

## Nuclear Science Research Division Superheavy Element Research Group

### 1. Abstract

The elements with atomic number  $Z \geq 104$  are called as trans-actinide or superheavy elements (SHEs). Superheavy Element Research Group 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 Group 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,  $Z = 113$ ), 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 installed 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  $^{169}\text{Tm} + ^{40}\text{Ar}$ ,  $^{208}\text{Pb} + ^{40}\text{Ar}$ , and  $^{208}\text{Pb} + ^{51}\text{V}$  reactions. Since October 2020, we have been conducting a synthesis experiment of isotopes of new element 119 in the  $^{248}\text{Cm} + ^{51}\text{V}$  reaction under the nSHE collaboration.

#### (2) Study of reaction mechanisms for production of the heaviest nuclei

SHE nuclei have been produced by complete fusion reactions of two heavy nuclei. However, the reaction mechanism of the fusion process is still not well understood both theoretically and experimentally. In 2022, the excitation functions for the evaporation residues and the quasielastic scattering of the  $^{51}\text{V} + ^{159}\text{Tb}$  reaction were measured to deepen our understanding of the  $^{51}\text{V}$ -induced reaction on the deformed target. In 2023, the data obtained were discussed by comparing with the CCFULL and FDBM model calculations.

#### (3) Study of chemical properties of the heaviest elements

Chemical characterization of newly-discovered SHEs is an extremely interesting and challenging research subject in modern nuclear and radiochemistry. In collaboration with Nuclear Chemistry Group 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 2023, 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  $\alpha$ /SF-spectrometry. In collaboration with Osaka University, co-precipitation of No ( $Z = 102$ ) with  $\text{BaSO}_4$  and  $\text{CaC}_2\text{O}_4$  and solid-liquid extraction of No with the Eichrom Sr resin are under study using  $^{255}\text{No}$  produced in the  $^{248}\text{Cm}(^{12}\text{C}, 5n)^{255}\text{No}$  reaction at the AVF cyclotron.

### Members

#### Director

Hiromitsu HABA

#### Senior Technical Scientist

Daiya KAJI

#### Special Temporary Technical Scientist

Masaki FUJIMAKI

**Visiting Scientists**

Marc ASFARI (IPHC / Univ. of Strasbourg)  
 Tomasz CAP (Nat'l Centre for Nucl. Res.)  
 Mahananda DASGUPTA (Australian Nat'l Univ.)  
 Olivier DORVAUX (Univ. of Strasbourg)  
 Benoit Jean-Paul GALL (Univ. of Strasbourg)  
 Zaiguo GAN (IMP, CAS)  
 David HINDE (Australian Nat'l Univ.)  
 Minghui HUANG (IMP, CAS)

Kieran KESSACI (Univ. of Strasbourg)  
 Hiroyuki KOURA (JAEA)  
 Satoshi SAKAGUCHI (Kyushu Univ.)  
 Mirei TAKEYAMA (Yamagata Univ.)  
 Taiki TANAKA (Univ. of Strasbourg)  
 Huabin YANG (IMP, CAS)  
 Zhiyuan ZHANG (IMP, CAS)

**Student Trainees**

Martin W. BORDEAU (Univ. of Strasbourg / IPHC)  
 Margaux S.A. FORGE (Univ. of Strasbourg)  
 Tomoki FUJII (Kyushu Univ.)  
 Donnie T. HOSKINS (Univ. of Tennessee)  
 Naoyuki KITAGAWA (Kyushu Univ.)

Haruki MATSUURA (Kyushu Univ.)  
 Yuya MICHIMOTO (Kyushu Univ.)  
 Naoto MIYASHITA (Kyushu Univ.)  
 Mikito NOMI (Kyushu Univ.)  
 Yuki YAMANOUCI (Kyushu Univ.)

**List of Publications & Presentations****Publications****[Original Paper]**

K. Teranishi, R. Morita, Y. Hayakawa, A. Sakaguchi, A. Nakajima, Y. Komori, T. Yokokita, D. Mori, H. Haba, and A. Yokoyama, "Incomplete fusion reaction producing Pa nuclides in the  $^{232}\text{Th} + ^7\text{Li}$  reaction," *Radiochim. Acta* **111**, 589–596 (2023).

**[Review Article]**

羽場宏光, 「理研がつくる応用研究用ラジオアイソトープ—新元素の探索からがん治療まで—」, *FBNews* No.558, 2–6 (2023).

**Presentations****[International Conferences/Workshops]**

- H. Sakai (invited) for nSHE research group, "SHE research at RIKEN Nishina Center," International Symposium on Physics of Unstable Nuclei 2023 (ISPUN23), Phu Quoc Island, Vietnam, May 4–8, 2023.
- H. Haba (invited), "Present status and perspective of superheavy element research at RIKEN," *Advances and Challenges in Nuclear Fission and Quasi-Fission of Very Heavy and Superheavy Elements*, Napoli, Italy, May 22–26, 2023.
- T. Niwase (oral), P. Schury, M. Wada, P. Brionnet, S. D. Chen, T. Gao, T. Hashimoto, H. Haba, Y. Hirayama, D. Hou, S. Iimura, H. Ishiyama, S. Ishizawa, Y. Ito, D. Kaji, S. Kimura, H. Koura, J. Liu, H. Miyatake, J. Y. Moon, K. Morimoto, K. Morita, D. Nagae, M. Rosenbusch, A. Takamine, Y. X. Watanabe, H. Wollnik, W. Xian, S. Yan, and J. M. Yap, "Direct mass measurement of  $^{257,258}\text{Db}$  by using an MRTOF-MS equipped with an  $\alpha$ -TOF detector," The 4th International Conference on Advances in Radioactive Isotope Science (ARIS), Avignon, France, June 4–9, 2023.
- H. Haba (invited), "Production and applications of radioisotopes at RIKEN RI Beam Factory—Search for new elements through therapy of cancer—," 5th International Conference on "Physics for Sustainable Development & Technology" (ICPSDT-2023), Chittagong, Bangladesh, September 7–8, 2023.
- H. Haba (invited), "Search for element 119 in the  $^{51}\text{V} + ^{248}\text{Cm}$  reaction," The 7th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN23), Huizhou, China, November 12–17, 2023.
- Y. Shigekawa (oral), A. Yamaguchi, N. Sato, A. Takamine, M. Wada, and H. Haba, "Development of a cryogenic RF-carpet gas cell for the chemistry of superheavy elements," The 7th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN23), Huizhou, China, November 12–17, 2023.
- K. Morimoto (invited) for nSHE Collaboration, "Status of new element search at RIKEN," 8th International Conference on Heavy-Ion Collisions at Near-Barrier Energies (Fusion2023), Shizuoka, Japan, November 19–24, 2023.
- T. Niwase (oral), P. Schury, M. Wada, P. Brionnet, S. D. Chen, T. Gao, T. Hashimoto, H. Haba, Y. Hirayama, D. Hou, S. Iimura, H. Ishiyama, S. Ishizawa, Y. Ito, D. Kaji, S. Kimura, H. Koura, J. Liu, H. Miyatake, J. Y. Moon, K. Morita, K. Morimoto, D. Nagae, M. Rosenbusch, A. Takamine, Y. X. Watanabe, W. Xian, H. Wollnik, S. Yan, and J. M. Yap, "Direct mass measurement of superheavy nuclides produced by fusion-evaporation reactions," 8th International Conference on Heavy-Ion Collisions at Near-Barrier Energies (Fusion2023), Shizuoka, Japan, November 19–24, 2023.
- H. Haba (invited) for nSHE Research Group, "Search for a new element 119," 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.
- P. Schury (oral), T. Niwase, M. Wada, M. Rosenbusch, P. Brionnet, Y. Hirayama, D. Kaji, S. Kimura, K. Morimoto, M. Mukai, Y. X. Watanabe, H. Haba, H. Wollnik, H. Ishiyama, W. Xian, and A. Takamine, "Decay-correlated time-of-flight mass spectroscopy using multi-reflection time-of-flight mass spectrographs," 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.
- H. Haba (invited), "Production and applications of radioisotopes at RIKEN RI Beam Factory—Search for new elements through therapy of cancer—," RIKEN Symposium The 1st Conference of Accelerator-Based Science and Technology (CAST2024), Serpong, Indonesia, February 19–22, 2024.

**[Domestic Conferences/Workshops]**

- 羽場宏光 (基調講演), 「ラジオアイソトープの製造と応用～新元素の探索からがん治療まで～」, 短寿命 RI 利用研究シンポジウム, 吹田市 (大阪大学吹田キャンパス銀杏会館), 2023 年 8 月 2-3 日.
- 羽場宏光 (特別講演), 「新元素の核化学」, 日本放射化学討論会第 67 回討論会 (2023), 東広島市 (広島大学東広島キャンパス), 2023 年 9 月 21-23 日.
- 庭瀬暁隆 (口頭発表), 和田道治, Schury Peter, 木村創大, Brionnet Pierre, Chaoyi Fu, 羽場宏光, 平山賀一, 石山 博恒, 伊藤由太, 加治大哉, 宮武宇也, 森本幸司, Rosenbusch Marco, 高峰愛子, 渡邊裕, 「高精度質量分析器による蒸発残留核断面積の励起関数測定」, 日本放射化学討論会第 67 回討論会 (2023), 東広島市 (広島大学東広島キャンパス), 2023 年 9 月 21-23 日.
- 細川浩由 (口頭発表), 永井歩夢, 榊枝優真, 干場香湖, 南部明弘, 重河優大, 羽場宏光, 坂口綾, 横山明彦, 「 $^{232}\text{Th} + ^7\text{Li}$  核反応における  $\alpha$  線放生成物の定量」, 日本放射化学討論会第 67 回討論会 (2023), 東広島市 (広島大学東広島キャンパス), 2023 年 9 月 21-23 日.
- 渡邊瑛介 (口頭発表), 中西諒平, 横北卓也, 王瑞麟, 大高咲希, 板倉悠大, 益田遼太郎, 重河優大, 南部明弘, 殷小杰, 羽場宏光, 金子政志, 柴本恭佑, 高宮幸一, 篠原厚, 笠松良崇, 「102 番元素ノーベリウムの硝酸系および塩酸系でのクラウンエーテルを用いた固液抽出」, 日本放射化学討論会第 67 回討論会 (2023), 東広島市 (広島大学東広島キャンパス), 2023 年 9 月 21-23 日.
- 大高咲希 (口頭発表), 笠松良崇, 中西諒平, 渡邊瑛介, 板倉悠大, 王瑞麟, 益田遼太郎, 金子政志, 羽場宏光, 重河優大, 南部明弘, 殷小杰, 横北卓也, 篠原厚, 「ノーベリウムの硫酸バリウム共沈」, 日本放射化学討論会第 67 回討論会 (2023), 東広島市 (広島大学東広島キャンパス), 2023 年 9 月 21-23 日.
- 中西諒平 (ポスター発表), 笠松良崇, 大高咲希, 渡邊瑛介, 板倉悠大, 王瑞麟, 益田遼太郎, 金子政志, 羽場宏光, 重河優大, 南部明弘, 殷小杰, 横北卓也, 篠原厚, 「ノーベリウムのシュウ酸カルシウム共沈」, 日本放射化学討論会第 67 回討論会 (2023), 東広島市 (広島大学東広島キャンパス), 2023 年 9 月 21-23 日.
- 羽場宏光 (特別講演), 「理研におけるラジオアイソトープの製造と応用～新元素の探索からがん治療まで～」, 日本量子医科学会第 3 回学術大会, 和光市 (理化学研究所), 2023 年 12 月 8-9 日.
- 横北卓也 (口頭発表), 笠松良崇, 渡邊瑛介, 小森有希子, 重河優大, 森大輝, 王洋, 二宮秀美, 速水翔, 東内克馬, ゴーシュコースタブ, 篠原厚, 羽場宏光, 「104 番元素ラザホージウムの硫酸塩錯形成における全生成定数の評価」, 日本化学会第 104 春季年会 (2024), 船橋市 (日本大学理工学部船橋キャンパス), 2024 年 3 月 18-21 日.

**[Seminar]**

- H. Haba (invited), “Synthesis and chemistry of superheavy elements,” Inspiring lecture, Badan Riset dan Inovasi Nasional (BRIN), Serpong, Indonesia, February 21, 2024.

**Awards**

- 羽場宏光, 「重イオンビームを用いた応用研究用ラジオアイソトープの開発」, 令和 5 年度 科学技術分野の文部科学大臣表彰 科学技術賞 (開発部門), 2023 年 4 月 19 日.
- M. Tanaka, P. Brionnet, M. Du, J. Ezold, K. Felker, B. J. P. Gall, S. Go, R. K. Grzywacz, H. Haba, K. Hagino, S. Hogle, S. Ishizawa, D. Kaji, S. Kimura, T. T. King, Y. Komori, R. K. Lemon, M. G. Leonard, K. Morimoto, K. Morita, D. Nagae, N. Naito, T. Niwase, B. C. Rasco, J. B. Roberto, K. P. Rykaczewski, S. Sakaguchi, H. Sakai, Y. Shigekawa, D. W. Stracener, S. VanCleve, Y. Wang, K. Washiyama, and T. Yokokita, “Probing optimal reaction energy for synthesis of element 119 from  $^{51}\text{V} + ^{248}\text{Cm}$  reaction with quasielastic barrier distribution measurement,” J. Phys. Soc. Jpn. **91**, 084201 (2022), 2023 Highly Cited Article (Award for top 10 articles highly cited in 2023, that were published in 2022), The Physical Society of Japan.

**Outreach Activities**

- 羽場宏光 (依頼講演), 「ニホニウム発見への道のり」, SSH サイエンスカフェ, つくば市 (茨城県立並木中等教育学校), 2023 年 6 月 8 日.
- 羽場宏光, 「がんの治療に新元素合成で貢献」, クローズアップ科学道 2023, 研究最前線, 2023 年 8 月 4 日.  
[https://www.riken.jp/pr/closeup/2023/20230804\\_1/index.html](https://www.riken.jp/pr/closeup/2023/20230804_1/index.html).
- 羽場宏光 (依頼講演), 令和 5 年度 2 年生「社会人と語る会」, 金沢市 (石川県立金沢泉丘高等学校), 2023 年 11 月 3 日.
- 羽場宏光 (ポスター発表), 「新元素でがん治療!〜アスタチン-211 の大量製造実現へ〜」, 第 37 回理化学研究所と産業界との交流会, 港区 (オークラ東京), 2024 年 2 月 7 日.
- 羽場宏光 (依頼講演), 「進化する元素周期表」, TFC × TEL 協働プログラム特別講演会, 「113 番元素ニホニウム発見とさらなる超重元素発見に向けて」, 仙台市 (東北大学片平キャンパス), 2024 年 3 月 9 日.