

## Partner Institution

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

**1. Abstract**

The Wako Nuclear Science Center (WNSC) of KEK aims to promote low-energy nuclear physics and nuclear astrophysics research as well as interdisciplinary studies using short-lived radioactive nuclides. WNSC operates the KEK Isotope Separation System (KISS), an electromagnetic isotope separator featuring elemental selectivity from resonance laser ionization in a gas catcher. The KISS facility uniquely provides various neutron-rich isotopes of refractory elements via multinucleon transfer reactions to users from universities. Its provision of nuclei in the vicinity of the neutron magic number  $N = 126$  and  $N = 152$ . Optical and  $\beta$ - $\gamma$  spectroscopy and mass spectrometry have been applied to these neutron-rich nuclear beams for nuclear structure and nuclear astrophysical studies. The WNSC leads comprehensive mass measurements of all-available nuclides at RIBF using multi-reflection time of flight mass spectrographs (MRTOF-MS). Three MRTOF setups were placed at the GARIS-II, the beam dump of the ZeroDegree spectrometer, and the KISS—the masses of more than 400 nuclides, including dozens of first masses. A new uranium isotope,  $^{241}\text{U}$ , was discovered at KISS-MRTOF by means of precise mass measurement. An upgrade plan, KISS-II, is being considered a future project of WNSC aiming at the study of the origin of uranium for the first time.

**2. Major Research Subjects**

- (1) Production and manipulation of radioactive isotope beams for nuclear experiments
- (2) Explosive nucleosynthesis ( $r$ - and  $rp$ -process)
- (3) Heavy ion reaction mechanism for producing heavy neutron-rich nuclei
- (4) Development of MRTOF mass spectrographs for short-lived nuclei
- (5) Comprehensive mass measurements of short-lived nuclei including superheavy elements
- (6) Development of KISS-II

**3. Summary of Research Activity**

The Wako Nuclear Science Center (WNSC) provides low-energy short-lived radioactive ion beams of neutron-rich refractory elements to university researchers using the KEK isotope separator system (KISS). In FY2021, five experiments were executed. Due to the restrictions of COVID-19, only a limited number of foreign collaborators participated in the experiments. Laser spectroscopy of neutron-rich refractory elements, including long-lived isotopes, is uniquely performed using the resonant laser ionization scheme of KISS and the capability of isobaric separation of the MRTOF device.

The team of WNSC leads comprehensive mass measurements of all available nuclides at RIKEN RIBF using multiple MRTOF mass spectrographs. Newly installed beta-ToF detectors to the GARIS-II MRTOF and the ZeroDegree MRTOF setups eliminate background events and allow for the determination of the lifetime of short-lived nuclides.

The WNSC announced two press releases; one is for discovering a new uranium isotope,  $^{241}\text{U}$ , the first neutron-rich new uranium isotope in the last 40 years. The other is for the disappearance of a neutron magic number,  $N = 34$ , for titanium and vanadium isotopes.

The WNSC plans to extend the present KISS facility to investigate the nuclides in the neutron-rich actinides using the multinucleon transfer reactions of actinide targets to study the origin of uranium. Some pilot developments are in progress, particularly for a large He gas catcher with a radiofrequency wire curtain device.

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## List of Publications & Presentations

### Publications

#### [Original Papers]

- T. Niwase, W. Xian, M. Wada, M. Rosenbusch, S. Chen, A. Takamine, J. Liu, S. Iimura, D. Hou, S. Yan, H. Ishiyama, H. Miyatake, S. Nishimura, D. Kaji, K. Morimoto, Y. Hirayama, Y. X. Watanabe, S. Kimura, P. Schury, and H. Wollnik, "Development of a  $\beta$ -TOF detector: An enhancement of the  $\alpha$ -TOF detector for use with  $\beta$ -decaying nuclides," *Prog. Theor. Exp. Phys.* **2023**, 031H01 (2023).
- T. Niwase, Y. X. Watanabe, Y. Hirayama, M. Mukai, P. Schury, A. N. Andreyev, T. Hashimoto, S. Iimura, H. Ishiyama, Y. Ito, S. C. Jeong, D. Kaji, S. Kimura, H. Miyatake, K. Morimoto, J. -Y. Moon, M. Oyaizu, M. Rosenbusch, A. Taniguchi, and M. Wada, "Discovery of new isotope  $^{241}\text{U}$  and systematic high-precision atomic mass measurements of neutron-rich Pa-Pu nuclei produced via multinucleon transfer reactions," *Phys. Rev. Lett.* **130**, 132502-1–6 (2023).
- T. Niwase, P. Schury, M. Wada, and SHE-Mass Collaborators, "Accurate event assignment from the decay-correlated mass measurement of the superheavy nuclide  $^{257}\text{Db}$ ," *J. Nucl. Radiochem. Sci.* **23**, 1–4 (2023).
- M. Rosenbusch, M. Wada, S. Chen, A. Takamine, S. Iimura, D. Hou, W. Xian, S. Yan, P. Schury, Y. Hirayama, Y. Ito, H. Ishiyama, S. Kimura, T. Kojima, J. Lee, J. Liu, S. Michimasa, H. Miyatake, M. Mukai, J. Y. Moon, S. Nishimura, S. Naimi, T. Niwase, T. Sonoda, Y. X. Watanabe, and H. Wollnik, "The new MRTOF mass spectrograph following the ZeroDegree spectrometer at RIKEN's RIBF facility," *Nucl. Instrum. Methods Phys. Res. A* **1047**, 167824 (2023).
- S. Iimura, M. Rosenbusch, A. Takamine, Y. Tsunoda, M. Wada, S. Chen, D. S. Hou, W. Xian, H. Ishiyama, S. Yan, P. Schury, H. Crawford, P. Doornenbal, Y. Hirayama, Y. Ito, S. Kimura, T. Koiwai, T. M. Kojima, H. Koura, J. Lee, J. Liu, S. Michimasa, H. Miyatake, J. Y. Moon, S. Naimi, S. Nishimura, T. Niwase, A. Odahara, T. Otsuka, S. Paschalis, M. Petri, N. Shimizu, T. Sonoda, D. Suzuki, Y. X. Watanabe, K. Wimmer, and H. Wollnik, "Study of the  $N = 32$  and  $N = 34$  shell gap for Ti and V by the first high-precision multireflection time-of-flight mass measurements at BigRIPS-SLOWRI," *Phys. Rev. Lett.* **130**, 012501-1–6 (2023).
- Y. Hirayama, M. Mukai, Y. X. Watanabe, P. Schury, H. Nakada, J. Y. Moon, T. Hashimoto, S. Iimura, S. C. Jeong, M. Rosenbusch, M. Oyaizu, T. Niwase, M. Tajima, A. Taniguchi, M. Wada, and H. Miyatake, "In-gas-cell laser resonance ionization spectroscopy of  $^{200,201}\text{Pt}$ ," *Phys. Rev. C* **106**, 034326-1–11 (2022).
- T. Aoki, Y. Hirayama, H. Ishiyama, S. C. Jeong, S. Kimura, Y. Makida, H. Miyatake, M. Mukai, S. Nishimura, K. Nishio, T. Niwase, T. Ogawa, H. Okuno, M. Rosenbusch, P. Schury, Y. Watanabe, and M. Wada, "Design report of the KISS-II facility for exploring the origin of uranium," arXiv:2209.12649.

#### [Review Article]

- 和田道治, 「超重元素同位体の精密質量測定」, *Isotope News* 10月号 (No.783), 6–10 (2022).

### Presentations

#### [International Conferences/Workshops]

- Y. Watanabe (invited), "Spectroscopy of neutron-rich nuclei produced in multinucleon transfer reactions at KISS," Physics with SPIRAL2 Heavy Ion Beams, Caen, France, December 12–16, 2022.
- Y. Watanabe (oral), "Experimental studies of neutron-rich nuclei around  $N = 126$  and beyond at KEK isotope separation system," 16th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG16), Ha Noi, Viet Nam, October 25–28, 2022.
- M. Wada (invited), "Comprehensive mass measurements of short-lived nuclides," 16th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG16), Ha Noi, Viet Nam, October 25–28, 2022.
- T. Niwase (poster), "Technique of decay correlated mass measurement via multi-reflection time-of-flight mass spectrograph with an  $\alpha/\beta$ -TOF detector," 19th International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS), Daejeon, Korea, October 3–7, 2022.
- M. Rosenbusch (poster), "High-precision MRTOF mass measurements of radioactive isotopes at RIKEN's RIBF facility: Recent projects for ion selection, wideband mass accuracy, and mirror potentials," 19th International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS), Daejeon, Korea, October 3–7, 2022.
- P. Schury (invited), "Multi-reflection time-of-flight mass spectroscopy of superheavy nuclides," 19th International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS), Daejeon, Korea, October 3–7, 2022.
- M. Rosenbusch (oral), "Exploring exotic nuclei by high-precision MRTOF mass measurements: The new ion catcher and mass spectrograph at RIKEN's RIBF factory," Trapped Charged Particles Conference 2022 (TCP 2022), Glashütten, Germany, September 25–30, 2022.

#### [Domestic Conferences/Workshops]

- 向井もも (口頭発表), 「安定イリジウム同位体周辺核の直接質量測定」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.
- M. Rosenbusch (口頭発表), 「Recent atomic mass measurements of radioactive species using the new ZD-MRTOF system at BigRIPS/RIKEN」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.
- 庭瀬暁隆 (口頭発表), 「超重核の直接質量測定」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.
- 庭瀬暁隆 (口頭発表), 「超重・超アクチノイド核の精密質量測定」, 2022 重元素化学研究会, あわら市, 2023 年 3 月 20–21 日.
- Y. Watanabe (invited), 「中性子過剰アクチノイド実験への展望」, RIBF ULIC ミニワークショップ「理論と実験で拓く中性子過剰核の核分裂」, Wako, Japan, February 16–17, 2023.

- 平山賀一 (招待講演), 「KISS での核分光研究」, 中世捕獲反応で迫る宇宙の元素合成, 文京区 (東京大学), 2023 年 2 月 9–10 日.
- 渡邊裕 (口頭発表), 「KISS での核分光研究」, 令和 4 年度専門研究会「短寿命 RI を用いた核分光と核物性研究 IX」, オンライン, 2023 年 1 月 11 日.
- M. Rosenbusch (oral), “New nuclear masses, recent and present developments, and future opportunities of the MRTOF-MS at the ZeroDegree spectrometer,” RIBF Users Meeting, Online, September 20–22, 2022.
- Y. Watanabe (oral), “Present status and future plan of KISS,” RIBF Users Meeting, Online, September 20–22, 2022.
- T. Niwase (oral), “First direct mass measurement of superheavy nuclide via MRTOF-MS equipped with  $\alpha$ -TOF detector,” RIBF Users Meeting, Online, September 20–22, 2022.
- 庭瀬暁隆 (招待講演), 「精密質量と崩壊事象の相関測定法の開拓による超重元素の直接質量測定」, 日本放射化学会第 66 回討論会 (2022), 文京区 (東京大学), 2022 年 9 月 16 日.
- 庭瀬暁隆 (口頭発表), 「精密質量測定による新同位体  $^{241}\text{U}$  の発見」, 日本物理学会 2022 年秋季大会, 岡山市 (岡山理科大学) & オンライン, 2022 年 9 月 6–9 日.
- 平山賀一 (口頭発表), 「KISS での低温ヘリウムガスセル開発」, 日本物理学会 2022 年秋季大会, 岡山市 (岡山理科大学) & オンライン, 2022 年 9 月 6–9 日.
- M. Rosenbusch (invited), “High-precision mass measurements for astrophysics and nuclear structure studies using the new ZD-MRTOF system,” 宇核連-RCNP 研究会「宇宙核物理の展開」, UKAKUREN-RCNP Conference on AstroNuclear Physics (ANP2022), Toyonaka, Japan & Online, July 20–21, 2022.
- Y. Watanabe (oral), “Production of neutron-rich nuclei around  $N = 126$  and beyond using multinucleon transfer reactions at KISS project,” Physics of RI: Recent progress and perspectives, Wako, Japan & Online, May 30–June 1, 2022.

#### [Seminars]

- M. Rosenbusch, “A first review of the SLOWRI-MRTOF mass spectrograph following the ZeroDegree spectrometer at BigRIPS,” The 315th RIKEN RIBF Nuclear Physics Seminar, Wako, Japan, February 14, 2023.
- M. Wada, “Study of the origins of heavy elements via comprehensive mass measurements of short-lived nuclides/重元素の起源と短寿命核の質量測定,” 高エネルギー加速器科学セミナー (2022 High Energy Accelerator Science Seminar), Online, June 8, 2022.

#### Press Releases

- チタン・バナジウム中性子過剰同位体で新魔法数の消失を観測～精密質量測定による原子核構造のより深い理解に期待～, KEK, RIKEN, Osaka University, 2023 年 1 月 6 日, <https://www.kek.jp/ja/press/202301061400/>.
- 40 年ぶりに中性子過剰なウラン同位体を新発見～ウランの起源解明に期待～, KEK, RIKEN, 2023 年 3 月 31 日, <https://www.kek.jp/ja/press/202304010000/>.

#### Awards

- 庭瀬暁隆, 「第 17 回 (2023 年) 日本物理学会実験核物理領域: 若手奨励賞 (Young Scientist Award of the Physical Society of Japan), 第 29 回原子核談話会新人賞」, 2023 年 3 月.
- T. Niwase, “RIBF Users Group Thesis Award,” September 2022.
- 庭瀬暁隆, 「日本放射化学会奨励賞」, 2022 年 9 月.
- 和田道治, 宮武宇也, 「2021 年度高エネルギー加速器科学研究奨励会西川賞」, 2022 年 5 月.