials science applications.

3. Summary of Research Activity

The KISS is an element-selective isotope separator using a magnetic mass separator combined with in-gas-cell resonant laser ionization. The gas cell filled with argon gas of 50 kPa is a central component of the KISS for extracting only the element of interest as ion beam for subsequent mass separation. In the cell, the element primarily produced by low-energy heavy ion reactions is stopped (thermalization and neutralization), transported by buffer gas (argon gas-flow of ~50 kPa in the present case), and then re-ionized by laser irradiation just before the exit. The gas cell was fabricated to efficiently correct the reaction products produced by the multi-nucleon transfer reaction of ^{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/u and 6 mg/cm^2, respectively. In FY2014, for the half-life measurement, β-ray telescopes and a tape transport system were installed at the focal point of KISS. The β-ray telescopes were composed of three double-layered thin plastic scintillators; thickness of the first layer and second one were 0.5 and 1 mm, respectively. In order to reduce the background, they were surrounded with low-activity lead blocks and a veto counter system consisting of plastic scintillator bars. The background rate of the present β-ray telescopes was measured to be 0.7 counts per second. After the installation of the detection system, we have successfully extracted laser-ionized ^{199}Pt which mainly formed $^{199}PtAr_2^+$ molecular ions and was transported with the mass separator as the molecular ions. The measured half-life of ^{199}Pt was $t_{1/2}$ = 33(4) min. which was good agreement with the reported value of 30.8(2) min.

Also, we investigated the extraction efficiency of ions from KISS, using ^{198}Pt elastic scattered particles. The ^{198}Pt was also extracted as $^{199}PtAr_2^+$ molecule. The extraction efficiency was measured to be about 0.2 % which was independent of the ^{136}Xe primary beam intensities. The obtained selectivity and purity were higher than 300 and 99.7 %, respectively, at the maximum primary beam intensity of 20 pnA. In order to improve the extraction efficiency, we have started to install a new sextupole ion-guide (SPIG) at the exit of the gas cell with lager angular acceptance, which is divided into two parts with different apertures of 8 and 3 mm diameters, respectively. At the off-line test for the newly installed SPIG, we have clearly observed the dissociation of molecular ions of laser-ionized iridium, by applying DC voltage between first and second parts of the SPIG. We can expect to improve the extraction efficiency, at least, by a factor of 1.5. In FY2015, we will perform the on-line test for the new SPIG to measure the improved extraction efficiency.

For measurements of half-lives of unknown neutron-rich nuclei on N = 126, the present background rate of β-rays telescopes is not low enough. We have constructed a new β-rays telescopes in which ΔE plastic scintillator would be exchanged to a smaller one. We can expect to reduce the background rate by several factors. Further, we have started to develop a gas counter as a ΔE counter to realize the background rate of our goal, several counts per hour or less.

As a continuing effort for search for effective laser ionization scheme of elements of our interest (Z<82), a reference cell was fabricated, and is currently being used to search for auto ionizing states in Ta, W, and etc…

In order to investigate the feasibility of the multi-nucleon transfer (MNT) in the reaction system of ^{136}Xe on ^{198}Pt for producing heavy neutron-rich isotopes around the mass number of 200 with the neutron magic number of 126, We performed the cross section measurement at GANIL in 2012 and the analysis of the data has been almost completed. The cross sections of target-like fragments around N =126 were comparable to those estimated using the GRAZING code, and they appear to be mainly contributed by the reactions with low total energy loss with the weak N/Z equilibration and particle evaporation. This suggests the promising use of the MNT reactions with a heavy projectile at the energies above the Coulomb barrier for production of the neutron-rich isotopes around N = 126.

The diffusion coefficient of lithium in solid materials used in secondary Li-ion batteries is one of key parameters that determine how fast a battery can be charged. The reported Li diffusion coefficients in solid battery materials are largely scattered over several order of magnitudes. We have developed an in-situ nanoscale diffusion measurement method using α-emitting radioactive ^{8}Li tracer. In the method, while implanting a pulsed ^{8}Li beam of 8 keV, the alpha particles emitted at a small angle (θ = 10 ± 1◦) relative to a sample surface were detected as a function of time. We can obtain Li diffusion coefficient from the time dependent yields of the α particles, whose energy loss can be converted to nanometer-scale position information of diffusing ^{8}Li. The method has been successfully applied to measure the lithium diffusion coefficients for an amorphous Li_4SiO_4 - Li_3VO_4 (LVSO) which was used as a solid electrotype in a solid-state Li thin film battery, well demonstrating that the present method has the sensitivity to the diffusion coefficients down to a value of 10^{-12} cm^2/s, corresponding with nanoscale Li diffusion. From FY2014, we have started to measure Li diffusion coefficients in a spinel type Li compound of $LiMn_2O_4$ (LMO), which is used as a positive electrode of a Li battery in an electric vehicle. We have observed a significant change on the time dependent yields of the α particles at the sample temperature of around 623 K and will continue the measurements to obtain temperature dependency of Li diffusion coefficients in LMO.

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Events (April 2014 - March 2015)

RIKEN

Apr. 10 - 11	The 3rd EURICA Workshop
Apr. 19	Wako Open campus
Jun. 1 - 6	The 2nd Conference on "Advances in Radioactive Isotope Science" (ARIS2014) http://ribf.riken.jp/ARIS2014/
Jun. 27 - 28	The 14th NP-PAC
Jul. 1 - 3	Nishina Center Advisory Council
Jul. 28 – Aug. 8	Nishina School
Aug. 7	The 4th In-PAC
Aug. 31 - Sep. 5	The 27th International Conference of the International Nuclear Target Development Society (INTDS-2014) http://ribf.riken.jp/intds2014/
Oct. 1	Start of Nuclear Transmutation Data Research Group associated with following three teams Fast RI Data Team, Slow RI Data Team and Muon Data Team Start of High-Intensity Accelerator R&D Group associated with following two teams High-Gradient Cavity R&D Team and High-Power Target R&D Team
Dec. 1-5	The 6th International Conference on Trapped Charged Particles and Fundamental Physics (TCP2014) http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1395
Dec. 10	Effect of MOU between Universitas Hasanuddin, Indonesia and RNC
Dec. 12 - 13	The 15th NP-PAC
Jan. 5	Effect of MOU between RNC and Peking University
Jan. 8 - 9	The 11th ML-PAC
Mar. 31	End of Mathematical Physics Laboratory led by associate chief scientist Koji Hashimoto

CNS

Aug. 28 - Sep. 03	The 12th CNS international Summer School (CNSS13) http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=81

Niigata Univ.

	not held in FY2014

KEK

Aug, 21-28	KEK Summer Challenge 2014 http://www2.kek.jp/ksc/8th_2014/index.html

Press Releases (April 2014 - March 2015)

RNC

Apr. 11	Elucidation of exotic structures in very neutron-rich nuclei -a unified picture for neutron-halo, magicity-loss and large deformation-	Joint PR: Released from Tokyo Tech.
Apr. 24	Hyperfine structure constant of the single neutron halo nucleus 11Be+ has been precisely measured to be A= -2677.302988±0.000072 MHz using laser microwave double resonance spectroscopy.	Michiharu WADA (SLOWRI Team)
Jun. 18	Neutron Halo Appears in a Neutron-rich Magnesium Isotope ---Suggesting that neutron halo is a more common feature of heavier, extremely neutron-rich nuclei---	Joint PR: Released from Tokyo Tech.
Jul. 22	Rewriting the history of volcanic forcing during the past 2000 years ---A year-by-year record of volcanic eruptions from a comprehensive Antarctic ice core array---	Yuko MOTIZUKI (Astro-Glaciology Research Unit) Joint PR with Desert Research Institute
Aug. 29	Nickel-78 has been confirmed to be a 'doubly magic' isotope -- Precise beta-decay half-life measurement of ^{78}Ni --	Z. Y. Xu & Shunji Nishimura (Radioactive Isotope Physics Lab.) Joint PR with the Univ. of Tokyo
Sep. 18	SUZAKU studies of the central engine in the typical Type I seyfert NGC 3227: Detection of multiple primary X-ray continua with distinct properties	Hirofumi Noda (High Energy Astrophysics Lab.) Joint PR with the Univ. of Tokyo
Sep. 18	Efficient production of muonium at room temperature--- Stringent survey of deviation from the standard model of particle physics comes closer to reality in Japan---	Katsuhiko Ishida (Advanced Meson Science Lab.) Joint PR: Released from KEK
Sep. 19	Synthesis of a carbonyl complex of element 106, seaborgium (Sg) ---Sg shows chemical properties characteristic to the group-6 elements in the periodic table---	Hiromitsu Haba (RI Applications Team) Joint PR with JAEA
Feb. 13	Muonium in Stishovite: Implications for the Possible Existence of Neutral Atomic Hydrogen in the Earth's Deep Mantle	Dai Tomono & Teiichiro MATSUZAKI (Muon Data Team) Released from the University of Tokyo
Mar. 9	Ensuring food safety using space technology ---technology originally designed for use in outer space to create a new system, called LANFOS, which can inexpensively and non-destructively detect radioactive cesium contamination in food---	Hiromitsu Haba (RI Applications Team) Joint PR with GTEC