# Nuclear Science and Transmutation Research Division
# Nuclear Transmutation Data Research Group
# Muon Data Team

## 1. Abstract

Dr. Yoshio Nishina observed muons in cosmic rays in 1937. The muon is an elementary particle similar to electron and classified to lepton group. The muon has positive or negative electric charge, and the lifetime is 2.2 $\mu$sec. The negative muon ($\mu^-$) is 207 times heavier than the electron and behaves as a "heavy electron" in materials. The negative muon is captured by atomic orbits of nuclei to form a muonic atom and cascades down to the $1s$ orbit to make muon nuclear capture. The muon is combined with a proton in the nucleus to convert to a neutron and a neutrino. The muon nuclear capture reaction on a nucleus ($^{A}_{Z}N$) with the atomic number $Z$ and mass number $A$ generates the isotopes of $^{A-x}_{Z-1}N$ ($x = 0, 1, 2, 3, 4$) by emitting some neutrons in the reaction. The phenomenon is called "muon nuclear transmutation." The reaction branching ratio of $^{A}_{Z}N(\mu^-, xn\nu)^{A-x}_{Z-1}N$ reactions ($x = 0, 1, 2, 3, 4$) is one of important factors toward various applications with nuclear transmutation technique. From a viewpoint of the nuclear physic, the muon nuclear capture reaction is very unique and interesting. A high-energy compound nuclear state is suddenly generated in the nuclei associated with a weak conversion process of proton to neutron and neutrino. Many experimental results have been so far reported, however, the reaction mechanism itself is not well clarified. The research team aims at obtaining the experimental data to investigate the reaction mechanism of muon nuclear capture, and also at theoretical understanding on the nuclear capture reaction.

## 2. Major Research Subjects

(1) Experimental clarification on the mechanism of nuclear muon capture reaction
(2) Theoretical understanding on the nuclear muon capture reaction
(3) Interdisciplinary applications with the nuclear transmutation technique

## 3. Summary of Research Activity

There are two experimental methods to study the muon nuclear capture reaction. The first one is "muon in-beam spectroscopy method." The neutron and $\gamma$-ray emissions from the excited states of $^{A-x}_{Z-1}N$ nuclei are prompt events and are observed by the "muon in-beam spectroscopy method" with a DC muon beam. The reaction branching ratio is directly determined by measuring the neutron multiplicity in the reaction. The DC muon beam is available at the MuSIC (Muon Science Innovative Channel) muon facility in the Research Center for Nuclear Physics (RCNP) at Osaka University. The second one is "muon activation method" with the pulsed muon beam. The produced unstable nuclei $^{A-x}_{Z-1}N$ make $\beta^{+/-}$ decays. The $\gamma$-rays associated with $\beta^{+/-}$ decays to the daughter nuclei are observed in the experiment. The build-up curve of $\gamma$-ray yield at muon beam-on and the decay curve at beam-off are measured. Since the half-lives and decay branching ratios of $\beta^{+/-}$-$\gamma$ decays are known, the reaction branching ratios to the $^{A-x}_{Z-1}N$ nuclei are determined by the $\gamma$-ray yield curves. The pulsed muon beam is available at the RIKEN-RAL Muon Facility in the UK and J-PARC muon facility.

Muon nuclear capture reactions are studied on five isotope-enriched palladium targets ($^{104, 105, 106, 108, 110}$Pd) and five isotope-enriched zirconium targets ($^{90, 91, 92, 94, 96}$Zr) employing two experimental methods. By obtaining the experimental data on the Pd and Zr targets, the reaction mechanism is investigated experimentally, and the results are compared with appropriate theoretical calculations. The $^{107}$Pd is classified to a long-lived fission product (LLFP) and is contained in a spent nuclear fuel. The study of muon nuclear capture on the Pd and Zr targets is aiming at exploring a possible reaction path to make the nuclear transmutation of the Pd and Zr metal extracted from the spent nuclear fuel without an isotope separation process. This research was funded by the ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

### (1) Experiments with "muon in-beam spectroscopy method"

Muon nuclear capture reactions were investigated on five palladium targets ($^{104, 105, 106, 108, 110}$Pd) by employing the DC muon beam at MuSIC. The $\gamma$-ray and neutron in the muon nuclear capture reaction were measured with the time information relative to muon beam arrival. The measured neutron multiplicity gives the reaction branching ratio of $^{A}_{46}$Pd$(\mu^-, xn\nu)^{A-x}_{45}$Rh reactions, where $A = 104, 105, 106, 108, 110$ and $x = 0, 1, 2, 3, 4$.

Employing a newly built neutron spectrometer, the neutron was measured to obtain the reaction branching ratios of muon capture reactions on the Pd targets. We have constructed a neutron spectrometer named "Seamine": **S**cintillator **E**nclosure **A**rray for **M**uon **I**nduced **N**eutron **E**mission. The spectrometer consists of 21 liquid scintillation counters, 2 Ge $\gamma$-ray detectors, 7 $BaF_2$ counters. The Pd target, muon beam counters and muon degraders are placed at the center of spectrometer. The neutron counter is a BC-501A liquid scintillation counter with 20 cm diameter and 5 cm depth and is connected to a 5" photo multiplication tube (H4144-01). The total neuron detection efficiency is estimated 5%, where the distance is 4 cm from the target to neutron counters. The Ge $\gamma$-ray detectors are placed at 10 cm form the target, and the typical detection efficiency is 0.5% for 200 keV $\gamma$-ray. The $BaF_2$ counters are located beneath the target to detect fast $\gamma$-rays emitted from the compound nucleus formed in the reactions. Signals from the liquid scintillation counters are processed in a CAEN V1730B waveform digitizer (16 channel, 14 bit, 500 M samplings/sec.). The neuron-$\gamma$ discrimination is performed on-line during the experiment, and the detailed data analysis is conducted off-line after the experiment. The neutron energy spectrum is constructed in the digitizer. Signals from Ge detectors are also processed in the digitizer to obtain the energy and time spectrum of $\gamma$-rays associated with the reaction. Signals from the $BaF_2$ counters and muon beam counters are sent to the digitizer to make the fast timing signals.

We have established the muon in-beam spectroscopy method employing the "Seamine" spectrometer. The neutron data analysis is in progress to obtain the multiplicity, the energy and the TOF spectrum using start signals given by $\gamma$-rays detected in the $BaF_2$ counters. The $\gamma$-ray data gives the energy spectrum of prompt $\gamma$-rays and muonic X-rays originated from the $^{104,105,106,108,110}$Pd targets.

**(2) Experiments with “muon activation method” at the RIKEN-RAL Muon Facility**

We conducted the experiments on the muon nuclear capture employing the muon activation method at the RIKEN-RAL Muon Facility in the UK. The pulsed muon beam was irradiated on the $^{104,105,106,108,110}$Pd targets. The $\gamma$-rays were detected by a Ge detector located at the downstream of the Pd targets to maximize the detection efficiency. The build-up and decay curves of $\gamma$-ray intensities were measured associated with $\beta^{+/-}$ decays of produced unstable nuclei to daughter nuclei. The $\gamma$-ray-yield curves give the absolute radiation activity produced by the reaction, and the reaction branching ratios are determined for ${}^{A}_{46}\mathrm{Pd}(\mu^-, xn\nu)^{A-x}_{45}\mathrm{Rh}$ reactions. The decay curves of $\gamma$-rays from the produced nuclei with long half-lives were measured under low $\gamma$-ray background at an experimental apparatus built in a separated room. The detailed off-line data analysis is in progress.

**(3) Experiments with “muon activation method” at J-PARC muon facility**

The experiments employing the muon activation method were performed at J-PARC muon facility. The five isotope-enriched Pd targets ($^{104,105,106,108,110}$Pd) were irradiated by the pulsed muon beam, and the build-up and decay curves of $\gamma$-ray intensities were measured.

In addition to the Pd targets, the experiments on five isotope-enriched Zr target ($^{90,91,92,94,96}$Zr) were conducted to obtain the reaction branching ratios of ${}^{A}_{40}\mathrm{Zr}(\mu^-, xn\nu)^{A-x}_{39}\mathrm{Y}$ reactions, where $A = 90, 91, 92, 94, 96$. The obtained reaction branching ratios on the Pd and Zr targets are important to understand the reaction mechanism of muon nuclear capture. The $^{93}$Zr is one of the LLFP and is contained in a spent nuclear fuel. The experiment on the Zr targets is to explore a possibility to realize the nuclear transmutation of the Zr metal extracted from the spent nuclear fuel.

In order to obtain the reaction branching ratio of ${}^{107}_{46}\mathrm{Pd}(\mu^-, xn\nu)^{107-x}_{45}\mathrm{Rh}$ reactions, the muon activation experiment was performed employing a Pd target containing $^{107}$Pd of 15.3%. The $\gamma$-ray intensities associated with $\beta^{+/-}$ decays of produced unstable nuclei were measured to obtain the build-up and decay curves. Once the branching ratios of the reactions on the $^{104,105,106,108,110}$Pd targets are obtained, these contributions are extracted from the branching-ratio data obtained for the Pd target with $^{107}$Pd. The reaction branching ratio of ${}^{107}_{46}\mathrm{Pd}(\mu^-, xn\nu)^{107-x}_{45}\mathrm{Rh}$ reactions is finally determined. The detailed off-line data analysis is in progress.

**(4) Comparison with theory**

The muon activation method gives the reaction branching ratios. The muon in-beam spectroscopy method gives the neutron multiplicity and the neutron energy spectrum. These experimental results are important to understand the compound nuclear state and neutron emission mechanism. The reaction branching ratios obtained by the muon activation method are compared with the results of neutron multiplicity measurements. The neutron energy spectrum is considered to be reflected by the energy distribution of compound nuclear state and neutron emission mechanism. The experimental results are compared with the appropriate calculations employing the neutron emission mechanisms due to an evaporation, a cascade and a direct emission processes with assuming the energy distribution at compound nuclear state.

## Members

**Team Leader**
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## List of Publications & Presentations

### Presentations

**[Domestic Conferences/Workshops]**

水野るり惠, 他, 「ミューオン原子 X 線分光のためのコンプトンサプレッサー付き Ge 検出器開発」, 日本物理学会 2021 年秋季大会, オンライン, 2021 年 9 月 14–17 日.

水野るり惠, 他, 「Ge 検出器を用いたミューオン原子 X 線分光のための光子検出システムの性能評価」, Muon 科学と加速器研究, 大阪府豊中市 (大阪大学), 2022 年 1 月 6–8 日.

水野るり惠, 他, 「ミューオン原子 X 線分光のための Ge 検出器を用いた広ダイナミックレンジ光子検出システムの性能評価」, 日本物理学会第 77 回年次大会, オンライン, 2022 年 3 月 15–19 日.

齋藤岳志, 「原子核ミューオン捕獲に伴う放出中性子の測定」, RCNP 研究会「ミューオン原子核捕獲反応による原子核関連研究の可能性」, 大阪府茨木市（大阪大学核物理研究センター）, 2022 年 3 月 24–25 日.

新倉潤, 他, 「ミューオン原子 X 線測定のための検出器開発」, RCNP 研究会「ミューオン X 線 $\gamma$ 線分光」, 大阪府茨木市（大阪大学核物理研究センター）, 2022 年 3 月 24–25 日.

齋藤岳志,「ミューオン原子 X 線分光とその将来について」, ソフトエラー研究会, 山口県大島郡（ゲストハウス HOSHI-KAZE）, 2022 年 3 月 28 日.

水野るり惠, 他,「Si ミューオン原子由来の生成原子核分岐比の絶対値測定実験」, ソフトエラー研究会, 山口県大島郡（ゲストハウス HOSHI-KAZE）, 2022 年 3 月 28 日.

## Others

### [Master Thesis]

水野るり惠,「ミューオン原子 X 線分光のためのコンプトンサプレッサー付きゲルマニウム検出器の開発」, 東京大学, 2022 年 3 月.

### [PhD. Thesis]

T. Saito, “Study of muonic X-ray spectroscopy and nuclear muon capture reaction”, University of Tokyo, March 2022.