

Subnuclear System Research Division Meson Science Laboratory

1. Abstract

Particles like muons, pions, and kaons have finite lifetimes, so they do not exist in natural nuclei or matters. By implanting these particles into nuclei/matters, exotic phenomena in various objects can be studied from new point of view.

For example, kaon is the second lightest meson, which has strange quark as a constituent quark. It is expected that if one embeds mesons into nuclei, the sizes of the nuclei become smaller, and one can form a high-density object beyond the normal nuclear density. Study of this object could lead to better understanding of the origin of the mass of the matter and may reveal the quark degree of freedom beyond the quark-confinement. The other example is the weak interaction in nuclear matter. It can only be studied by the weak decay of hypernuclei, which have Lambda particle in the nuclei.

Muon provides even wider scope of studies, covering condensed matter physics as well as nuclear and atomic physics, and we are trying to extend the application field further into chemical and biological studies. For instance, stopping positively charged muon in a material, we obtain information on the magnetic properties or the local field at the muon trapped site (μ SR). Injecting negatively charged muon to hydrogen gas, muonic hydrogen atom (μp) is formed. We use muonic atoms for proton magnetic radius measurement, muon catalyzed fusion and elemental analysis with muonic X-rays. We are also interested in precision measurement of muon property itself, such as muon anomalous magnetic moment ($g-2$).

In our research, we introduce different kind of impurities into nuclei/matters, and study new states of matter, new phenomena, or the object properties.

2. Major Research Subjects

- (1) Study of meson property and interaction in nuclei
- (2) Origin of matter mass/quark degree of freedom in nuclei
- (3) Condensed matter and material studies with muon
- (4) Nuclear and particle physics studies via muonic hydrogen
- (5) Development of ultra cold muon beam, and its application from material science to particle physics

3. Summary of Research Activity

(1) Hadron physics at J-PARC, RIKEN-RIBF, GSI and Spring-8

Kaon and pion will shed a new insight to the nuclear physics. The recent discovery of deeply bound pionic atom enables us to investigate the properties of mesons in nuclear matter. At RIKEN-RIBF, we are preparing precise experimental study of the pionic atom. Very lately, we succeeded to discover kaonic nuclear bound state, " K^-pp ," at J-PARC. The yield dependence on momentum-transfer shows that observed system is unexpectedly small. We extended our study on $\Lambda(1405)$ that could be $K-p$ bound state. By these experiments, we are studying the KN^- interaction, and clarify the nature of kaon in nuclei. At Spring-8 and at GSI, we are planning to study omega and η^1 nuclei. By these experiments, we aim to be a world-leading scientific research group using these light meta-stable particles.

(1-1) Deeply bound kaonic nuclei

J-PARC E15 experiment had been performed to explore the simplest kaonic nuclear bound state, " K^-pp ." Because of the strong attraction between KN^- , the K^- in nuclei may attract surrounding nucleons, resulting in forming a deeply bound and extremely dense object. Measurement of the kaon properties at such a high-density medium will provide precious information on the origin of hadron masses, if the standard scenario of the hadron-mass-generation mechanism, in which the hadron masses are depends on matter density and energy, is correct. Namely, one may study the chiral symmetry breaking of the universe and its partial restoration in nuclear medium.

The E15 experiment was completed to observe the " K^-pp " bound state by the in-flight ${}^3\text{He}(K^-, n)$ reaction, which allows us the formation via the invariant-mass spectroscopy by detecting decay particles from " K^-pp ." For the experiment, we constructed a dedicated spectrometer system at the secondary beam-line, K1.8BR, in the hadron hall of J-PARC.

With the Λpn final states obtained in the first stage experiment, we observed a kinematic anomaly in the Λp invariant mass near the mass threshold of $M(K^-pp)$ (total mass of kaon and two protons) at the lower momentum transfer q region. We conducted a successive experiment to examine the nature of the observed kinematical anomaly in the Λpn final state, and we confirmed the existence of the bound state below the mass threshold of $M(K^-pp)$ at as deep as the binding energy of 40 MeV. The momentum transfer q naturally prefers lower momentum for the bound state formation, but the observed event concentration extended having the form-factor parameter ~ 400 MeV/c. Based on the PWIA calculation, the data indicated that the " K^-pp " system could be as small as ~ 0.6 fm. It is astonishingly compact in contrast to the mean nucleon distance ~ 1.8 fm.

This observed signal shows that *a meson (qq^-) forms a quantum state where baryons (qqq) exist as nuclear medium, i.e., a highly excited novel form of nucleus with a kaon, in which the mesonic degree-of-freedom still holds.* This is totally new form of nuclear system, which never been observed before.

(1-2) Precision X-ray measurement of kaonic atom

To study the KN^- interaction at zero energy from the atomic state level shift and width of kaon, we have performed an X-ray spectroscopy of atomic $3d \rightarrow 2p$ transition of negatively charged K-mesons captured by helium atoms. However, our first experiment is insufficient in energy resolution to see the K^- -nucleus potential. Aiming to provide a breakthrough from atomic level observation,

we introduce a novel X-ray detector, namely superconducting transition-edge-sensor (TES) microcalorimeter offering unprecedented high energy resolution, being more than one order of magnitude better than that achieved in the past experiments using conventional semiconductor detectors. The experiment J-PARC E62 aims to determine $2p$ -level strong interaction shifts of kaonic ${}^3\text{He}$ and ${}^4\text{He}$ atoms by measuring the atomic $3d \rightarrow 2p$ transition X-rays using TES detector with 240 pixels having about 23 mm^2 effective area and the average energy resolution of 7 eV (FWHM) at 6 keV. We carried out the experiment at J-PARC in June 2018 and successfully observed distinct X-ray peaks from both atoms. The energies were determined to be 6224.5 ± 0.4 (stat) ± 0.2 (syst) eV and 6463.7 ± 0.3 (stat) ± 0.1 (syst) eV, and widths to be 2.5 ± 1.0 (stat) ± 0.4 (syst) eV and 1.0 ± 0.6 (stat) ± 0.3 (syst) eV, for kaonic ${}^3\text{He}$ and ${}^4\text{He}$, respectively. These values are nearly 10 times more precise than in previous measurements. The results exclude the large strong-interaction shifts and widths that are suggested by a coupled-channel approach and agree with calculations based on optical-potential models.

Another important X-ray measurement of kaonic atom would be $2p \rightarrow 1$ transition of kaonic deuteron (K^-d). We have measured same transition of kaonic hydrogen (K^-p), but the width and shift from electro-magnetic (EM) value reflect only isospin average of the $K^{\text{bar}}N$ interaction. We can resolve isospin dependence of the strong interaction by the measurements both for K^-p and K^-d . The experiment J-PARC E57 aims at pioneering measurement of the X-rays from K^-d atoms. Prior to full (stage-2) approval of the E57 proposal, we performed a pilot run with hydrogen target in March 2019.

(1-3) Deeply bound pionic atoms and η^1 mesonic nuclei

We have been working on precision spectroscopy of pionic atoms systematically, which leads to understanding of the non-trivial structure of the vacuum and the origin of hadron masses. The precision data set stringent constraints on the chiral condensate at nuclear medium. We are presently preparing for the precision systematic measurements at RIBF. A pilot experiment performed in 2010 showed a unprecedented results of pionic atom formation spectra with finite reaction angles. The measurement of pionic ${}^{121}\text{Sn}$ performed in 2014 provided high-precision data and set constraints on the pion-nucleus strong interaction, which led to deduction of the chiral condensate at the normal nuclear density. In 2021, systematic high precision spectroscopy of pionic Sn atoms were performed and the analysis is ongoing.

We are also working on spectroscopy of η^1 mesonic nuclei in GSI/FAIR. Theoretically, peculiarly large mass of η^1 is attributed to UA (1) symmetry and chiral symmetry breaking. As a result, large binding energy is expected for η^1 meson bound states in nuclei (η^1 -mesonic nuclei). From the measurement, we can access information about gluon dynamics in the vacuum via the binding energy and decay width of η^1 -nuclear bound state. In 2022, we performed a new experiment using a large solid angle detector of WASA at GSI to search for the η^1 -nucleus bound state with an enhanced signal-to-noise ratio.

(1-4) ${}^3_{\Lambda}\text{H}^{3,4}\text{H}$ lifetime puzzle and our approach

Three recent heavy ion experiments (HypHI, STAR, and ALICE) announced surprisingly short lifetime for ${}^3_{\Lambda}\text{H}$ hyper-nucleus's *Mesonic Weak Decay* (MWD), which seems to be inconsistent with the fact that the ${}^3_{\Lambda}\text{H}$ is a very loosely bound system. It is very interesting to study this with a different experimental approach. We proposed a direct measurement of ${}_{\Lambda}\text{H}$ MWD lifetime with resolution at J-PARC hadron facility by using K-meson beam at 1 GeV/c. As for the feasibility test, we also measure ${}^4_{\Lambda}\text{H}$ lifetime.

A Cylindrical Detector System (CDS) used in J-PARC E15/E31 experiment is employed to capture the delayed π^- as a weak decay product from ${}^3,4_{\Lambda}\text{H}$ a calorimeter is installed in the very forward region to tag fast π^0 meson emission at ~ 0 degree, which ensures that the Λ hyperon production with small recoil momentum. By this selection, we can improve the ratio between ${}^3,4_{\Lambda}\text{H}$ and quasi-free Λ and Σ background. A test beam for feasibility study with ${}^4\text{He}$ target has been conditionally approved by J-PARC PAC. We will conduct the experiment and to present the data in short.

(1-5) Study of properties of vector mesons in nuclei

Preparation of the experiment E16 at J-PARC Hadron Experimental Facility is underway with several Grant-in-Aids. This experiment aims to perform a systematic study of the spectral modification of low-mass vector mesons in nuclei through the dielectron decay channel, in order to explore the physics of chiral symmetry breaking and restoration in dense nuclear matter.

In JFY 2020, a new primary beam line for E16 was completed in J-PARC. Commissioning runs of the beam line and of our spectrometer were performed. The detectors almost satisfied the design performance. Unexpected beam micro structures which deteriorates the DAQ performance were found, and countermeasures were proposed. They will be applied in the test beam time, which is planned in 2023. Based on the result, approval of physics beam time will be discussed in PAC held in Winter 2023–24.

This activity was moved to Meson Science Laboratory after the closing of Radiation Laboratory.

(2) Muon science at RIKEN-RAL branch

The research area ranges over particle physics, condensed matter studies, chemistry and life science. Our core activities are based on the RIKEN-RAL Muon Facility located at the Rutherford-Appleton Laboratory (UK), which provides intense pulsed-muon beams. We have variety of important research activities such as particle/nuclear physics studies with muon's spin and condensed matter physics by muon spin rotation/relaxation/resonance (μSR).

(2-1) Condensed matter/materials studies with μSR

We share experimental equipment with those of RAL in order to make organization of RIKEN beam time schedules easier and to enhance the efficiency to carry out RIKEN's experiments. We use shared cryostats and manpower supports available from RAL as well we other experimental areas. Both two μSR spectrometers, ARGUS (Port-2) and CHRNUUS (Port-4), are working well with maintenance supports provide from RAL. Among our scientific activities on μSR studies from year 2017 to 2022, following studies are most important subjects of material sciences at the RIKEN-RAL muon facility:

- (1) Multi magnetic transitions in the Ru-based pyrochlore systems, $\text{R}_2\text{Ru}_2\text{O}_7$;
- (2) Magnetic properties of the nano-cluster gold in the border of macro- and micro- scale;

- (3) Novel magnetic and superconducting properties of nano-size La-based high-TC superconducting curates;
- (4) Novel superconducting properties in quasi two-dimensional organic molecular systems.
- (5) Determination of muon positions estimated from density functional theory (DFT) and dipole-field calculations;
- (6) Chemical muonic states in DNA molecules.

(2-2) Nuclear and particle physics studies via ultra-cold muon beam and muonic atoms

If we can improve muon beam emittance, timing and energy dispersion (so-called “ultra-cold muon”), then the capability of μ SR studies will be drastically improved. The ultra-cold muon beam can stop in a thin foil, multi-layered materials and artificial lattices, so one can apply the μ SR techniques to surface and interface science. The development of ultra-cold muon beam is also very important as the source of pencil-like small emittance muon beam for muon $g-2$ measurement. Ultra-cold muon beam has been produced by laser ionization of muoniums in vacuum (bound system of μ^+ and electron). We developed a very promising materials for muonium production, laser ablated silica aerogel. We also developed a high power Lyman- α laser in collaboration with laser group at RIKEN. In this laser development, we succeeded to synthesize novel laser crystals Nd:YGAG and Nd:YSAG, which has an ideal wavelength property for laser amplification to generate Lyman- α by four-wave mixing in Kr gas cell. We are now building the actual muon source to be used for muon $g-2$. The first part of the muon ionization chamber was manufactured and is being tested using the muon beam at J-PARC.

(3) QED study of the lepton $g-2$

We are conducting research on Quantum Electrodynamics (QED) theory related to the determination of the theoretical and experimental values of the lepton anomalous magnetic moment ($g-2$). The contribution of QED to $g-2$ can be obtained through perturbative calculations using Feynman diagrams. We are carrying out both analytical validation and numerical computation improvements to determine the value of the 10th-order perturbation term. Additionally, we are also investigating the quantum corrections by QED to the experimental determination formula of the electron $g-2$.

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List of Publications & Presentations

Publications

[Original Papers]

- A. Jamaludin *et al.*, "Density functional theory investigation of muon hyperfine interaction in guanine-cytosine double-strand DNA," *J. Phys. Soc. Jpn.* **91**, 024301 (2022).
- M. Redo Ramadhan *et al.*, "Estimation of the on-site coulomb potential and covalent state in La_2CuO_4 by muon spin rotation and density functional theory calculations," *Phys. Rev. Res.* **4**, 033044 (2022).
- A. Ito *et al.*, "Antiferromagnetic ordering of organic mott insulator λ -(BEDSe-TTF) $_2$ GaCl $_4$," *Phys. Rev. B* **106**, 045114 (2022).
- W. N. Zaharim *et al.*, "Density functional theory study of muon hyperfine interactions in 12 mer single-strand adenine, cytosine, and thymine oligomers," *J. Phys. Soc. Jpn.* **91**, 094301 (2022).
- T. Takayama *et al.*, "Competing spin-orbital singlet states in the $4d^4$ honeycomb ruthenate $\text{Ag}_3\text{LiRu}_2\text{O}_6$," *Phys. Rev. Res.* **4**, 043079 (2022).
- M. Cataldo *et al.*, "A novel non-destructive technique for cultural heritage: Depth profiling and elemental analysis underneath the surface with negative muons," *J. Phys. Soc. Jpn.* **91**, 024301 (2022).

- C. Zhang *et al.*, “Modeling the diffusion of muonium in silica aerogel and its application to a novel design of multi-layer target for thermal muon generation,” *Nucl. Instrum. Methods Phys. Res. A* **1042**, 167443 (2022).
- G. A. Green *et al.*, “Negative muons reveal the economic chaos of rome’s AD 68/9 civil wars,” *Archaeol. Anthropol. Sci.* **14**, 165 (2022).
- J-PARC E31 Collaboration, “Pole position of $\Lambda(1405)$ measured in $d(K^-, n)^{\pi}\Sigma$ reactions,” *Phys. Lett. B* **837**, 137637 (2023).
- T. Nishi *et al.*, piAF Collaboration, “Chiral symmetry restoration at high matter density observed in pionic atoms,” *Nat. Phys.* **19**, 788 (2023).
- N. Ikeno *et al.*, “Pion-nucleon sigma term $\sigma_{\pi N}$ and deeply bound pionic atoms,” *Prog. Theor. Exp. Phys.* **2023**, 033D03 (2023).

[Books]

- A. D. Hillier *et al.*, “Depth-dependent bulk elemental analysis using negative muons,” in *Handbook of Cultural Heritage Analysis*, S. D’Amico and V. Venuti (eds.), Springer 2022, pp. 23–44.
- K. Itahashi, “Pionic Atoms in Experiment,” in *Handbook of Nuclear Physics*, I. Tanihata, H. Toki, and T. Kajino, (eds.), Springer, Singapore, https://doi.org/10.1007/978-981-15-8818-1_36-1.

[Proceedings]

- Y. Ma *et al.*, “Status of J-PARC E73 experiment: first direct Hypertriton lifetime measurement with ${}^3\text{He}(K^-, \pi^0)\text{H}^3\text{L}$ reaction,” *Suplemento de la Revista Mexicana de Fisica* **30308120**, 1 (2022).
- F. Sakuma *et al.*, “J-PARC hadron experimental facility extension project,” *EPJ Web Conf.* **271**, 11001 (2022).
- F. Sakuma *et al.*, “Summary of the K^-pp bound-state observation in E15 and future prospects,” *EPJ Web Conf.* **262**, 01008 (2022).
- S. Nakasuga *et al.*, “Commissioning of the electron identification system for Dilepton measurement in pA collisions at J-PARC,” *Nucl. Instrum. Methods Phys. Res. A* **1041**, 167335 (2022).
- K. Ozawa *et al.*, “Towards the measurement of the mass modifications of vector mesons in a finite density matter,” *Acta Phys. Pol. A* **142**, 399 (2022).
- M. Ichikawa *et al.*, “Commissioning runs of J-PARC E16 experiment,” *Acta Phys. Pol. B Proc. Suppl.* **16**, 1-A143 (2023).
- K. Ozawa *et al.*, “J-PARC heavy ion project,” *EPJ Web Conf.* **271**, 11004 (2022).
- Ce Zhang, T. Hiraki, K. Ishida, S. Kamal, S. Kamioka, T. Mibe, A. Olin, N. Saito, K. Suzuki, S. Uetake, and Y. Mao, “Modeling the diffusion of muonium in silica aerogel and its application to a novel design of multi-layer target for thermal muon generation,” *Nucl. Instrum. Methods Phys. Res. A* **1042**, 167443G (2022).

Presentations

[International Conferences/Workshops]

- T. Yamaga (invited), “Kaonic nuclei at J-PARC,” Third International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (3rd J-PARC HEF-ex WS), J-PARC, March 14–16, 2023.
- T. Hashimoto (invited), “Experimental study of the four-body kaonic nuclear state, KbarNNN ,” EXOTICO: EXOTic Atoms Meet Nuclear Collisions for a New Frontier Precision Era in Low Energy Strangeness Nuclear Physics ECT*, Trento, Italy, October 17, 2022.
- T. Yamaga (invited), “Result of KbarRNN search at J-PARC and future projects,” EXOTICO: EXOTic Atoms Meet Nuclear Collisions for a New Frontier Precision Era in Low Energy Strangeness Nuclear Physics ECT*, October 17, 2022.
- T. Yamaga (invited), “Experimental investigation of KbarNN state using $K^- + {}^3\text{He}$ reaction at J-PARC,” EMMI workshop, “Meson and hyperon interactions with nuclei,” Kitzbuhel, Austria, September 14–16, 2022.
- M. Iwasaki (invited), “ Kbar nuclear bound state—Toward revolutionary Nuclear Study via revealing Internal Structure of Kaonic Nuclei,” The 28th International Nuclear Physics Conference (INPC 2022), Cape Town, South Africa, September 11–16, 2022.
- T. Yamaga (invited), “Experimental study of KbarNN and future Kbar -nuclei experiments at J-PARC,” The 9th International Conference on Quarks and Nuclear Physics (QNP2022), Online, September 5–9, 2022.
- T. Hashimoto (invited), “Experimental study of kaonic nuclei and kaonic atoms at J-PARC,” the 15th Asia Pacific Physics Conference (APPC15), South Korea, August 21–26, 2022.
- F. Sakuma (invited), “J-PARC hadron hall extension project,” 14th International Conference on Hypernuclear and Strange Particle Physics - HYP2022, Prague, Czech Republic, June 27–July 1, 2022.
- T. Yamaga (invited), “Experimental study of KbarNN and future experiments for kaonic nuclei,” 14th International Conference on Hypernuclear and Strange Particle Physics - HYP2022, Prague, Czech Republic, June 27–July 1, 2022.
- Y. Ma (invited), “Current status of hypertriton lifetime measurement with J-PARC E73 experiment,” 14th International Conference on Hypernuclear and Strange Particle Physics - HYP2022, Prague, Czech Republic, June 27–July 1, 2022.
- T. Hashimoto (oral), “Search for the KbarNNN bound state in the Λ dn final states of the in-flight K^- reaction on ${}^4\text{He}$,” 14th International Conference on Hypernuclear and Strange Particle Physics - HYP2022, Prague, Czech Republic, June 27–July 1, 2022.
- K. Kanno (oral), “Commissioning of a hadron blind detector for dielectron measurement in pA reactions at J-PARC,” MPGD2022, Weizmann Institute, Rehovot, Israel/Hybrid, December 11–16, 2022.
- S. Yokkaichi (invited), “Measurements of spectral change of vector mesons in nuclear matter at finite density,” Third International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility, J-PARC, Tokai, Japan & Online, March 14–16, 2023.
- K. Ishida on behalf of the J-PARC muon $g-2$ /EDM Collaboration (E34), “Muon $g-2$ /EDM experiment at J-PARC,” Fifth Plenary Workshop of the Muon $g-2$ Theory Initiative, Edinburgh, September 5–9, 2022.
- K. Itahashi (invited), “What can pionic atoms tell about the QCD vacuum,” XVth Quark confinement and the hadron spectrum, Stavanger,

August 1–6, 2022.

K. Itahashi (invited), “Pionic atoms and chiral symmetry,” 4th Jagiellonian Symposium, Krakow, July, 2022.

[Domestic Conferences/Workshops]

山我拓巳 (招待講演), “Study of mesonic decay of KNN and perspectives of kaonic nuclei experiments at J-PARC,” J-PARC ハドロン研究会, 東海村 (KEK), 2023 年 3 月 27–29 日.

橋本直 (招待講演), 「J-PARC における K 中間子原子核研究の状況と展望」, ELPH 研究会 C033 「ハドロン分光に迫る反応と構造の物理」, 仙台市 (東北大学電子光物理学研究センター), 2022 年 12 月 6–7 日.

高橋智則 (口頭発表), 「J-PARC E16 実験の DAQ の現状と課題」, RCNP 研究会「原子核実験の次世代データ収集システム基盤開発にむけて」, 茨木市 (RCNP) & オンライン, 2022 年 5 月 16–17 日.

T. N. Takahashi (招待講演), “Development of continuous readout electronics for precise measurement of dielectron spectra at J-PARC,” 第 8 回クラスター階層領域研究会, 大阪大学 & オンライン, 2023 年 2 月 9–11 日.

石田勝彦, 「ラザフォードアップルトン研究所ミュオン施設の紹介」, 第 7 回文理融合シンポジウム 量子ビームで歴史を探る—加速器が紡ぐ文理融合の地平—, つくば市 (KEK), 2022 年 11 月 3 日.

石田勝彦, 「ミュオン触媒核融合の利用」, 中間子科学の将来討論会, 和光市 (理研), 2022 年 11 月 9–11 日.

石田勝彦, 「理研 RAL 施設と原子・原子核研究」, 第 13 回 muon 科学と加速器研究研究会, 和光市 (理研), 2023 年 1 月 10–11 日.

[Seminar]

四日市悟, 「J-PARC E16 実験の現状と展望」, 第 14 回 J-PARC-HI の物理を語る夕べ (セミナーシリーズ), オンライン, 2022 年 8 月 19 日.

Press Releases

「K 中間子と陽子が織りなす風変わりなバリオンを測定」, 大阪大学核物理研究センター, 高エネルギー加速器研究機構, J-PARC センター, 理化学研究所, 日本原子力開発機構, 東北大学電子光物理学研究センター, INFN-LNF, SMI 共同プレスリリース, 2023 年 1 月 26 日.

「 π で探る真空の秘密」, 理化学研究所, 奈良女子大, 鳥取大学, 阪大核物理研究センター, 共同プレスリリース, 2023 年 3 月 27 日.