

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, nuclear astrophysics research, and interdisciplinary studies using short-lived radioactive nuclides. WNSC operates the KEK Isotope Separation System (KISS), an electromagnetic isotope separator featuring elemental selectivity from resonant laser ionization in a gas catcher. The KISS facility uniquely provides various neutron-rich isotopes of refractory elements and the nuclei in the vicinity of the neutron magic numbers $N = 126$ and $N = 152$ via multinucleon transfer reactions to users from universities. Optical and β - γ spectroscopy and mass spectrometry have been applied to these neutron-rich nuclear beams for nuclear structure and nuclear astrophysical studies. WNSC leads comprehensive mass measurements of all nuclides available 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 KISS—the masses of more than 400 nuclides, including dozens of first masses, were measured. An upgrade plan, KISS-1.5, has been launched and is currently underway to study 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 upgrade facility, KISS-1.5

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 separation system (KISS). Laser spectroscopy of neutron-rich refractory elements, including long-lived isomers, is uniquely performed using the resonant laser ionization scheme of KISS and the MRTOF device's capability of isobaric separation. In FY2024, we carried out a precision mass measurement experiment using the MRTOF-MS for nuclei in the vicinity of $N = 126$, produced via multinucleon transfer reactions with a ^{136}Xe beam and a ^{198}Pt target.

The WNSC team leads comprehensive mass measurements of all nuclides available at RIKEN RIBF using three MRTOF mass spectrographs: GARIS-II MRTOF, ZeroDegree MRTOF, and KISS MRTOF. The MRTOF connected to GARIS-II has been making systematic measurements of neutron-rich nuclides produced by offline fission sources. The ZeroDegree MRTOF station has had a very successful year of commensal measurement campaigns with the in-beam gamma measurement group and the addition of the GARI detector station for analyzing the unstopped beam portion after the gas cell. The MRTOF at KISS has also had mass measurements steadily approaching the $N = 126$ region.

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

A. Yamaguchi, Y. Shigekawa, H. Haba, H. Kikunaga, K. Shirasaki, M. Wada, and H. Katori, "Laser spectroscopy of triply charged ^{229}Th isomer for a nuclear clock," *Nature* **629**, 62–66 (2024).

- Y. Shimizu, T. Kubo, T. Sumikama, N. Fukuda, H. Takeda, H. Suzuki, D. S. Ahn, N. Inabe, K. Kusaka, M. Ohtake, Y. Yanagisawa, K. Yoshida, Y. Ichikawa, T. Isobe, H. Otsu, H. Sato, T. Sonoda, D. Murai, N. Iwasa, N. Imai, Y. Hirayama, S. C. Jeong, S. Kimura, H. Miyatake, M. Mukai, D. G. Kim, E. Kim, and A. Yagi, “Production of new neutron-rich isotopes near the $N = 60$ isotones ^{92}Ge and ^{93}As by in-flight fission of a 345 MeV/nucleon ^{238}U beam,” *Phys. Rev. C* **109**, 044313 (2024).
- Y. Hirayama and KISS Collaboration, “Progress of isotope separators and KISS facility for the study of exotic nuclei,” *Eur. Phys. J. Spec. Top.* **233**, 1209–1223 (2024).
- T. T. Yeung, A. I. Morales, J. Wu, M. Liu, C. Yuan, S. Nishimura, V. H. Phong, N. Fukuda, J. L. Tain, T. Davinson, K. P. Rykaczewski, R. Yokoyama, T. Isobe, M. Niikura, Zs. Podolyák, G. Alcalá, A. Algora, J. M. Allmond, J. Agramunt, C. Appleton, H. Baba, R. Caballero-Folch, F. Calvino, M. P. Carpenter, I. Dillmann, A. Estrade, T. Gao, C. J. Griffin, R. K. Grzywacz, O. Hall, Y. Hirayama, B. M. Hue, E. Ideguchi, G. G. Kiss, K. Kokubun, F. G. Kondev, R. Mizuno, M. Mukai, N. Nepal, M. N. Nurhafiza, S. Ohta, S. E. A. Orrigo, M. Pallàs, J. Park, B. C. Rasco, D. Rodríguez-García, H. Sakurai, L. Sexton, Y. Shimizu, H. Suzuki, A. Vitéz-Sveicz, H. Takeda, A. Tarifeno-Saldivia, A. Tolosa-Delgado, J. A. Victoria, Y. X. Watanabe, and J. M. Yap, “First exploration of monopole-driven shell evolution above the $N = 126$ shell closure: New millisecond isomers in ^{213}Tl and ^{215}Tl ,” *Phys. Rev. Lett.* **133**, 072501 (2024).
- S. Kimura, M. Wada, H. Haba, H. Ishiyama, S. Ishizawa, Y. Ito, T. Niwase, M. Rosenbusch, P. Schury, and A. Takamine, “Comprehensive mass measurement study of ^{252}Cf fission fragments with MRTOF-MS and detailed study of masses of neutron-rich Ce isotopes,” *Phys. Rev. C* **110**, 045810 (2024).
- M. Mazzocco, N. Keeley, A. Lagni, A. Boiano, C. Boiano, M. La Commara, C. Manea, C. Parascandolo, D. Pierroutsakou, C. Signorini, E. Strano, D. Torresi, H. Yamaguchi, D. Kahl, P. Di Meo, J. Grebosz, A. Guglielmetti, Y. Hirayama, N. Imai, H. Ishiyama, N. Iwasa, S. C. Jeong, H. M. Jia, Y. H. Kim, S. Kimura, S. Kubono, G. La Rana, C. J. Lin, H. Miyatake, M. Mukai, T. Nakao, M. Nicoletto, S. Pigliapoco, K. Rusek, Y. Sakaguchi, A. M. Sánchez-Benítez, F. Soramel, T. Teranishi, N. Toniolo, Y. Wakabayashi, Y. X. Watanabe, L. Yang, Y. Y. Yang, and H. Q. Zhang, “Inclusive ^7Be production cross section in the $^8\text{B} + ^{208}\text{Pb}$ system at the Coulomb barrier,” *Phys. Rev. C* **110**, 044611 (2024).
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- J. L. Chen, H. Watanabe, P. M. Walker, Y. Hirayama, Y. X. Watanabe, M. Mukai, C. F. Jiao, M. Ahmed, M. Brunet, T. Hashimoto, S. Ishizawa, F. G. Kondev, G. J. Lane, Yu. A. Litvinov, H. Miyatake, J. Y. Moon, T. Niwase, J. H. Park, Zs. Podolyak, M. Rosenbusch, P. Schury, M. Wada, and F. R. Xu, “Direct observation of β and γ decay from a high-spin long-lived isomer in ^{187}Ta ,” *Phys. Rev. C* **111**, 014304 (2025).
- M. Mukai, Y. Hirayama, P. Schury, Y. X. Watanabe, T. Hashimoto, N. Hinohara, S. C. Jeong, H. Miyatake, J. Y. Moon, T. Niwase, M. Reponen, M. Rosenbusch, H. Ueno, and M. Wada, “Evidence for shape transitions near ^{189}W through direct mass measurements,” *Phys. Rev. C* **111**, 014322 (2025).
- Y. Shigekawa, A. Yamaguchi, N. Sato, A. Takamine, M. Wada, and H. Haba, “Development of an RF-carpet gas cell coupled to the RIKEN gas-filled recoil ion separator for chemistry of superheavy elements,” *Nucl. Instrum. Methods Phys. Res. A* **1075**, 170421 (2025).

[Review Article]

Peter Schury, 伊藤由太, 和田道治, 「超重核研究のための多重反射型飛行時間測定式質量分光器」, 日本物理学会誌 **80**, 72–78 (2025).

[Proceedings]

- Y. Hirayama, M. Mukai, Y. Watanabe, P. Schury, T. Niwase, H. Choi, T. Hashimoto, S. Iimura, S. C. Jeong, H. Miyatake, J. Y. Moon, H. Nakada, M. Oyaizu, M. Rosenbusch, A. Takamine, M. Tajima, A. Taniguchi, and M. Wada, “In-gas-cell laser ionization spectroscopy at KISS,” *Interactions* **245**, (2024), 41.
- Y. Watanabe, Y. Hirayama, M. Mukai, T. Niwase, P. Schury, M. Rosenbusch, H. Ishiyama, S. C. Jeong, H. Miyatake, M. Wada, S. Kimura, S. Iimura, J. Y. Moon, T. Hashimoto, A. Taniguchi, and KISS collaboration, “Spectroscopy of neutron-rich nuclei produced by multinucleon transfer reactions at KISS,” *EPJ Web of Conferences* **306**, (2024), 01016.

Presentations

[International Conferences/Workshops]

- M. Wada (invited), “An expedition to neutron-rich heavy and superheavy nuclides,” International Workshop on Nuclear Physics Related to HIAF, Huizhou, China, April 16–19, 2024.
- Y. Hirayama (oral), “In-gas-cell laser ionization spectroscopy of heavy refractory nuclei produced at KISS,” Merger of the Poznan Meeting on Lasers and Trapping Devices in Atomic Nuclei Research and the International Conference on Laser Probing (PLATAN2024), Jyväskylä, Finland, June 9–14, 2024.
- Y. Watanabe (invited), “Future plan of KISS for spectroscopy of neutron-rich actinoids,” International workshop MNT2024—Exploring the Heavy Exotic Neutron-rich Nuclides via Multinucleon Transfer Reactions (MNT2024), Wako, Japan, July 2–5, 2024.
- Y. Hirayama (invited), “KISS for nuclear spectroscopy of MNT products,” International Workshop MNT2024—Exploring the Heavy Exotic Neutron-rich Nuclides via Multinucleon Transfer Reactions (MNT2024), Wako, Japan, July 2–5, 2024.
- S. Kimura (invited), “Current status and prospects of MNT study with helium gas-cell + MRTOF system towards $N = 126$ and 152,” International Workshop MNT2024—Exploring the Heavy Exotic Neutron-rich Nuclides via Multinucleon Transfer Reactions (MNT2024), Wako, Japan, July 2–5, 2024.
- M. Mukai (invited), “The progress of in-gas-cell laser ionization spectroscopy of neutron-rich tungsten isotopes,” International Workshop

MNT2024—Exploring the Heavy Exotic Neutron-rich Nuclides via Multinucleon Transfer Reactions (MNT2024), Wako, Japan, July 2–5, 2024.

- Y. Hirayama (invited), “Nuclear spectroscopy of the nuclei in the vicinity of $N = 126$ at KISS,” Structure of Neutron-rich Matter Revealed by Beta Decay, Wako, Japan, July 29–30, 2024.
- Y. Watanabe (invited), “Spectroscopy of Neutron-Rich Nuclei Produced in Multinucleon Transfer Reactions at KISS,” 14th International Conference on Nucleus Nucleus Collisions (NN2024), Vancouver, Canada, August 18–23, 2024.
- P. Schury (invited), “Analyzing superheavy element nuclides with a multi-reflection time-of-flight mass spectrograph,” 14th International Conference on Nucleus Nucleus Collisions (NN2024), Vancouver, Canada, August 18–23, 2024.
- Y. Watanabe (oral), “KISS-1.5 Outline and timeline,” SSRI-PNS Collaboration Meeting 2024 on Zoom, Online, September 4–5, 2024.
- Y. X. Watanabe (oral), “TOPTIER Subproject 1 (RI production) Diverse RI production techniques at RIBF,” Korea-Japan Symposium on TOPTIER Platform in Extreme Rare Isotope Science, Seoul, Korea, December 16–17, 2024.
- Y. X. Watanabe (invited), “KISS project—Spectroscopy of neutron-rich nuclei around $N = 126$ and actinides,” RNCP-CENUM-OMEG Symposium on Nuclear Structure, Reaction, and Astrophysics (NuSRAP2024), Ibaraki, Japan, December 18–20, 2024.
- Y. X. Watanabe (invited), “Nuclear Physics at WNSC, IPNS, KEK,” TRIUMF-KEK Scientific Symposium 2025, Tsukuba, Japan, January 29–31, 2025.
- Y. Hirayama (oral), “In-gas-cell laser ionization spectroscopy of the nuclei in the vicinity of $N = 126$ at KISS,” Single-particle and Collective Motions from Nuclear Many-body Correlation (PCM2025), Aizu, Japan, March 4–7, 2025.
- P. Schury (invited), “Development of a low-cost HV system for HYPATIA,” HYPATIA Workshop, London, UK, March 20, 2025.

[Domestic Conferences/Workshops]

- 渡辺裕 (口頭発表), 「KISS の将来計画」, 素核研の発展—現行計画から将来計画へ—, 熱海市 (ハートピア熱海), 2024 年 4 月 25–26 日.
- 平山賀一 (口頭発表), 「KISS のこれまでの成果と現状」, 素核研の発展—現行計画から将来計画へ—, 熱海市 (ハートピア熱海), 2024 年 4 月 25–26 日.
- 和田道治 (招待講演), 「原子質量測定と重元素の起源」, 原子衝突学会第 49 回年会, 奈良市 (奈良女子大学), 2024 年 8 月 7–9 日.
- 平山賀一 (招待講演), 「KISS での精密核分光実験による r 過程重元素合成研究」, 核子系と電子系における対相関と対凝縮相, 吹田市 (大阪大学), 2024 年 9 月 9–11 日.
- 平山賀一 (招待講演), 「KISS での核分光実験で迫る重元素合成の謎」, 日本放射化学会第 68 回討論会, 静岡市 (静岡大学), 2024 年 9 月 23–25 日.
- 平山賀一 (招待講演), 「重元素合成の天体環境解明を目指して~KISS, KISS-1.5 での核分光」, 筑波大学 宇宙史研究センター 2024 年度 第 2 回構成員会議・成果報告&交流会, つくば市 (筑波大学), 2024 年 12 月 16 日.
- 渡辺裕 (口頭発表), 「KISS での核分光研究の現在と将来」, 令和 6 年度専門研究会「短寿命 RI を用いた核分光と核物性研究 XI」, 泉南郡 (京都大学複合原子力科学研究所), 2024 年 12 月 26 日.
- Y. X. Watanabe (invited), “Present status and future plan of KISS,” RIBF Users Meeting 2025, Wako (RIKEN), Japan, January 21, 2025.
- W. Xian (oral), “Recent status of ZD-MRTOF and precision mass of neutron-rich $A \sim 90$ nuclei constrain element abundances,” RIBF Users Meeting 2025, Wako (RIKEN), Japan, January 21, 2025.
- 渡辺裕 (招待講演), 「KISS-1.5 計画 宇宙の進化と物質の起源の解明を目指して」, 宇核連研究会 2025~元素の起源天体と星の化学進化~, つくば市 (KEK), 2025 年 3 月 24–26 日.
- P. Schury (招待講演), 「Current status and future plans for MRTOF at WNSC」, 宇核連研究会 2025~元素の起源天体と星の化学進化~, つくば市 (KEK), 2025 年 3 月 24–26 日.
- 木村創大 (招待講演), 「 ^{84}Mo 近傍陽子過剰核の精密質量測定と rp 過程への影響」, 宇核連研究会 2025~元素の起源天体と星の化学進化~, つくば市 (KEK), 2025 年 3 月 24–26 日.
- 向井もも (招待講演), 「KISS での核分光」, 宇核連研究会 2025, つくば市 (KEK), 2025 年 3 月 24–26 日.

[Seminars]

- 平山賀一, 「原子核研究で探る宇宙での元素合成/Exploring nucleosynthesis in the universe from nuclear」, 総研大高エネルギー加速器研究機構加速器科学セミナー, つくば市 (KEK), 2024 年 7 月 17 日.
- 和田道治, 「宇宙でつくられた大量の金の秘密とまだ見ぬ『安定の島』」, おとなのサイエンスカフェ 第 8 夜, つくば市 (つくばセンター co-en), 2024 年 8 月 9 日.
- 渡辺裕, 「KISS-1.5 計画 宇宙の進化と物質の起源の解明を目指して」, 第 151 回素核研運営会議オープンセッション, つくば市 (KEK), 2024 年 9 月 12 日.
- Yoshikazu Hirayama, “Nuclear spectroscopy at KISS,” ISLODE seminar, Geneva, Switzerland, October 25, 2024.

Award

- 庭瀬暁隆, “Discovery of new isotope ^{241}U and systematic high-precision atomic mass measurements of neutron-rich Pa-Pu nuclei produced via multinucleon transfer reactions,” 宇宙核物理連絡協議会 第 1 回 若手奨励賞.