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Fundamental physics using exotic atoms at J-PARC

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"The HEATES collaboration has been studying exotic atoms using an innovative X-ray detector known as "an array of superconducting Transition-Edge Sensor (TES) microcalorimeter"which has both excellent energy resolution and collection efficiency. Three experimental results on the kaonic and muonic atom studies have been published over the past few years [1-3], and a new challenging experiment on muonic molecules was conducted recently. Here we present these recent progresses.

Exotic atoms are atomic systems in which negatively-charged particles other than the usual electrons orbit the nucleus. We especially focused on negatively-charged muons (μ-) and kaons (K-), which have the longest lifetimes among the second-generation particles and composite particles in the Standard Model of particle physics. The atomic systems bound by these particles are used to perform precision spectroscopies on the following four types of X-rays:
(a) X-rays from kaonic atoms [1]
(b) X-rays from muonic atoms [2]
(c) Characteristic X-rays from electrons bound to muonic atoms [3]
(d) X-rays from muonic "molecules"
In these experiments, we have studied fundamental physics as follows: (a) the strong interaction between a kaon and a nucleus working at short distances [1], (b) testing quantum electrodynamics (QED) under an ultra-strong electric field environment between a muon and a nucleus [2,4], (c) the femtosecond dynamics of negative muon and bound electrons in the muonic atom formation process [3], and (d) the complex quantum mechanical dynamics process of muon-catalyzed fusion (μCF) process [5].

All these experiments make the most of the advantages of the TES detector, which can cover a wide energy range with both high energy resolution and detection efficiency. Very recently (February 2024), new TES detectors capable of measuring high-energy X-rays above 40 keV and 100 keV have been introduced to the J-PARC muon facility, which will cover a region that cannot be covered by a crystal spectrometer and is expected to be a successor to the experiment (b) for more precise QED verification. In this talk, we would like to review these four studies and discuss future developments.

[1] T. Hashimoto et al., Phys. Rev. Lett. 128, 112503 (2022).
[2] T. Okumura et al., Phys. Rev. Lett. 130, 173001 (2023).
[3] T. Okumura et al., Phys. Rev. Lett. 127, 053001 (2021).
[4] N. Paul et al., Phys. Rev. Lett., 126, 173001 (2021).
[5] T. Yamashita et al., Scientific Reports 12, 6393 (2022)."

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