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 (μSR). 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' 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 ${}^3\mathrm{He}(K^-, n)$ 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}He and ^{4}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}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 kaonic atom would be $2p \rightarrow 1$ stransition 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 $K^{\mathrm{bar}}N$ 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' 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}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' mesonic nuclei in GSI/FAIR. Theoretically, 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 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.

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

Three recent heavy ion experiments (HypHI, STAR, and ALICE) announced surprisingly short lifetime for $^{3}_{\Lambda}$H hyper-nucleus's *Mesonic Weak Decay* (MWD), which seems to be inconsistent with the fact that the $^{3}_{\Lambda}$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 $^{3}_{\Lambda}$H MWD lifetime with ~20% resolution at J-PARC hadron facility by using K-meson beam at 1 GeV/c. As for the feasibility test, we also measure $^{4}_{\Lambda}$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 $^{3,4}_{\Lambda}$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 $^{3,4}_{\Lambda}$H and quasi-free Λ and Σ background. A test beam for feasibility study with ^{4}He target has been conditionally approved by J-PARC PAC. We will conduct the experiment and to present the data in short.

(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).

(3) 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 CHRNUS (Port-4), are working well with maintenance supports provide from RAL. Among our scientific activities on μSR studies from year 2017 to 2021, 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, $R_2Ru_2O_7$;
(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) Determination of muon positions estimated from density functional theory (DFT) and dipole-field calculations;
(5) Chemical muonic states in DNA molecules.

(3-1) 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 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 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 $g-2$. Basic design has been completed and the manufacture is in progress.

We are planning a precise measurement of proton Zemach radius (with charge and magnetic distributions combined) using the laser spectroscopy of hyperfine splitting energy in the muonic hydrogen atom. As a key parameter for designing the experiment, we need to know the quench rate of the muonic proton polarization. We are analyzing data on muonic deuterium and muonic proton polarization obtained in low pressure hydrogen gas.

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List of Publications & Presentations

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[International Conferences/Workshops]

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F. Sakuma (invited), "Summary of the *K-pp* bound-state observation in E15 and future prospects," International Conference on Exotic Atoms and Related Topics (EXA 2021), Online, September 13–17, 2021.

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T. Akaishi, "Experimental status toward the direct lifetime measurement of Hypertriton using the (K^-, π^0) reaction at J-PARC," Particles and Nuclei International Conference (PANIC), Online, September 5–10, 2021.

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石田勝彦,「パルスミュオン施設でのミュオン科学研究」,「ミューオン X 線 γ 線分光 非破壊分析, 化学, 原子核物理への新展開」,「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」, 合同研究会, 豊中市（大阪大学 RNCP）&オンライン, 2022 年 3 月 24 日.

Press Release

神田聡太郎, 下村浩一郎, 他「『理想の水素原子』で未知の物理現象を探索する, ミュオニウムのマイクロ波分光実験がスタート」, 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, 東京大学大学院理学系研究科, 東京大学大学院総合文化研究科, 2021 年 4 月 16 日.