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Precision X-ray spectroscopy of muonic atoms to explore QED under strong electric fields

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Precision X-ray spectroscopy of the muonic atoms isolated in vacuum is an ideal probe to explore quantum electromagnetic dynamics (QED) under extremely strong electric fields, which is one of the major topic in fundamental atomic physics. We have performed the measurement using an X-ray spectrometer based on multi-pixel array of superconducting transition-edge-sensor (TES) microcalorimeters at J-PARC MLF muon facility (Tokai, Japan).

Negatively-charged muon can be bound by the Coulomb field of an atomic nucleus, so-called muonic atom. In this system, the internal electric field strength between muon and nucleus is proportional to the square of the mass ratio of electron and muon. Muon is about 200 times more massive than electron, so it is 40,000 times stronger than ordinary atoms. Furthermore, since the internal electric field strength is proportional to the cube of the atomic number Z, it is possible to realize an ultra-strong electric field by using heavy muon atoms.

In QED, the electric field strength Ec = 1.32 × 10^18 [V/m] called Schwinger limit is a scale above which the electromagnetic field is expected to become nonlinear. However, it has never verified QED in a strong electric field above Ec, and it is unknown what kind of physics will appear there. The purpose of this study is to accurately determine the transition energy of muonic atoms and compare it with the latest QED calculation to verify the QED under extremely high electric field conditions exceeding Ec [1].

In order to perform such high-precision muonic-atom X-ray spectroscopy, it is important to prepare muonic atoms in which no bound electrons are present. This is because if the bound electrons remain, the shielding effect of the electrons shifts the energy level of the muonic atom, which hinders the highly accurate determination of the QED effect.
The muonic atom generated in the highly excited state is stripped of bound electrons during the deexcitation process, and conveniently becomes a highly-charged muon-atom ion composed only of an atomic nucleus and a muon. However, if a high-density target is used, electrons will be refilled from surrounding atoms during deexcitation. Therefore, it is essential to use a low-density gas target (~ 0.1 atm). However it is experimentally difficult to efficiently stop muons in such a low-density target due to the large momentum distribution of muon beam, resulting in insufficient x-ray yield with the conventional high-resolution x-ray spectroscopy technology.

We have performed the high-resolution muonic atom X-ray spectroscopy with low-density gas target with a combination of the world highest intensity pulsed negative muon beam at J-PARC and an X-ray spectrometer based on a 240 pixel array of TES microcalorimeters in March 2019 [2] and January 2020. In this presentation we will give an overview of this project and report the latest results.

[1] N. Paul et al., Physical Review Letters 126 (2021) 173001.
[2] S. Okada et al., Journal of Low Temperature Physics 200 (2020) 445.

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