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

1. Abstract

The elements with atomic number $Z \geq 104$ are called as trans-actinide or superheavy elements (SHEs). Superheavy Element Production Team synthesizes SHE nuclei including new elements and investigates synthesis mechanisms of SHE nuclei, nuclear properties of SHE nuclei, and chemical properties of SHEs in collaboration with Superheavy Element Devise Development Team and Nuclear Chemistry Research Team of RIKEN Nishina Center.

2. Major Research Subjects

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

3. Summary of Research Activity

(1) Search for new superheavy elements

In November 2016, the 7th period of the periodic table was completed with the official approval of four new elements, nihonium (Nh, atomic number $Z = 113$), moscovium (Mc, $Z = 115$), tennessine (Ts, $Z = 117$), and oganesson (Og, $Z = 118$) by International Union of Pure and Applied Chemistry. We have started to search for new elements to expand the chart of the nuclides toward to the island of stability and the periodic table of the elements toward the 8th period. In January 2020, RIKEN heavy-ion Linear ACcelerator (RILAC) was upgraded as Superconducting RIKEN heavy-ion Linear ACcelerator (SRILAC). We developed the new gas-filled recoil ion separator GARIS-III on the beam line of SRILAC. In June–July 2020, we conducted the commissioning of SRILAC and GARIS-III using the ^{169}Tm + ^{40}Ar, ^{208}Pb + ^{40}Ar, and ^{208}Pb + ^{51}V reactions. Since October 2020, we have been conducting a synthesis experiment of isotopes of new element 119 in the ^{248}Cm + ^{51}V reaction under the nSHE collaboration.

(2) Decay spectroscopy of the heaviest nuclei

In collaboration with KEK, we developed a multi-refection time-of-fight mass spectrograph (MRTOF-MS) equipped with an α-TOF detector on the focal plane of GARIS-II at RRC for decay-correlated mass measurements of low-yield and short-lived SHE isotopes. In 2021, the first high-precision direct determination of the atomic mass of a superheavy nuclide was successfully conducted for ^{257}Db ($Z = 105$) produced in the ^{208}Pb(^{51}V, $2n$)^{257}Db reaction. The atomic masses of $^{206,\,207g,\,m}$Ra were also measured in the ^{159}Tb(^{51}V, 4;$3n$)$^{206,\,207g,\,m}$Ra reactions.

(3) Study of reaction mechanisms for production of the heaviest nuclei

SHE nuclei have been produced by complete fusion reactions of two heavy nuclei. However, the reaction mechanism of the fusion process is still not well understood both theoretically and experimentally. We measured excitation functions for the quasielastic scattering of the ^{248}Cm + ^{51}V reaction using GARIS III at SRILAC. The result was utilized to estimate the optimal incident beam energy for production of isotopes of new element 119.

(4) Study of chemical properties of the heaviest elements

Chemical characterization of newly-discovered SHEs is an extremely interesting and challenging subject in modern nuclear and radiochemistry. In collaboration with Nuclear Chemistry Research Team of RIKEN Nishina Center, we are developing SHE production systems as well as rapid single-atom chemistry apparatuses for chemistry studies of SHEs. We installed a gas-jet transport system to the focal plane of GARIS at RILAC. This system is a promising approach for exploring new frontiers in SHE chemistry: the background radiations from unwanted products are strongly suppressed, the intense primary heavy-ion beam is absent in the gas-jet chamber, and hence the high gas-jet extraction yield is attained. Furthermore, the beam-free conditions make it possible to investigate new chemical systems. In 2021, we continued to develop an ultra-rapid gas-chromatograph apparatus, which consists of an RF carpet gas cell and a cryo-gas-chromatograph column with a Si detector array, at the focal plane of GARIS for the gas chemistry of SHEs. To realize aqueous chemistry studies of Sg ($Z = 106$) and Bh ($Z = 107$), we have been developing a continuous and rapid solvent extraction apparatus which consists of a continuous dissolution apparatus Membrane DeGasser (MDG), a Flow Solvent Extractor (FSE), and a liquid scintillation detector for α/SF-spectrometry. In 2021, we also conducted model experiments for ion-exchange studies of Rf ($Z = 104$) in HNO_3 and H_2SO_4 using long-lived radiotracers of ^{88}Zr and ^{175}Hf.

Members

Team Leader

Hiromitsu HABA

Research & Development Scientist

Daiya KAJI

Special Postdoctoral Researcher

Tomohiro HAYAMIZU

Visiting Scientists

Marc ASFARI (IPHC/Strasbourg Univ.)
Mahananda DASGUPTA (Australian Nat'l Univ.)
Olivier DORVAUX (Strasbourg Univ.)
Benoit Jean-Paul GALL (Strasbourg Univ.)
Zaiguo GAN (Chinese Academy of Sci.)
Shintaro GO (Kyushu Univ.)
David HINDE (The Australian Nat'l Univ.)
Minghui HUANG (IMP, CAS)
Hiroyuki KOURA (JAEA)
Daisuke NAGAE (Kyushu Univ.)
Satoshi SAKAGUCHI (Kyushu Univ.)
Mirei TAKEYAMA (Yamagata Univ.)
Taiki TANAKA (The Australian Nat'l Univ.)
Huabin YANG (IMP, CAS)
Zhiyuan ZHANG (IMP, CAS)

Student Trainees

Yuichi ISHIBASHI (Kyushu Univ.)
Tamito KAI (Kyushu Univ.)
Kieran KESSACI (IPHC/Strasbourg Univ.)
Raiden LEMON (The Australian Nat'l Univ.)
Milan LEONARD (The Australian Nat'l Univ.)
Sotaro MATSUNAGA (Kyushu Univ.)
Ikuto MURAKAMI (Kyushu Univ.)
Taiga MUTO (Kyushu Univ.)
Yuto NAGATA (Kyushu Univ.)
Koichi SUGIYAMA (Kyushu Univ.)
Taro TOMIMATSU (Kyushu Univ.)

List of Publications & Presentations

Publications

[Original Papers]

P. Schury, T. Niwase, M. Wada, P. Brionnet, S. Chen, T. Hashimoto, H. Haba, Y. Hirayama, D. S. Hou, S. Iimura, H. Ishiyama, S. Ishizawa, Y. Ito, D. Kaji, S. Kimura, H. Koura, J. J. Liu, H. Miyatake, J. -Y. Moon, K. Morimoto, K. Morita, D. Nagae, M. Rosenbusch, A. Takamine, Y. X. Watanabe, H. Wollnik, W. Xian, and S. X. Yan, "First high-precision direct determination of the atomic mass of a superheavy nuclide," Phys. Rev. C **104**, L021304 (2021).

T. Niwase, M. Wada, P. Schury, P. Brionnet, S. D. Chen, T. Hashimoto, H. Haba, Y. Hirayama, D. S. Hou, S. Iimura, H. Ishiyama, S. Ishizawa, Y. Ito, D. Kaji, S. Kimura, J. Liu, H. Miyatake, J. Y. Moon, K. Morimoto, K. Morita, D. Nagae, M. Rosenbusch, A. Takamine, T. Tanaka, Y. X. Watanabe, H. Wollnik, W. Xian, and S. X. Yan, "α-decay-correlated mass measurement of ^{206,207g,m}Ra using an α-TOF detector equipped multireflection time-of-flight mass spectrographs system," Phys. Rev. C **104**, 044617 (2021).

T. Aoki, R. Sreekantham, B. K. Sahoo, B. Arora, A. Kastberg, T. Sato, H. Ikeda, N. Okamoto, Y. Torii, T. Hayamizu, K. Nakamura., S. Nagase, M. Ohtsuka, H. Nagahama, N. Ozawa, M. Sato, T. Nakashita, K. Yamane, K. S. Tanaka, K. Harada, H. Kawamura, T. Inoue, A. Uchiyama, A. Hatakeyama, A. Takamine, H. Ueno, Y. Ichikawa, Y. Matsuda, H. Haba, and Y. Sakemi, "Quantum sensing of the electron electric dipole moment using ultracold entangled Fr atoms," Quantum Sci. Technol. **6**, 044008 (2021).

A. Yakushev, L. Lens, C. E. Düllmann, M. Block, H. Brand, M. Dasgupta, T. Calverley, A. D. Nitto, M. Götz, S. Götz, H. Haba, L. Harkness-Brennan, R-D. Herzberg, F. P. Heßberger, D. Hinde, A. Hübner, E. Jäger, D. Judson, J. Khuyagbaatar, B. Kindler, Y. Komori, J. Konki, J. V. Kratz, J. Krier, N. Kurz, M. Laatiaoui, B. Lommel, C. Lorenz, M. Maiti, A. K. Mistry, C. Mokry, Y. Nagame, P. Papadakis, A. Såmark-Roth, D. Rudolph, J. Runke, L. G. Sarmiento, T. K. Sato, M. Schädel, P. Scharrer, B. Schausten, J. Steiner, P. Thörle-Pospiech, A. Toyoshima, N. Trautmann, J. Uusitalo, A. Ward, M. Wegrzecki, and V. Yakusheva, "First study on nihonium (Nh, element 113) chemistry at TASCA," Front. Chem. **9**, 753738 (2021).

E. Watanabe, Y. Kasamatsu, T. Yokokita, S. Hayami, K. Tonai, H. Ninomiya, N. Kondo, Y. Shigekawa, H. Haba, Y. Kitagawa, M. Nakano, and A. Shinohara, "Anion-exchange experiment of Zr, Hf, and Th in HNO_3 and quantum chemical study on the nitrate complexes toward chemical research on element 104, Rf," Solvent Extr. Ion Exch. published online (December 31, 2021). DOI: 10.1080/07366299.2021.2020956 .

T. Hayamizu, H. Haba, K. Nakamura, T. Aoki, H. Nagahama, K. S. Tanaka, N. Ozawa, M. Ohtsuka, and Y. Sakemi, "Development of ultracold francium atomic sources towards the permanent EDM search," Few-Body Syst. **63**, 11 (2022).

T. Yokokita, S. Yano, Y. Komori, and H. Haba, "Anion- and cation-exchange studies of Zr, Hf, and Th using ion-exchange resin and fiber in H_2SO_4 media for chemical characterization of sulfate complex of Rf," J. Radioanal. Nucl. Chem. **331**, 1127 (2022).

[Book]

羽場宏光, 「新元素ニホニウムはいかにして創られたか」, 東京化学同人, 176 ページ, 2021 年 12 月 17 日.

Presentations

[International Conferences/Workshops]

H. Haba (invited), "Production and applications of radioisotopes at RIKEN RI Beam Factory," International Discussion Meeting on Future of Accelerator Applications and Radiotracers Research (FAAARR2021), Online, July 26–27, 2021.

H. Haba (invited), "Production of radioisotopes for application studies at RIKEN RI Beam Factory," Snowmass'21 Workshop on High Power Cyclotrons/FFAs, Online, September 7–9, 2021.

H. Haba (invited), "Production and applications of radioisotopes at RIKEN RI Beam Factory—Search for new elements through diagnosis and therapy of cancer—," RIKEN-KFU (Kazan Federal University) 3rd Joint Symposium, Online, November 5–6, 2021.

T. Aoki (poster), R. Sreekantham, B. K. Sahoo, B. Arora, A. Kastberg, T. Sato, H. Ikeda, N. Okamoto, Y. Torii, T. Hayamizu, K. Nakamura, S. Nagase, M. Ohtsuka, H. Nagahama, N. Ozawa, M. Sato, T. Nakashita, K. Yamane, K. S. Tanaka, K. Harada, H. Kawamura, T. Inoue, A. Uchiyama, A. Hatakeyama, A. Takamine, H. Ueno, Y. Ichikawa, Y. Matsuda, H. Haba, and Y. Sakemi, "Quantum sensing of the electron electric dipole moment using quantum entangled atoms," International Symposium on Novel Materials and Quantum Technologies (ISNTT2021), Online, December 16, 2021.

[Domestic Conferences/Workshops]

羽場宏光 (口頭発表), 「理研 RI ビームファクトリーにおける RI 製造供給」, 第 58 回アイソトープ・放射線研究発表会, オンライン, 2021 年 7 月 7–9 日.

羽場宏光 (口頭発表), 「RIBF 施設紹介」, 新学術領域研究（研究領域提案型）『学術研究支援基盤形成』短寿命 RI 供給プラットフォーム成果報告会 兼 RI 利用研究会, オンライン, 2021 年 7 月 19–20 日.

羽場宏光 (依頼講演), 「核化学ロードマップについて」, 第 59 回核化学夏の学校, オンライン, 2021 年 8 月 26–27 日.

庭瀬暁隆 (口頭発表), P. Schury, 和田道治, P. Brionnet, S. Chen, 橋本尚志, 羽場宏光, 平山賀一, D. S. Hou, 飯村俊, 石山博恒, 石澤倫, 伊藤由太, 加治大哉, 木村創大, 小浦寛之, 宮武宇也, J. Y. Moon, 森本幸司, 森田浩介, 長江大輔, M. Rosenbusch, 高峰愛子, 渡辺裕, H. Wollnik, W. Xian, S. X. Yan, 「超重核 ^{257}Db の直接質量測定」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

庭瀬暁隆 (口頭発表), 和田道治, P. Schury, P. Brionnet, S. D. Chen, 橋本尚志, 羽場宏光, 平山賀一, D. S. Hou, 飯村俊, 石山博恒, 石澤倫, 伊藤由太, 加治大哉, 木村創大, J. Liu, 宮武宇也, J. Y. Moon, 森本幸司, 森田浩介, 長江大輔, M. Rosenbusch, 高峰愛子, 田中泰貴, 渡辺裕, H. Wollnik, W. Xian, S. X. Yan, 「MRTOF と α-TOF 検出器による, α 崩壊に相関した精密質量測定法の開拓」, 日本放射化学会第 65 回討論会 (2021), オンライン, 2021 年 9 月 22–24 日.

武藤大河 (口頭発表), P. Brionnet, 浅井雅人, 郷慎太郎, R. Grzywacz, 羽場宏光, 加治大哉, 木村創太, T. King, 森本幸司, K. Rykaczewski, 坂口聡志, 酒井英行, 森田浩介, 庭瀬暁隆, 田中聖臣, 「Si 検出器の波形解析による軽粒子識別」, 第 127 回日本物理学会九州支部例会, オンライン, 2021 年 12 月 4 日.

木村創大 (口頭発表), 和田道治, 羽場宏光, 石澤倫, 森本幸司, 庭瀬暁隆, Marco Rosenbusch, Peter Schury for the SHE-Mass Collaboration, 「MRTOF-MS を用いた ^{252}Cf 自発核分裂片の網羅的精密質量測定」, 日本物理学会第 77 回年次大会 (2022 年), オンライン, 2022 年 3 月 15–19 日.

庭瀬暁隆 (口頭発表), P. Schury, 和田道治, P. Brionnet, S. Chen, 羽場宏光, 平山賀一, D. S. Hou, 飯村俊, 石山博恒, 伊藤由太, 加治大哉, 木村創大, 小浦寛之, 宮武宇也, 森本幸司, 森田浩介, 長江大輔, M. Rosenbusch, 高峰愛子, 渡辺裕, H. Wollnik, W. Xian, S. X. Yan, 「MRTOF+α-TOF による ^{257,258}Db の精密質量測定」, 日本物理学会第 77 回年次大会 (2022 年), オンライン, 2022 年 3 月 15–19 日.

横北卓也 (口頭発表), 羽場宏光, 「Zr 及び Hf のスルファト錯体推定に向けた TOA/H_2SO_4 系の溶媒抽出」, 日本化学会第 102 春季年会 (2022), オンライン, 2022 年 3 月 23–26 日.

Outreach Activities

羽場宏光 (依頼講演), 「ニホニウム発見への道のり」, 大宮北高校 SSH 特別講演会, 大宮市, 2021 年 10 月 4 日.

羽場宏光（依頼講演）, 「新元素でがん治療〜RIBF がつくるラジオアイソトープ〜」, 第 9 回理研イノベーションセミナー, オンライン, 2022 年 1 月 21 日.

羽場宏光（依頼講演）, 「ニホニウム発見への道のり」, 早稲田大学本庄高等学院課外講義, オンライン, 2022 年 3 月 12 日.