X ray spectroscopy on Ξ^- atoms (J-PARC E03, E07 and future)

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Abstract. X-ray spectroscopy of hadronic atoms is a powerful method to study strong interaction between hadrons and nuclei. At J-PARC, we have conducted two experiments, J-PARC E07 and E03, for hadronic atoms with a doubly strange hyperon, Ξ^-, aiming at the world-first detection of their X-rays. The first measurement is performed as a byproduct of J-PARC E07 experiment with the hybrid emulsion technique. The second one, J-PARC E03, is a dedicated experiment for detection of Ξ^- Fe atom X rays. The preliminary results and the present status of E07 and E03 are shown in this article. Future prospects of Ξ^--atomic X-ray spectroscopy are also discussed. A new measurement has been proposed for detecting Ξ^- C atom X rays, where a novel Ξ^- tracking method will be applied to realize an improved signal to noise ratio.

1 Introduction

X-ray spectroscopy of hadronic atoms gives us various information on strong interaction between hadrons and nuclei. This method has been successfully applied for negatively charged hadrons, such as π^-, K^-, $\overline{p}$, and Σ^-. The negatively charged hadrons can approach the nuclear surface, leading to energy shifts of atomic states by attractive/repulsive strong interaction as well as their energy widths by nuclear absorption. These energy shifts and widths, which provide information on the real and imaginary parts of the hadron-nucleus optical potential, can be determined by measuring X rays from the transition between atomic states. In the S (strangeness) $= -1$ sector, more than twenty data points are available for Σ^- atoms for a wide mass range of nuclei, giving constraints for the Σ-nuclear optical potential [1]. In the $S = -2$ sector, strong mixing between ΞN and $\Lambda\Lambda$ is expected because their mass difference is as small as 28 MeV, being much smaller than the case of the $S = 0$ and 1 sectors. Such baryon-baryon coupling effects may play a dominant role, especially in the $S = -2$ systems.

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Furthermore, understanding of the $\Xi^- N$ interaction is essential to clarify the role of Ξ^- in neutron stars. However, little is known experimentally on the $S = -2$ systems.

Ξ^--atomic X-ray data for light nuclei may have another impact on emulsion data for $S = -2$ hypernuclei. For example, the "NAGARA" event, which gives the binding energy of double Λs ($B_{\Lambda\Lambda}[^{6}_{\Lambda\Lambda}\mathrm{He}]$) of 6.91±0.16 MeV [3], was analyzed based on the binding energy of Ξ^- C atom (B_Ξ) of 0.13 MeV assuming that the Ξ^- absorption occurred in the $3D$ Ξ^--atomic state. However, the atomic state before the absorption may be different if the absorption strength differs from the expectation. The absorption strength, and thus the absorption state, should be determined by Ξ^--atomic X-ray spectroscopy. Therefore, Ξ^--atomic X-ray data for nuclei contained in the emulsion (carbon, nitrogen, and oxygen) help the emulsion analysis.

In this situation, experimental data of Ξ^- atomic X rays have been eagerly awaited [2], but no experiment has been performed yet. Aiming at the world-first detection of the X rays, we have conducted two experiments, J-PARC E07(2016-2017) and J-PARC E03(2020-2021). Preliminary reports from these experiments are given in sections 2 and 3. Future prospects of Ξ^--atomic X-ray spectroscopy are also discussed in section 4.

2 First measurement in J-PARC E07

Our first measurement of Ξ^--atomic X rays has been performed as a byproduct of the J-PARC E07 experiment, a search for double Λ hypernuclei and Ξ hypernuclei with the hybrid emulsion technique [4]. The data taking was done in 2016-2017. In this experiment, hypernuclei were produced via Ξ^- capture by nuclei in emulsion stack. Ξ^-s were produced via the (K^-, K^+) reaction and injected into the emulsion. Stopped Ξ^-s form Ξ^- atoms before the hypernuclear production reaction. The tracks of Ξ^- were measured by silicon strip detectors and used in the microscope analysis for Ξ^- track following in the emulsion. By applying this method, called the hybrid emulsion technique, we found Ξ^- stop events efficiently. A germanium (Ge) detector array, Hyperball-X [5], was installed near the emulsion stack for X-ray measurement. When Ξ^-s stop in emulsion, they form Ξ^- atoms with nuclei contained in the emulsion, C, O, N, O, Br and Ag. It is noted that yields of Ξ^- atoms with Ag and Br are expected to be large because Ξ^- is mostly captured by heavy nuclei. In addition, some of Ξ^-s may also stop inside the Ξ^- production target, a 3.2 g/cm^2-thick diamond, and form Ξ^- C atoms. Ξ^- stop identification is essential for the X-ray measurement because more than 90% of the produced Ξ^- will decay before stopping, leading to a huge number of background events. In this measurement, we applied two methods to observe Ξ^--atomic X rays: (1) combined analysis with Ξ^- stop identification from emulsion image and (2) coincidence with only Ξ^- production without emulsion image.

In the combined analysis, a good signal to noise ratio for the X-ray spectrum is expected because Ξ^- stop events can be unambiguously identified using emulsion image. However, the X-ray yield rate is limited by a low Ξ^- survival ratio due to decay before reaching the emulsion, the small abundance of each nucleus contained in the emulsion and a not-optimized configuration of the X-ray detector array. X rays from Ξ^- atoms on Br and Ag are expected to be detected with this method. The expected X-ray transitions to the "last" Ξ^--atomic states, from which the Ξ^- is absorbed, are $(n, l) = (7, 6) \to (6, 5)$ for Br (315 keV) and $(8, 7) \to (7, 6)$ for Ag (370 keV). In the present analysis, X-ray peaks are not observed. It is because the expected X-ray yield is as small as a few counts due to insufficient emulsion analysis efficiency. Further progress in the emulsion analysis is necessary.

In the analysis without emulsion, we tried to select events in which Ξ^-s do not reach silicon strip detectors placed just downstream of the diamond target for the X-ray measurement of Ξ^- C atoms. The signal to noise ratio of the X-ray spectrum is lower than the emulsion combined analysis, while the ratio is partly improved by an additional analysis selecting Ξ^-s

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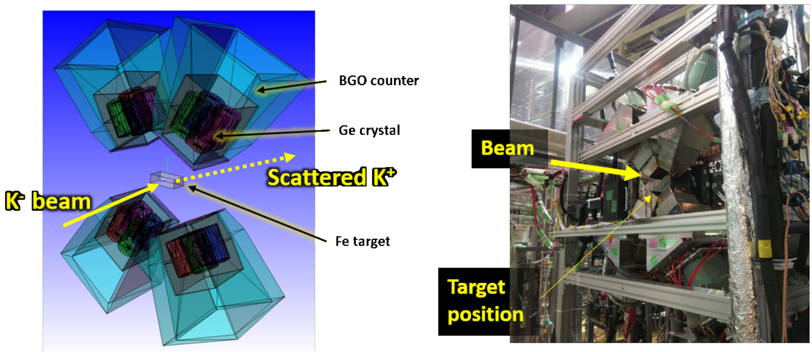

Figure 1. A schematic view and a photo of the detector setup around the experimental target in J-PARC E03. A Ge detector array Hyperball-X' consists of four Ge + BGO units covering the upper and lower directions from the target.

with low recoil momenta. The expected X-ray yield is also low as in the case of the combined analysis. The X-ray transition to the "last" Ξ^--atomic state is expected to be $3D \to 2P$ in the case of weak absorption suggested by a theoretical study with the lattice QCD potential [6], of which the corresponding X-ray energy is 154 keV. A preliminary result shows no clear peak structure in the X-ray spectrum. The upper limit for the branching ratio of the $3D \to 2P$ transition was obtained to be ~40%/ Ξ^- stop [7], which is close to a value suggested by a theoretical case study [6]. Recently, we made a plan for a new measurement for Ξ^- C atoms with improved sensitivity. Details are shown in section 4.

3 Second measurement in J-PARC E03

Our second measurement of Ξ^--atomic X rays was performed as a dedicated X-ray spectroscopy experiment (J-PARC E03) [8]. We selected iron as a target because (1) iron is dense enough (7.9 g/cm^3) with a higher Ξ^- stopping probability, and (2) the expected absorption strength corresponding to the energy width of 4 keV is suitable for the measurement. Since the J-PARC beam intensity is currently insufficient to take the requested full statistics data, we decided to take 10% of the full statistics data as the 1st-phase run. Even with the 1st-phase statistics, a peak of the X-ray transition to the "last" Ξ^- Fe atomic state, the $(6, 5) \to (5, 4)$ transition (~286 keV), is expected to be observed if the energy width is smaller than 1 keV. Furthermore, the upper X-ray transition of $(7, 6) \to (6, 5)$ (172 keV) will be observed without peak broadening. The ratio between the yields of the upper and the lower X-ray transitions gives information on the absorption strength. In this measurement, Ξ^-s were produced by the (K^-, K^+) reaction and stopped in the target. Ξ^- production was tagged with the missing mass method by reconstructing momenta of the beam K^-s and the scattered K^+s with the K1.8 beam line spectrometer and the KURAMA spectrometer, respectively. For X-ray detection, a Ge detector array, Hyperball-X', was installed near the target as shown in Fig. 1. Hyperball-X' consists of four Ge + BGO units covering the upper and lower directions from the target to avoid self-absorption of X rays inside the horizontally wide iron target. "Clover-type" Ge detectors were mounted to the array to realize both a large solid angle in total and a low counting rate for each Ge crystal. To optimize the Ge detector readout with respect to a low beam intensity of ~250 kHz, a conventional type of the shaping amplifiers, ORTEC 671, were used for Hyperball-X', while a high-rate type of the shaping amplifiers should be used in the full

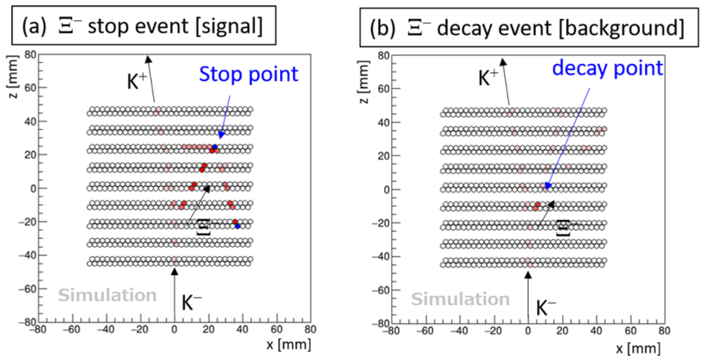

Figure 2. Simulated event displays of AFT for a Ξ^- stop event (a) and a Ξ^- decay event (b) in the J-PARC E96.

statistics run in the future. The typical energy resolution was ~2.3 keV (FWHM) for 307 keV. Data taking for the 1st-phase was done in Apr. 2021 with the total irradiated K^- of 9.5×10^{10}. Analysis has started for selecting the (K^-, K^+) reaction and detecting X rays. We confirmed that Ξ^- production events can be clearly tagged by the missing mass method through the momentum reconstruction with the magnetic spectrometers. The performances of Hyperball-X' were also evaluated for resolutions, efficiencies and background suppression. In the E03 as well as the E07 experiments, a precise in-beam energy calibration was successfully carried out through the whole beam time with a trigger generated by LSO scintillators with natural activity of ^{176}Lu [5]. Further analysis for event selections and calibrations is necessary to obtain the final X-ray spectrum. The result will be reported in the near future.

4 Future measurement in J-PARC E96

We are planning future measurements of Ξ^--atomic X rays simultaneously with high resolution Ξ hypernuclear spectroscopy experiments using the S-2S spectrometer [9]. Systematic measurements with a carbon target (J-PARC E70 [10]) and a lithium target (J-PARC E75 [11]) will be performed shortly. By using the Ξ^- hyperons produced in these experiments with the S-2S spectrometer, we will be able to take Ξ^--atomic X-ray data in parallel. The first experiment with the S-2S spectrometer (J-PARC E70) will start in 2023 with a carbon target. We will retry the X-ray measurement for Ξ^- C atoms in this experiment. Active Fiber Target (AFT) will be used as a carbon target. AFT consists of ϕ3 mm scintillating fibers, of which hit information will be used for correcting energy loss of K^-s and K^+s in the target. For the X-ray measurement, the hit information of the AFT fibers allows us to identify Ξ^- stop events and gives a good signal to noise ratio, although a low density of the target will limit the Ξ^- stopping probability. Event selection can be made by finding tracks of Ξ^-s produced via the (K^-, K^+) reaction followed by a vertex of the Ξ^- absorption on carbon nuclei. We can reject dominant background sources such as (1) Ξ^-s passing through and exiting the target and (2) Ξ^-s decaying in-flight. Figure 2 shows simulated event displays of a Ξ^- stop event and a Ξ^- decay event. The background rejection ratio is expected to be ~95%. This event selection will improve the signal to noise ratio for X-ray measurement. We estimated the sensitivity for Ξ^- C atomic X rays to be better than the previous measurement in J-PARC E07 by a factor of ~3. Detection of X rays are expected for both upper $4F \to 3D$ and lower

$3D \rightarrow 2P$ transitions of Ξ^- C atoms. We submitted a new proposal (J-PARC E96 [12]) for this X-ray measurement of Ξ^- C atoms and started preparing the detector system. The S-2S magnets were installed in the J-PARC K1.8 beam line. Detector installation for the spectrometer is in progress. Data-taking will start in 2023 after installing the Ge detector array, Hyperball-X', after modification of geometrical configuration.

5 Summary

X-ray spectroscopy of hadronic atoms is a powerful tool to investigate strong interaction between hadrons and nuclei. We are aiming at the world-first measurement of X rays from Ξ^- atoms in J-PARC experiments. We have conducted two experiments for Ξ^- C atoms (J-PARC E07) and Ξ^- Fe atoms (J-PARC E03). The sensitivity will be improved in the newly proposed experiment (J-PARC E96) for Ξ^- C atoms again by introducing the AFT system. This measurement will be performed in 2023. Furthermore, we plan to take Ξ^--atomic X-ray data for a wide mass range of nuclei in future measurements in order to understand the ΞN interaction.

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