Precision Spectroscopy of Kaonic Helium-3 X-rays at J-PARC

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Abstract. We will measure the x-rays from kaonic $^3$He $3d \rightarrow 2p$ transition with a precision below 2 eV. It can provide crucial information on the $K^- - nucleus$ strong interaction. The experiment (J-PARC E17) will be performed as Day-1, which is one of the first experiments in the J-PARC hadron facility in the year 2011. An overview and the present status of the J-PARC E17 experiment are described.

1. Introduction

Kaonic atoms are an important tool to probe the $\bar{K}N$ interaction at the threshold energy. Due to the presence of the strong interaction between the kaon and the nucleus, its energy levels are shifted and broaden from the purely-electromagnetic value. This energy shift and width broadening is pronounced at last orbit, in which the strong-interaction absorption width becomes larger than the radiative-transition width. The strong interaction induced shift and width can be derived by measuring the x-rays emitted in transitions from highly-excited states to the last orbit. Therefore, a precision x-ray spectroscopy of kaonic atoms can provide direct information on the kaon-nucleus strong interaction.
From the experimental side, over the last decade, spectroscopies for light kaonic atoms have been intensively performed in KEK in Japan and LNF in Italy, especially for atoms with the atomic numbers of $Z = 1$ and 2. In this paper, we focus our interest to $Z = 2$, kaonic helium atoms. Recently, KEK-PS E570 group measured the Balmar-series x-rays from kaonic helium-4 atoms at KEK 12 GeV proton synchrotron [1]. The experiment was motivated by a long-standing discrepancy between experiments and theory: Before E570, three measurements on kaonic helium-4 were performed around 1980’s, and the average of the $2p$ level shift indicates a large repulsive-type shift of $-43 \pm 8$ eV [2, 3, 4]. On the other hand, theoretical calculations based on optical models claim the very small $2p$ level shift below 1 eV [5, 6]. This situation is called as kaonic helium puzzle.

In E570, x-rays from kaonic helium-4 atoms were precisely measured with a novel x-ray detector, silicon drift detector (SDD), and the strong-interaction induced shift was deduced to be

$$\Delta E_{2p} = 2 \pm 2 \text{(stat.)} \pm 2 \text{(sys.)} \text{eV}.$$ 

This result settles the kaonic helium puzzle, and was confirmed very recently by SIDDHARTA group at LNF [7]. Furthermore, an application of SDDs to a precision spectroscopy of kaonic atoms have been established in these two experiments.

2. J-PARC E17 experiment
2.1. Motivation
One of the hotly-debated issues in the strangeness physics nowadays is the existence of the nuclear $K$ bound states. Many studies has been stimulated by a pioneering theoretical work by Y. Akaishi and T. Yamazaki [8]. The calculation is based on a phenomenological potential with a coupled channel approach. They also calculate the $2p$ level shift of the kaonic helium-3 and -4 [9]. Contrary to the calculations with optical models, their calculation claims possibilities of a large $2p$ level shift ($\sim 10$ eV) for kaonic helium-3 and/or -4 atoms in association with the strength of the $K^-$-nucleus potential. From the results of the KEK-PS E570 experiment, the energy shift of the $2p$ level of kaonic helium-4 is strictly constraint to be the small value, however, a large energy shift of the kaonic helium-3 is still possible with a certain deep potential. Thus, the measurement of the $2p$ level shift of kaonic helium-3 can pin down the strength of the potential in their framework, and is a matter of great interest.

Very recently, SIDDHARTA group has reported the energy shift of kaonic $^3$He $2p$ level to be $\Delta E_{2p} = -2 \pm 2 \text{(stat.)} \pm 4 \text{(syst.)} \text{eV}$ [10]. They claim that the observed energy shift is in good agreement with theoretical values by optical models. However, due to the large uncertainty of the measured value, the result cannot discriminate the possibility of the non-zero shift discussed in Ref. [9]. Therefore, the spectroscopy with precision below a few eV is extremely important.

2.2. Experimental setup
The experiment J-PARC E17 will be performed in the K1.8BR beamline in the J-PARC hadron facility [11]. Figure 1 shows a schematic view of the experimental setup. It is consisted of 4 components; a beamline spectrometer, a liquid helium-3 target, a cylindrical detector system (CDS) and silicon drift x-ray detectors (SDDs). $K^-$’s transferred through the beamline spectrometer (not shown in the figure) are stopped inside the liquid helium-3 target after being slowed down by a carbon block. They are separated from a number of contaminating particles, such as $\pi^-$, by a Lucite cherenkov counter (LC), and their trajectories and timing are measured by a beamline drift chamber (BLC) and a beam-timing counter (E0), respectively. X-rays from the kaonic helium-3 atoms are measured by 8 SDDs whose geometrical acceptance is about 1% in total. For the background suppression, it is important to detect secondary charged particles after
$K^-$ nuclear absorption. That becomes possible with CDS, which is consisted with a cylindrical drift chamber (CDC) and scintillator hodoscope counters (CDH). Together with the trajectories of the $K^-$ beam, the reaction vertex is reconstructed, and the fiducial target volume region is selected in the offline analysis (fiducial volume cut).

The most important issue to accomplish a precision measurement is accuracy of the absolute energy calibration. Since the gain of the x-ray detector is known to be fluctuated by its incident x-ray hit rate, an in-beam energy calibration is the most essential way to overcome this. The energy of the kaonic helium-3 x-ray locates at 6.2 keV whose energy range is similar to those of K-series fluorescence x-rays of 3d transition metals. $K_\alpha$ lines for titanium (4.5 keV) and nickel (7.5 keV) are selected for the calibration sources. Since the $K^-$ beam is contaminated with a number of other particles (mostly $\pi^-$’s), calibration foils installed close to the target are activated by those particles, and fluorescence x-rays from the foils are obtained simultaneously with the kaonic helium-3 x-rays.

In the following subsections, the detail and the present status of each apparatus are described.

![Figure 1. A schematic side view of the J-PARC E17 experimental setup. Definitions of each abbreviation are described in the text.](image)

2.3. Beamline spectrometer
The K1.8BR beamline provides secondary charged particles, such as $K^\pm$, from a production target where the primary proton beam from 50 GeV PS is bombarded. A part of the optical components of the K1.8BR beamline is schematically shown in Fig. 2, where D, Q and S denote dipole, quadrupole and sextupole magnets, respectively. Between D3 and S3, a beam hodscope counter (BHD) was installed to measure the beam profile. It is segmented into 20 to have high-rate capability. Trajectories at the up- and down-stream of D5 are measured by two-sets of drift chambers to analyze the momentum of the beam. We have already started beam commissioning at the K1.8BR beamline, and its detail is discussed in a dedicated paper [12].

2.4. Liquid helium-3 target
Figure 3 shows the cross-sectional view of the liquid helium-3 cryostat. Most of the cryostat is based on that for liquid helium-4 target used in KEK experiments [13]. This cryostat is
developed for an experimental search for nuclear $K^-$ bound states with $^3\text{He}(K^- , n)$ reaction (J-PARC E15 [14]). We adopted L-shape cryostat to install the target cell into the center of the detector system. Operational concept of this cryostat is as followings: Gaseous helium-3 (450 litter at STP) is hermetically connected to the target cell via a heat exchanger where gaseous helium-3 is condensed by a thermal contact with liquid helium-4 of 1.4 K ($^4\text{He}$ evaporator). Although the distance between the target cell and the heat exchanger is rather large ($\sim$ 1 m), convection flow of the liquid helium-3 between the heat exchanger and the target cell helps to transfer heat load effectively.

We installed the SDDs together with their preamplifiers inside the cryostat near the liquid helium-3 target cell. Although the temperature of the SDDs and preamplifiers are rather high ($> 100$ K at SDDs and $> 270$ K at preamplifiers), proper thermal insulation and heat anchor to the liquid nitrogen shield work well, and we can successfully condense gaseous helium-3 and achieve the liquid helium-3 temperature of 1.4 K.

![Figure 2. A schematic drawing of beam spectrometer at K1.8BR beamline. S,D,Q denote dipole, quadrupole and sextupole magnets, respectively.](image)

![Figure 3. A cross-sectional drawing of liquid $^3\text{He}$ cryostat. The figures in brackets indicate the achieved temperatures at the cooling test.](image)

2.5. Cylindrical detector system
To detect secondary charged particles from $K^-$ absorption, a cylindrical detector system is installed around the liquid helium-3 target. It consists of a cylindrical drift chamber (CDC) and cylindrical detector hodoscope (CDH). This detector system is originally developed for J-PARC E15, combined with a solenoid magnet, however, magnetic field is unnecessary in E17 because the particle identification and momentum analysis of the secondary charged particles are dispensable.

A photograph of CDC is shown in the upper panel of Fig. 4. The geometry of CDC is 106 cm thick cylindrical shape with the length of 95 cm. CDC has 15 layers of hexagonal cells with
maximum drift length of 9 mm. Each layer grouped into 7 super layers (A1, U1, V1, A2, U2, V2, A3, where A, U and V denote axial and stereo layers with tilted angle of ±3.5 degrees). The number of the readout wires is 1816 out of the total wires of 8064. Typical position resolution is about 200 µm achieved with cosmic rays, as shown in the lower panel of Fig. 4.

CDH is consisted with 36-segmented scintillation counters with PMTs on both ends. The size of each CDH is 790 mm in length and 99 mm in width with the thickness of 300 mm, which covers the polar angle of 54 to 126 degrees. The hit information of CDH provides the hardware trigger for secondary charged particles. Typical time resolution of CDH is 70 ps estimated with cosmic-ray events.

2.6. Silicon drift detector
To detect x-rays from kaonic helium-3 atom, a silicon drift detector (SDD) which was developed by KETEK [15] is adopted. This detector has an excellent energy and time resolution around 6 keV, compared with other conventional x-ray detector, like Si(Li).

For the precise determination of the x-ray energy, the line shape of the detector response is extremely important to minimize the systematic errors. Basic studies for the SDD performances, such as low-temperature behavior or incident-angle and position dependence of the detector response, is now carefully under investigation, in parallel with the installation of SDDs into the liquid helium-3 cryostat. The preliminary results of the basic studies are presented in Ref. [16].

As shown in the lower panel of Fig. 5, the energy resolution of SDD around the energy region from 4.5 to 7.5 keV is confirmed to be well-understood by the empirical formula. The energy resolution at the energy of kaonic helium-3 \( L_\alpha \) can be precisely estimated to be 140 eV in FWHM, which is much better than 185 eV achieved in the previous KEK-PS E570 experiment.

3. Summary
We will measure the x-rays of kaonic helium-3 atoms at K1.8BR beamline in the J-PARC hadron facility. Most of the detector construction has been completed with the expected performances. The beam commissioning at the K1.8BR beamline has been started, and the J-PARC E17 experiment will start its data taking in Day-1 at the J-PARC hadron facility in 2011.

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Figure 4. A photograph of CDC (Top) and position resolution of each layer with cosmic ray (Bottom). Colored plots are obtained with Monte Carlo simulation assuming representative resolution of 150 (red), 200 (green) and 250 µm (blue).

Figure 5. Top: Typical SDD spectrum with fluorescence x-rays. Bottom: the energy dependence of the energy resolution. Dotted line represents an empirical formula of (1) in the text with fitted parameters of a noise constant ($W_N$) and Fano factor ($F$).

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