Nuclear Science 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 matter. By implanting these particles into nuclei or matter, exotic phenomena in various objects can be studied from a new point of view.

For example, the kaon is the second lightest meson and contains a strange quark as a constituent. It is expected that embedding mesons into nuclei will make the nuclei smaller, forming a high-density object beyond normal nuclear density. Studying this object could lead to a better understanding of the origin of mass and may reveal the quark degree of freedom beyond quark confinement. Another example is the weak interaction in nuclear matter, which can only be studied through the weak decay of hypernuclei containing a Lambda particle.

Muon provides an 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, by stopping a positively charged muon in a material, we obtain information on the magnetic properties or the local field at the muon-trapped site (μSR). By injecting a negatively charged muon into hydrogen gas, a 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 measurements of the muon itself, such as the muon anomalous magnetic moment (g-2).

In our research, we introduce different kinds of impurities into nuclei or matter and study new states of matter, new phenomena, and the properties of these objects.

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

The kaon and pion will provide new insights into nuclear physics. The recent discovery of deeply bound pionic atoms enables us to investigate the properties of mesons in nuclear matter. At RIKEN-RIBF, we are preparing for a precise experimental study of the pionic atom. Recently, we succeeded in discovering a kaonic nuclear bound state, "*K-pp*," at J-PARC. The yield dependence on momentum transfer shows that the observed system is unexpectedly small. We extended our study on Λ(1405), which could be a *K-p* bound state. Through these experiments, we study the KN- interaction and clarify the nature of the kaon in nuclei. At GSI, we are planning to study η' nuclei. Through these experiments, we aim to become a world-leading scientific research group using these light meta-stable particles.

(1-1) Deeply bound kaonic nuclei

The J-PARC E15 experiment was conducted to explore the simplest kaonic nuclear bound state, "K^-pp." Due to the strong attraction between K^- and nucleons, the K^- in nuclei may attract surrounding nucleons, resulting in the formation of a deeply bound and extremely dense object. Measurement of the kaon properties in such a high-density medium will provide valuable information on the origin of hadron masses, if the standard scenario of the hadron-mass-generation mechanism, which suggests that hadron masses depend on matter density and energy, is correct. Namely, this allows the study of chiral symmetry breaking in the universe and its partial restoration in nuclear medium.

The E15 experiment aimed to observe the "K^-pp" bound state through the in-flight ^{3}He(K^-, n) reaction, which enables formation via invariant-mass spectroscopy by detecting decay particles from "K^-pp". For this 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 of the experiment, we observed a kinematic anomaly in the Λp invariant mass near the mass threshold of M(K^--pp) (the total mass of the kaon and two protons) in the lower momentum transfer q region. We conducted a successive experiment to examine the nature of the observed kinematic anomaly in the Λpn final state, confirming the existence of the bound state below the mass threshold of M(K^--pp) with a binding energy as deep as 40 MeV. The momentum transfer q naturally prefers lower momentum for bound state formation, but the observed event concentration extended, having a form-factor parameter of ~400 MeV/c. Based on the PWIA calculation, the data indicated that the "K^-pp" system could be as small as ~0.6 fm, which is astonishingly compact compared to the mean nucleon distance of ~1.8 fm.

This observed signal shows that a meson ($\bar{q}q$) forms ***a quantum state where baryons (qqq) exist as a 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 a completely new form of nuclear system that has never been observed before.

For further understanding of kaonic nuclear bound states, we have proposed the new experiment J-PARC E80, which aims at the precise measurement of kaonic nuclear bound states, focusing on the $\bar{K}NNN$ (A = 3) system as a first step towards a comprehensive study of light kaonic nuclei from $\bar{K}N$ ($\equiv \Lambda$ (1405)) to $\bar{K}NNN$. Through these experiments and detailed theoretical calculations, we will unravel the nature of kaonic nuclei from the property changes depending on the mass number A. To achieve systematic measurements, we are constructing a new 4π Cylindrical Detector System (CDS) to drastically increase acceptance; a cold mass of a superconducting solenoid magnet and a cylindrical drift chamber were completed in FY2023.

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

To study the $\bar{K}N$ interaction at zero energy from the atomic state level shift and width of kaon, we have performed an X-ray spectroscopy of atomic $3d \to 2p$ 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 a 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}He and ^{4}He atoms by measuring the atomic $3d \to 2p$ 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}He and ^{4}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 the kaonic atom would be $2p \to 1s$ transition of kaonic deuteron (K^--d). We have measured the same transition of kaonic hydrogen (K^--p), but the width and shift from the electromagnetic (EM) value reflect only isospin average of the $\bar{K}N$ 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' mesonic nuclei

We have been systematically working on precision spectroscopy of pionic atoms, which has led to an 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 in nuclear media. We are currently preparing for precision systematic measurements at RIBF. A pilot experiment performed in 2010 showed unprecedented results in pionic atom formation spectra with finite reaction angles. The measurement of pionic ^{121}Sn performed in 2014 provided high-precision data and set constraints on the pion-nucleus strong interaction, leading to the deduction of the chiral condensate at normal nuclear density. In 2021, systematic high-precision spectroscopy of pionic Sn atoms was performed, and the analysis is ongoing.

We are also working on the spectroscopy of η'-mesonic nuclei at GSI/FAIR. Theoretically, the peculiarly large mass of η' is attributed to UA (1) symmetry and chiral symmetry breaking. As a result, large binding energy is expected for η' meson bound states in nuclei (η'-mesonic nuclei). From the measurement, we can access information about gluon dynamics in the vacuum via the binding energy and decay width of the η'-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'-nucleus bound state with an enhanced signal-to-noise ratio. The analysis is still ongoing.

(1-4) $^{3}_{\Lambda}$H lifetime puzzle in relation with $^{4}_{\Lambda}$H and our approach

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

A Cylindrical Detector System (CDS) used in the J-PARC E15/E31 experiment will be employed to capture the delayed π^- as a weak decay product from $^{3}_{\Lambda}$H ($^{4}_{\Lambda}$H). A calorimeter will be installed in the very forward region to tag the fast π^0 meson emission at approximately 0 degrees, which ensures Λ hyperon production with small recoil momentum. By this selection, we can improve the ratio between $^{3}_{\Lambda}$H ($^{4}_{\Lambda}$H) and the quasi-free Λ and Σ background. A test beam for the feasibility study with a ^{4}He target has been conditionally approved by the J-PARC PAC. We will conduct the experiment in 2024 and present the data shortly.

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

We are conducting a detailed study on the properties of vector mesons in nuclei, focusing on how their spectral characteristics are modified in a nuclear medium. This research aims to enhance our understanding of chiral symmetry breaking and its restoration in dense nuclear matter. By analyzing the di-electron decay channel, we can gain insights into the interaction dynamics and changes that occur in vector mesons when they are embedded in a nuclear environment. Our experiments at the J-PARC Hadron Experimental Facility, E16, are designed to systematically investigate these phenomena.

Preparation for the E16 experiment at the J-PARC Hadron Experimental Facility is underway with the support of 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 di-electron decay channel, to explore the physics of chiral symmetry breaking and restoration in dense nuclear matter.

In JFY 2020, a new primary beamline for the E16 experiment was completed at J-PARC. Commissioning runs of the beamline and our spectrometer were performed. The detectors almost met the design performance. Unexpected microstructures of DC beam, which deteriorate the DAQ performance, were found, and countermeasures were proposed. These measures were applied during the test beam time in June 2023, and the effects of the countermeasure were almost verified within the limited beam time of only 21 hours (10% of the plan) because the experiment was interrupted by a fire accident at the J-PARC facility. After the next beam time in April-May 2024, approval of the physics run will be discussed in the J-PARC PAC.

(2) Muon science at RIKEN-RAL branch

The research area ranges over particle physics, condensed matter studies, chemistry, and life science. 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

Among our scientific activities on μSR studies following studies are the most important subjects of material sciences at the RIKEN-RAL muon facility:

(1) Determination of muon positions estimated from density functional theory (DFT) and dipole-field calculations.
(2) Chemical muonic states in DNA molecules.
(3) Development of a new μSR data analysis method using machine learning.

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

If we can improve muon beam emittance, timing and energy dispersion (so-called "ultra-cold muon"), then the capability of μSR 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 μSR 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 material for muonium production, laser-ablated silica aerogel. We also developed a high-power Lyman-α laser in collaboration with the laser group at RIKEN. In this laser development, we succeeded to synthesize novel laser crystals Nd:YGAG and Nd:YSAG, which have 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.

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List of Publications & Presentations

Publications

[Original Papers]

T. Akaishi *et al*., "Precise lifetime measurement of ^{4}H hypernucleus using in-flight ^{4}He$(K^-,0)^4$H reaction," Phys. Lett. B **845**, 138128 (2023).

T. N. Murakami *et al*., "Construction of gas electron multiplier tracker for the J-PARC E16 experiment," Nucl. Instrum. Methods Phys. Res. A **1058**, 168817 (2024).

E. Liu *et al*., "A compact start time counter using plastic scintillators readout with MPPC arrays for the WASA-FRS HypHI experiment," Nucl. Instrum. Methods Phys. Res. A **1064**, 169384 (2024).

T. Goto *et al*., "Electron transfer channel in the sugar recognition system assembled on nano gold particle," J. Phys. Soc. Jpn. **92**, 124705 (2023).

H. Yamauchi *et al*., "Quantum critical behavior of the hyperkagome magnet Mn_3CoSi," Phys. Rev. Res. **6**, 013144 (2024).

P. Jaikaeu *et al*., "Surfacemuon production at J-PARC muon facility," Interactions **245**, 24 (2024).

S. Charoenphone *et al*., "Structural, electronic, and magnetic properties of pyrochlore $Nd_2Ir_2O_7$ studied by first-principles calculations," Interactions **245**, 73 (2024).

W. N. Zaharim *et al*., "Density functional theory investigation of electronic structure and muon hyperfine interaction in isolated adenine and thymine," Interactions **245**, 47 (2024).

L. M. Kien *et al*., "μ^+SR study on ferromagnetism of Na-K alloy clusters in zeolite low-silica X," Interactions **245**, 29 (2024).

[Proceedings]

H. Noumi *et at*., "Measurement of K$^{\mathrm{bar}}$N scattering below the K$^{\mathrm{bar}}$N mass threshold," EPJ Web Conf. **291**, 05011 (2024).

K. Kanno *et al*., "Commissioning of a hadron blind detector for dielectron measurement in *p*A reactions at J-PARC," J. Instrum. **18**, C06021 (2023).

K. Aoki *et al*., "Experimental study of in-medium spectral change of vector mesons at J-PARC," Few-Body Syst. **64**, 63 (2023).

Y. K. Tanaka *et al*., "WASA-FRS experiments in FAIR phase-0 at GSI," Acta. Phys. Polon. Suppl. **16**, 4 (2023).

T. R. Saito *et al*., "Studies of three-and four-body hypernuclei with heavy-ion beams, nuclear emulsions and machine learning," J. Phys. Conf. Ser. **2586**, 012148 (2023).

C. Rappold *et al*., "Study of light hypernuclei in Europe: The hypertriton and nnΛ puzzles," EPJ Web Conf. **290**, 09007 (2023).

Presentations

[International Conferences/Workshops]

T. Yamaga (invited), "Study of the K^{bar}NN cluster at J-PARC," Workshop on Nuclear Cluster Physics (WNCP2023), Toyonaka (Osaka University), Japan, November 27–29, 2023.

M. Iwasaki (invited), "The history and future of hadronic-molecule/cluster with strangeness," ECT* Workshop, "ROCKSTAR: Towards a ROadmap of the crucial measurements of key observables in strangeness reactions for neutron sTARs equation of state," ECT*, Italy, October 9–13, 2023.

T. Hashimoto (invited), "Experimental study of the K^{bar}NNN state and beyond at J-PARC," ECT* Workshop, "ROCKSTAR: Towards a ROadmap of the crucial measurements of key observables in strangeness reactions for neutron sTARs equation of state," ECT*, Italy, October 9–13, 2023.

T. Hashimoto (invited), "Kaonic nuclei and atoms at J-PARC," International Workshop on J-PARC Hadron Physics 2023 (J-PARC Hadron 2023), Tokai (J-PARC), Japan, September 12–15, 2023.

F. Sakuma (invited), "The J-PARC hadron experimental facility extension project," The 20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023), Genova, Italy, June 5–9, 2023.

H. Noumi (invited), "Overview of J-PARC physics," The 20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023), Genova, Italy, June 5–9, 2023.

F. Sakuma (invited), "The hadron experimental facility extension at J-PARC," 17th International Workshop on Meson Physics (MESON2023), Kraków, Poland, June 22–27, 2023.

H. Noumi (invited), "Measurement of K^{bar}N scattering below the K^{bar}N mass threshold," 17th International Workshop on Meson Physics (MESON2023), Kraków, Poland, June 22–27, 2023.

T. Nanamura (oral), "Future experiments on kaonic nuclei at K1.8BR," Fourth International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (HEF-ex 2024), Tokai (J-PARC), Japan, February 19–21, 2024.

T. N. Murakami (poster), "Measurement of the mass spectrum of vector mesons in nuclei at J-PARC," 30th International Conference on Ultra-relativistic Nucleus-Nucleus Collisions (QM2023), Houston, Texas, USA, September 3–9, 2023.

K. Itahashi, "Chiral symmetry restoration in nuclear medium observed in pionic atoms," Hadron 2023, Genova, Italy, June 5–9, 2023.

R. Sekiya, "Search for eta'-mesic nuclei in ^{12}C(p, dp) reaction with the WASA detector at GSI-FRS," Hadron 2023, Genova, Italy, June 5–9, 2023.

[Domestic Conferences/Workshops]

板橋健太 (招待講演), 「π 中間子原子精密分光により原子核中のカイラル凝縮定量評価」, ELPH C035, 仙台市 (東北大学), 2023 年 11 月 9 日.

七村拓野 (口頭発表), "Experimental study of K^{bar}NN and future kaonic nuclei experiments at J-PARC," ELPH シンポジウム 2024, 仙台市 (東北大学電子光理学研究センター), 2024 年 3 月 8 日.

木村佑斗 (口頭発表), 「K 中間子束縛原子核探索のための中性子カウンターの性能評価」, 日本物理学会 2024 年春季大会, オンライン, 2024 年 3 月 19 日.

鶴田雅人 (oral), 「J-PARC における 3Λ の寿命直接測定のためのカロリメーターのテスト実験」, 日本物理学会 2024 年春季大会, オンライン, 2024 年 3 月 21 日.

四日市悟 (招待講演), "Vector mesons in nuclear matter," 領域横断型研究会「IWASK2024」, 和光市 (理化学研究所), 2024 年 3 月 5 日.

Yue Ma (招待講演), "Hypertriton lifetime puzzle and our solution," 領域横断型研究会「IWASK2024」, 和光市 (理化学研究所), 2024 年 3 月 5 日.

板橋健太 (招待講演), "eta-prime nuclei and axial U(1) quantum anomaly," 領域横断型研究会「IWASK2024」, 和光市 (理化学研究所), 2024 年 3 月 5 日.

岩崎雅彦 (招待講演), "Physical Researches conducted at RIKEN—as a Chief Scientist—," 領域横断型研究会「IWASK2024」, 和光市 (理化学研究所), 2024 年 3 月 5 日.

[Seminars]

K. Itahashi, 京都大学, 2023 年 8 月 28 日.

K. Itahashi, RIBF セミナー, 2023 年 9 月 26 日.

K. Itahashi, Heavy Ion Pub, 2024 年 3 月 9 日.