Accelerator Applications Research Division Nuclear Transmutation Data Group

1. Abstract

The Nuclear Transmutation Data Group, which had been established in 2014, was reformed in 2023. The Group was orginally designed to conduct a part of the ImPACT project entitled "Reduction and Resource Recycling of High-level Radioactive Waste through Nuclear Transmutation." In the project, nuclear reaction data for Long-lived Fission Products (LLFP) were systematically obtained via inverse kinematics with radioactive isotope beams delivered at the RIBF facility. The data obtained were utilized to construct a new nuclear reaction database of JAEA "JENDLE/ImPACT-2018." In parallel, experiments of muon capture reaction for LLFP's were conducted at RCNP Osaka University, RAL and J-PARC.

After the ImPACT project finished in 2019, the Group continues to provide the nuclear reaction data to solve the raioactive waste problem as well as to meet other nuclear engineering needs and social demands.

2. Major Research Subjects

- (1) Study of nuclear reactions via inverse kinematics with long-lived nuclear beams at RIBF and development of its applications.
- (2) Study of muon capture reaction and development of its applications.
- (3) Development of new radioactive isotope beams and of new methods in reaction studies.

3. Summary of Research Activity

(1) Nuclear data with fast radioactive isotope beams

The ImPACT project boosted up reaction study with LLFP's and physics runs for study of spallation reaction were successfully organized at RIBF in 2015–2017. The reaction data obtained with both fast and energy-degraded beams at RIBF encouraged the nuclear data group of JAEA, and a new database called "JENDLE/ImPACT-2018" has been released. The new database has been generated by a newly developed reaction model "DEURACS" which treats deuteron-induced reactions. DEURACS reproduces very well cross section data, and much better than other reaction models. A simulation code "PHITS" has been re-coordianted to use the database information.

Our activity has been demonstrated and recognized internationally. In December 2018, Hideaki Otsu, was invited to join Technical Meeting of IAEA, "Novel Multidisciplinary Applications with Unstable Ion Beams and Complementary Techniques." In November 2020, Hideaki Otsu organized a domestic conference of "RIKEN Symposium on Nuclear Data 2020."

At the end of fiscal year 2021, the spallation reaction data with ⁹⁹Tc beam was obtained and a secondary beam test for ²³⁷Np production was conducted. The data analysis is in progress. In the experiment campaing, a new ion-chamber with Xe based gas, which was proposed by the Group, was successfully operated to identify heavy secondary beams.

Two new projects have been discussed with JAEA. One is DPA measurement to develop radiation resistant materials, where heavy ion primary beams such as a uranium beam will be irradiated to give a high LET to the materials. The other is study of the Pb/Bi spallation reactions in inverse kinematics with Pb/Bi beams, of which data is useful in development of Pb/Bi targets for ADS.

Collaboration with the Super-Kaiokande group has been formed to obtain the spallation data for ¹⁶O, which is necessary to precisely estimate backgrounds in detecting supernova relic neutrino. Intensive discussions have been made under the collobation including reaction theorists.

The Group has joined JST ERATO "Sekiguchi Three Nuclear Force Project" since October 2023, and has been in charge of the nuclear data applications for society, in collaboation with JAEA nuclear data group.

(2) Muon capture reaction

The muon capture reaction is a unique "tool" for nuclear transmutation and other applications, as well as for study of dynamics in hot nuclei.

In the ImPACT project, the muon capture program started at RCNP, Osaka University in 2016 and the data for Pd isotopes were successfully obtained in 2017–2019 via in-beam method with c.w. beams, and via activation method with pulsed beams at J-PARC and ISIS-RAL/RIKEN facilities. In 2023, the ISIS data was published in Physical Review C. In this work, the in-beam activation method was firstly employed.

Lifetime of muonic atoms is essenially important in deducing muon capture rate. The isotope dependence of the lifetime was studied at J-PARC MLF in 2023–2024. The data analysis is in progress. The measurement was based on an achievement of detector development for muonic X-ray and de-excitation gamma-ray measurements. A new calibiration method for Ge detectors was successfully developed and the results were published in PTEP and NIM 2023.

Muon capture reaction can be uniquely applied to radioactive isotope production. Compared with other reactions, the range of final reaction products in the muon capture is rather limited and their proton numbers are different from those in target. Hence, high specific activity and simple chemical separation treatment are achieved. The applications for production of ^{99m}Tc and ²²⁵Ac were discussed in Journal of Radioanalytical and Nuclear Chemistry in 2024.

To create a muon capture database is being proposed by the Group and being discussed with with the nuclear data community in Japan.

Members

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List of Publications & Presentations

Publications

[Original Papers]

- N. Imai *et al.*, "Neutron capture reaction cross-section of ⁷⁹Se through the ⁷⁹Se(d, p) reaction in inverse kinematics," Phys. Lett. B **850**, 138470 (2024).
- M. Niikura *et al.*, "Measurement of the production branching ratios following nuclear muon capture for palladium isotopes using the in-beam activation method," Phys. Rev. C **109**, 014328 (2024).
- R. Mizuno *et al.*, "Response of germanium detectors for high-energy γ -rays by ²⁷Al (p, γ) ²⁸Si at $E_p = 992$ keV," Prog. Theo. Exp. Phys. **2023**, 053H01 (2023).
- R. Mizuno *et al.*, "Development of wide range photon detection system for muonic X-ray spectroscopy," Nucl. Instrum. Methods Phys. Res. A **1060**, 169029 (2024).
- T. Matsuzaki and H. Sakurai, "⁹⁹Mo production via ⁹⁹Tc (μ⁻, ν)⁹⁹Mo reaction with recycled ⁹⁹Tc," J. Radioanal. Nucl. Chem., published online (March 18, 2024). DOI:10.1007/s10967-024-09418-5.
- T. Matsuzaki and H. Sakurai, "²²⁵Ac production via ²²⁶Ra(μ^- , ν)²²⁵Fr reaction with ²²⁶Ra target," J. Radioanal. Nucl. Chem., published online (May 10, 2024). DOI:10.1007/s10967-024-09514-6.
- B. A. Hofmann *et al.*, "An arrowhead made of meteoritic iron from the late Bronze Age settlement of Mörigen, Switzerland and its possible source," J. Archaeol. Sci. **157**, 105827 (2023). DOI:10.1016/j.jas.2023.105827.
- S. Kawase *et al.*, "Effect of large-angle incidence on particle identification performance for light-charged ($Z \le 2$) particles by pulse shape analysis with a pad-type nTD silicon detector," Nucl. Instrum. Methods Phys. Res. A **1059**, 168984 (2024). DOI:10.1016/j.nima.2023.168984.
- M. Heines *et al.*, "Muonic X-ray spectroscopy on implanted targets," Nucl. Instrum. Methods Phys. Res. B **541**, 173 (2023). DOI:10.1016/j.nimb.2023.05.036.
- S. Manabe *et al.*, "Emissions of Hydrogen Isotopes from the Nuclear Muon Capture Reaction in ^{nat}Si," EPJ Web Conf. **284**, 01029 (2023). DOI:10.1051/epjconf/202328401029.

[Proceedings]

- M. Niikura et al., "Muon nuclear data," Proc. Joint Symp. on Nuclear Data and PHITS 2023, arXiv:2403.19965 (2024).
- R. Matsumura, H. Otsu, H. Wang, and X. Sun, "New analytical model for momentum distribution on the spallation reaction in inverse kinematics," Proceedings of the 2022 Symposium on Nuclear Data, JAEA-Conf 2023-001. DOI:10.11484/jaea-conf-2023-001.

Presentations

[International Conferences/Workshops]

- H. Otsu (invited), "Direct measurement of proton and deuteron induced reaction cross sections on long lived fission products using inverse kinematics," The 1st Conference of Accelerator-based Sciences and Technology, Serpong, Indonesia, February 19–22, 2024.
- M. Niikura (invited), "Muon nuclear data," Workshop on Recent Advances in Nuclear Data Studies, Hawaii, US, November 26–December 1, 2023.
- R. Mizuno (invited), "In-beam activation measurement of muon nuclear capture reaction on Si isotopes," The workshop on frontier nuclear studies with gamma-ray spectrometer arrays (gamma24), Osaka, Japan, March 26–28, 2024.

- H. Sakurai (oral) and T. Matsuzaki, "⁹⁹Mo production via ⁹⁹Tc (μ^- , ν)⁹⁹Mo reaction with recycled ⁹⁹Tc," The 11th International Conference on Isotopes (11ICI), Saskatoon (TCU Place), Saskatchewan, Canada, July 23–27, 2023.
- H. Sakurai (oral) and T. Matsuzaki, "²²⁵Ac production via ²²⁶Ra(μ^- , ν)²²⁵Fr reaction with ²²⁶Ra target," The 11th International Conference on Isotopes (11ICI), Saskatoon (TCU Place), Saskatchewan, Canada, July 23–27, 2023.
- R. Matsumura (oral), "Isotopic production of ⁹⁹Tc via proton- and deuteron-induced reactions and new analytical model for its longitudinal momentum distribution," The 2023 Fall Meeting of the Division of Nuclear Physics of the APS and JPS (HAWAII2023), Hawaii, USA, November 26–December 1, 2023.
- C. Fukushima (oral), "Production cross section of ²³⁷Np," The 2023 Fall Meeting of the Division of Nuclear Physics of the APS and JPS (HAWAII2023), Hawaii, USA, November 26–December 1, 2023.
- R. Mizuno (oral), "Muon nuclear capture reaction on ^{28,29,30}Si," The 2023 Fall Meeting of the Division of Nuclear Physics of the APS and JPS (HAWAII2023), Hawaii, USA, November 26–December 1, 2023.
- R. Mizuno (oral), "Evaluation of muonic X-ray spectrometer with Compton suppressors in a wide energy range," Workshop for muon elemental analysis research 2023, online, April 27, 2023.
- R. Mizuno (poster), "Study of muon capture reaction on Si via in-beam muon activation," Advances in Radioactive Isotope Science (ARIS), Avignon, France, June 5–9, 2023.

[Domestic Conferences/Workshops]

新倉潤 (招待講演),「ミューオン核データ」, 2023 年度核データ研究会, 東海村 (東海村産業・情報プラザ iVil), 2023 年 11 月 15–17 日. 新倉潤 (招待講演),「ミューオン核データ」, ミューオン核データ研究会, 和光市 (理化学研究所), 2023 年 12 月 14 日.

- 新倉潤 (招待講演),「インビーム放射化法によるミューオン核データの測定」,日本原子力学会 2024 年春の年会,東大阪市 (近畿大学), 2024 年 3 月 26-28 日.
- 水野るり惠 (招待講演),「ミューオン原子核捕獲反応による生成核分岐比の測定」, Stop and Slow RI 12th meeting(SSRI), 豊島区 (立教大学), 2023 年 9 月 4-5 日.
- 松崎禎一郎(口頭発表),「ミュオンによる no-carrier added ²²⁵Ac の製造」, 第 14 回「Muon 科学と加速器研究」, つくば市(KEK), 2024 年 1 月 16–17 日.
- R. Matsumura (poster), "Isotopic production of high-radiotoxic nuclide ⁹⁰Sr via proton- and deuteron-induced reactions and new analytical model for its longitudinal momentum distributions," Symposium on Nuclear Data 2023, Tokai, Japan, November 15–17, 2023.
- C. Fukushima (poster), "Production cross section of ²³⁷Np," Symposium on Nuclear Data 2023, Tokai, Japan, November 15–17, 2023.

Award

Riku Matumura, Poster Award of Atomic Energy Society of Japan's Nuclear Data Section, 2023.

Outreach Activity

古川猛,「理化学研究所が高レベル放射性廃棄物の低減と資源化に向けた核変換研究を推進」,インタビュー記事,月刊コロンブス 2023 年 11 月号,東方通信社.