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Kaonic Atom Experiments at J-PARC

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Two kaonic atom experiments are being performed in the J-PARC hadron experimental facility. One is a precision measurement of kaonic helium-3 and helium-4 X-rays to investigate the $\bar{K}$-nucleus potential. The other one is aiming at first measurement of X-rays from kaonic deuterium to extract iso-spin dependent $\bar{K}N$ scattering amplitude. In June 2018, we conducted data taking of the kaonic helium experiment using transition-edge-sensor microcalorimeters, where X-ray peaks were observed with an excellent FWHM energy resolution below 10 eV at 6 keV. Operation of the silicon drift detectors, to be used in the kaonic deterium experiment, was also confirmed under the realistic beam condition.

KEYWORDS: $\bar{K}N$ interaction, kaonic atom, X-ray spectroscopy, J-PARC

1. Introduction

A kaonic atom is a Coulomb-bound system of a negatively charged kaon and an atomic nucleus. X-ray spectroscopy of kaonic atoms is a unique method to probe the anti-kaon ($\bar{K}$) nucleon/nucleus interaction at very low energy, which is almost impossible to be accessed with a standard scattering experiment. Kaonic hydrogen and kaonic deuterium have special importance since we can extract iso-spin dependent $\bar{K}N$ scattering length by measuring strong-interaction-induced energy-level shift and broadening in $1s$ states. However, it is experimentally difficult to measure X-rays from the $2p \rightarrow 1s$ transition in these atoms due to the low X-ray yields and the large natural line widths. Recent development of experimental techniques made it possible to measure X-rays from kaonic hydrogen [1,2], while no one observed X-rays from kaonic deuterium whose yield is even lower and the width is wider.

Systematic X-ray measurements of heavier kaonic atoms are important to determine the $\bar{K}$-nucleus potential. Recent theoretical calculation [3] suggests that it would be possible to distinguish two major theoretical potential models if we can measure the $2p$ shifts of kaonic helium-3/4 atoms with a precision below 1 eV.

These X-ray measurements, of kaonic deuterium and kaonic helium atoms, could have not only fundamental importance for describing the $\bar{K}N$ interaction in general, but also unique impact on an interpretation of the recent observation of the kaonic nuclear bound state in J-PARC E15 [4].

2. Experiments

We are conducting experiments to measure X-rays from kaonic deuterium and kaonic helium atoms at the K1.8BR beamline in the J-PARC hadron experimental facility. In principle, we stop a negatively charged kaon beam in the target nuclei to form kaonic atoms, and observe X-rays coming out from the target region with an X-ray detector system. However, since the parameters of the objective X-ray transitions are quite different, except for the X-ray energy, as summarized in table I, we employed different detector technologies for the two experiments.

2.1 *Kaonic Helium $3d \rightarrow 2p$ with TES (J-PARC E62)*

J-PARC E62 aims at measuring the $2p$ shifts and widths in kaonic helium-3 and -4 atoms to constrain a $\bar{K}$-nucleus potential model. As already discussed, we need a precision below 1 eV for the shifts, which cannot be achieved with a conventional semi-conductor X-ray detector. We developed a new application technique of superconducting transition-edge-sensor microcalorimeters (TES) to make a breakthrough in energy resolution; more than one order of magnitude better compared to a semi-conductor detector [5]. The collecting area of the TES system is reasonably large for the kaonic helium experiment thanks to the multiplexing readout technique. One of the keys in this high-precision measurement is the absolute energy calibration for every single readout channel. We use the

Table I. Comparison of the two kaonic-atom experiments at J-PARC.

	J-PARC E57	J-PARC E62
Atom	K^-p/K^-d	K^{-3}He/K^{-4}He
Transition	$2p \to 1s$	$3d \to 2p$
X-ray energy [keV]	6–10	6.22/6.46
X-ray width [eV]	300–1000	< 5
Target density [g/cm^3]	3.0×10^{-3}/5.7×10^{-3} (gas)	0.081/0.145 (liquid)
X-ray yield per stopped K^- [%]	~1 / ~0.1	~7
Detector	SDD	TES
Resolution at 6 keV [eV FWHM]	< 200	< 10
Timing resolution [μs FWHM]	0.5–1.0	0.6
Number of readout channels	384	240
Total collecting area [cm^2]	240	0.23
Status	K^-p run in March 2019	Data taking in June 2018

X-ray generators and secondary target metals of chromium, cobalt, and copper based on the result of a test experiment [6, 7]. Details of the experimental setup are described in reference [8].

2.2 *Kaonic Deuterium* $2p \to 1s$ *with SDD (J-PARC E57)*

In J-PARC E57, we try to observe X-ray peak from kaonic deuterium, which no one succeeded to do so far, to resolve iso-spin dependence of the $\bar{K}N$ interaction together with kaonic hydrogen data [9]. The difficulties of the experiment come from low X-ray yield even with a gaseous target and a large absorption width. Therefore, we cover a large solid angle with many arrays of silicon drift detectors (SDDs). In addition, a cylindrical detector system used in J-PARC E15 experiment plays essential role for suppressing background events. With its tracking capability, we can reconstruct a reaction vertex to select target region. We can also remove charged-particle hits on SDDs, which sometimes make fake signals in the region of interest. Details of the experimental setup are described in reference [9].

3. Present status

In June 2016, we executed a commissioning experiment to stop negatively charged kaons in the target. We established a method how to optimize the degrader thickness to get maximum number of stopped kaons. We also tested the TES spectrometer in the realistic kaon beam condition [10]. We confirmed a good enough performance for the scientific campaign, as is expected from the results of a test experiment using π^- beam in 2014 [6].

In June 2018, the scientific campaign of the E62, kaonic-helium experiment, was carried out. During ~20-day beamtime at J-PARC, we collected more than 100-count X-rays from the $3d \to 2p$ transition in both kaonic helium-3 and helium-4 atoms. Fig. 1 shows a correlation plot between X-ray energies and X-ray pulse timings with respect to a kaon trigger. We can clearly identify kaon-beam correlated events with an FWHM timing resolution of ~600 ns, and an event concentration at around 6.46 keV indicates the observation of kaonic helium-4 X-rays. From the analysis of the calibration lines, an FWHM resolution is estimated to be ~7 eV at 6 keV. Further analysis is now ongoing towards publications.

We also installed SDDs, to be used in the kaonic deuterium experiment, in the E62 experimental setup, to monitor the number of stopped kaons in the target. Fig. 2 shows a typical ADC spectrum of 1 SDD readout channel. We can clearly see the kaonic helium-4 X-ray lines, in addition to the calibration lines coming from titanium and zirconium foils installed around the target cell. The FWHM

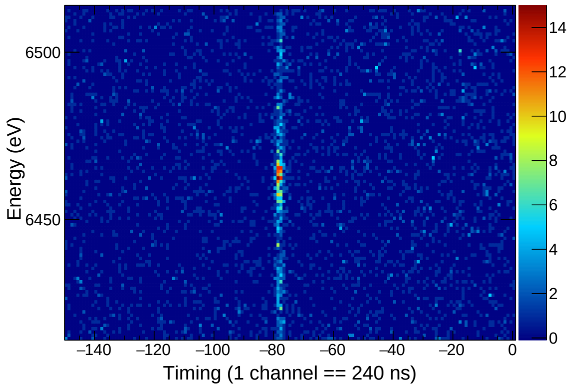

Fig. 1. Energy versus pulse timing with respect to a kaon trigger, detected by TES with the helium-4 target.

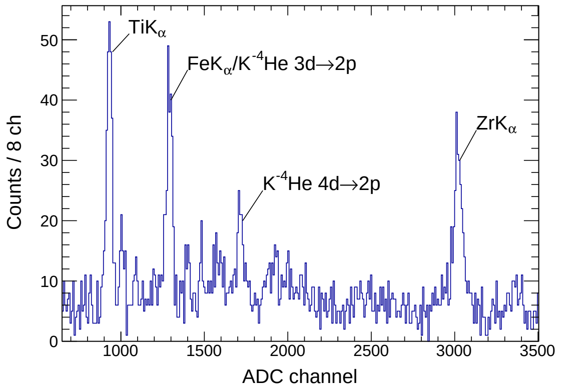

Fig. 2. Typical ADC spectrum of 1 SDD readout channel with the helium-4 target in E62.

resolution achieved was below 200 eV at 6 keV, which is sufficient for the kaonic deuterium experiment, E57. In March 2019, we start data taking with a hydrogen target to prove our experimental principle of E57, especially in terms of a background suppression. Data taking with a deuterium target will follow it.

4. Summary

We carried out X-ray spectroscopy of kaonic helium atoms at J-PARC in June 2018, with a cryogenic X-ray detector, TES. Distinct X-ray peaks at ~6 keV were observed from the $3d \rightarrow 2p$ transitions in the two isotope atoms. The energy resolution achieved was below 10 eV in FWHM, being one order of magnitude better than past experiments. We will deduce $2p$ shifts and widths to discuss the $\bar{K}$-nucleus potential. We are also preparing for a kaonic deuterium experiment to extract iso-spin dependent $\bar{K}N$ scattering length. Developments of the experimental components are completed and the performance of silicon drift X-ray detectors were confirmed in the kaonic-helium atom experiment. Following a pilot experiment with a hydrogen target in March 2019, the kaonic deuterium measurement will be performed in near future.

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