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X-ray spectroscopy experiments on exotic Ξ^- atoms at J-PARC

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X-ray spectroscopy of hadronic atoms is a powerful method to determine the strong interaction between the hadron and nuclei. At J-PARC, we have conducted two experiments on exotic atoms with a doubly strange hyperon, Ξ^-, aiming at the world-first detection of the X rays. One is performed as a byproduct of J-PARC E07 experiment (search for double hypernuclei with hybrid emulsion technique) where Ξ^- is stopped on the emulsion. The other is a dedicated experiment for the detection of Ξ^- Fe atom X rays (J-PARC E03). The preliminary result of E07 and the status of the ongoing analysis for E03 are shown in this article. Future prospects of Ξ-atomic X-ray spectroscopy are also discussed.

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1. Introduction

X-ray spectroscopy of hadronic atoms give us various information on strong interaction between hadrons and nuclei. This method has been successfully applied for negatively charged hadrons (π^-, K^-, $\bar{p}$, and Σ^-). The negatively charged hadrons can approach to the nuclear surface, giving energy shifts of atomic states by attraction/repulsion as well as their energy widths by absorption. Therefore, the X-ray energy shift and width give information on the real and imaginary parts of the optical potential. In the $S = -1$ sector, more than twenty data points are available for Σ^- atoms for a wide mass range of nuclei which give constraint for Σ^--nuclear optical potential [1]. In the $S = -2$ sector, strong mixing between ΞN and $\Lambda\Lambda$ is expected because the mass difference is as small as 28 MeV, which is much smaller than the case of the $S = 0$ and 1 sectors. Baryon coupling effects may play a dominant role especially in $S = -2$ systems. Furthermore, understanding of the ΞN interaction is essential to clarify a role of Ξ^- in neutron starts. However, little is known experimentally on $S = -2$ systems. While some emulsion events of Ξ^- nuclear system have been reported [2, 3], they are not sufficient for understanding of the ΞN interaction. In near future, Ξ^- hypernuclear spectroscopy experiments via the (K^-, K^+) reaction will be performed in J-PARC [4], which may give information on the ΞN interaction if clear peak structure is observed. In addition, Ξ-atomic X-ray data is also awaited which may help to understand the interaction [5]. Furthermore, Ξ-atomic X-ray data for light nuclei may have another impact on emulsion data, such as "NAGARA" event which gives the binding energy of double Λs ($B_{\Lambda\Lambda}[^{6}_{\Lambda\Lambda}\mathrm{He}]$) of 6.91 ± 0.16 MeV [6]. In this analysis, the binding energy of Ξ^- C atom (B_Ξ) is necessary to obtain the $B_{\Lambda\Lambda}$ value from kinematics at the production point of $^{6}_{\Lambda\Lambda}\mathrm{He}$. The B_Ξ value of 0.13 MeV, corresponding to the binding energy of $3D$ Ξ-atomic state, was assumed according to a theoretical suggestion. However, the "last" Ξ^- C atomic state may be different if the absorption strength is different from the expectation. The absorption strength, and thus which state is the "last", should be confirmed by Ξ-atomic X-ray spectroscopy. Ξ-atomic X-ray data for nuclei contained in the emulsion (carbon, nitrogen and oxygen) may help the emulsion analysis. No experimental data for Ξ-atomic X ray exists at present. 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 shown in section 2 and 3. Future prospects for Ξ-atomic X-ray spectroscopy, to cover a wide mass range of target nuclei, are also discussed later.

2. Ξ-atomic X-ray spectroscopy in J-PARC E07

Our first measurement of Ξ-atomic X rays has been performed as a byproduct of J-PARC E07 experiment, search for double Λ hypernuclei and Ξ hypernuclei with hybrid emulsion technique. The data taking was done in 2016-2017. Figure 1(a) shows experimental setup around the target. In this experiment, hypernuclei were produced via Ξ^- capture by nuclei in a emulsion stack. Ξ^-s were produced via the (K^-, K^+) reaction and injected into the emulsion. Stopped Ξ^-s should form Ξ atoms before the hypernuclear production reaction. Tracks of Ξ^-, measured by KURAMA spectrometer, were used for a track following procedure for emulsion analysis. By applying this method called hybrid emulsion technique, we found Ξ^- stop events efficiently. For the X-ray measurement, a germanium(Ge) detector array, Hyperball-X, was installed near the emulsion stack.

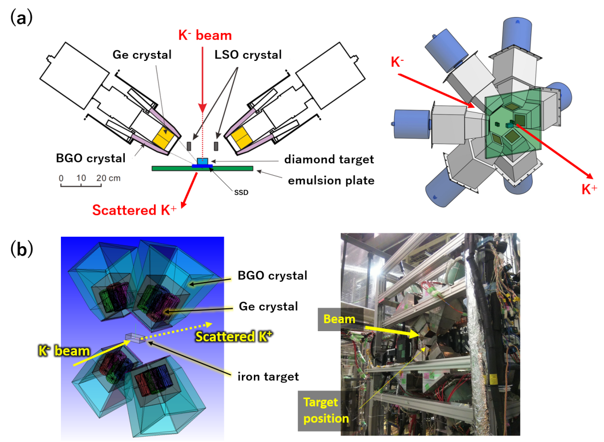

Figure 1: Schematic views and a photo of the detector setup around experimental targets. (a) a Ge detector array Hyperball-X was installed with emulsion plate in J-PARC E07. (b) a Ge detector array Hyperball-X' was installed near the iron target in J-PARC E03.

The array can mount six detector units which consist of a Ge detector and BGO counters for background suppression. When Ξ^-s stop in emulsion, it is possible to 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^- will be 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. Ξ^- C atoms can be formed in such events. In this measurement, we applied two methods to observe Ξ-atomic X rays; (1) combined analysis with Ξ^- stop identification using emulsion information, and (2) coincidence with only Ξ^- production without emulsion information.

Combined analysis with emulsion information

By selecting Ξ^- stop events with emulsion information, a good signal to noise ratio for the X-ray spectrum is expected while the yield should be low because of a low Ξ^- stopping probability and small abundance of each target nuclei in the emulsion: C, N, O, Br and Ag. Furthermore, the solid angle for the Ge detectors was limited by interference with the emulsion and tracking system. As already mentioned, X rays from Ξ^- atoms on Br and Ag are expected to be seen in the Ge detector spectra with this method. Expected X-ray transitions to the "last" Ξ^--atomic states, which can not emit X rays due to strong absorption, are $(n, l) = (7, 6) \to (6, 5)$ for Br and $(8, 7) \to (7, 6)$ for Ag. Corresponding X-ray energies are 315 and 370 keV, respectively. At present, the emulsion analysis is ongoing and the number of identified Ξ^- stop events is about 20% of the expected number in full statistics. It is difficult to see peak structure in the X-ray spectrum because expected X-ray counts is $\sim$4 with this statistics analysis. Further progress in emulsion analysis is necessary.

Analysis without emulsion information

Ξ^- C atoms can be formed when produced Ξ^-s stop in the diamond target. In this analysis, we tried to select events in which Ξ^-s do not reach a SSD placed at just downstream of the diamond target. In addition, by selecting Ξ^-s with low recoil momenta, true X-ray events will be selected efficiently because of high stop probabilities of those Ξ^-s. However, the signal to noise ratio is lower than the emulsion combined analysis in which Ξ^- stop events are clearly identified. The expected X-ray transition to the "last" Ξ^--atomic state is $3D \to 2P$ in case of weak absorption, of which corresponding X-ray energy is 154 keV. Unlike in the previous method, full statistics is available at present in this analysis without the emulsion analysis. Preliminary result shows no clear peak structure in the X-ray spectrum. We estimated the upper limit for the branching ratio of the $3D \to 2P$ transition to be ~40% / Ξ^- stop, which is close to a value suggested by a theoretical case study with the lattice QCD potential [7]. Recently, we made a plan to re-try this measurement with improved sensitivity in a future experiment. Details were shown in section 4.

3. Ξ-atomic X-ray spectroscopy in J-PARC E03

Our second measurement on Ξ-atomic X rays has been performed as J-PARC E03 which is a dedicated experiment for Ξ-atomic X-ray spectroscopy. We selected iron as a target because of (1) a technical reason; Iron is dense (7.9 g/cm^3) enough with a higher Ξ^- stopping probability and (2) a physical reason; the expected absorption strength corresponding to the energy width of 4 keV is suitable for our measurement. Since the J-PARC beam intensity is currently not enough 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, it is expected that a peak structure of the X-ray transition to the "last" Ξ^- Fe atomic state, (6, 5) →(5, 4) transition, of which energy is ~286 keV, can be seen if the energy width is 1 keV, while the full statistics is necessary in the case of 4 keV energy width. Furthermore, the upper X-ray transition, (7, 6) →(6, 5) transition with corresponding energy of 172 keV, will be observed without peak broadening due to its narrow energy width. 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 in a 24 g/cm^2 thick iron target and stopped in it. Ξ^- production was tagged by the missing mass analysis by reconstructing momenta of beam K^-s and scattered K^+s with the magnetic spectrometers, K1.8 beam line spectrometer and KURAMA spectrometer. X rays were detected by a Ge detector array by taking a coincidence with magnetic spectrometers. The Ge detector array, Hyperball-X', was installed near the target as shown in Fig.1(b), instead of another Ge detector array, Hyperball-J, which will be used for the full statistics run. 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 satisfy both a large solid angle in total and a low counting rate for each Ge crystal. High energy resolution has a great merit in the 1 keV energy width case, even if dead time due to signal pileup is longer. To optimize for 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 statistics run for a higher beam intensity. The 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 with momentum reconstruction in the beam line spectrometer and the KURAMA spectrometer. Performances of Hyperball-X' were also evaluated for resolutions, efficiencies and background suppression. In addition, an energy calibration accuracy of 0.05 keV was achieved by taking in-beam calibration data with a trigger generated by LSO scintillator with natural activity of ^{176}Lu. Further analysis for event selections and calibrations is necessary to obtain the final X-ray spectrum. The result will be reported in near future.

4. Future prospects of Ξ-atomic X-ray spectroscopy in J-PARC

We are planning next measurement on Ξ-atomic X rays simultaneously with high resolution Ξ hypernuclear spectroscopy experiments using the S-2S spectrometer. Systematic measurements with various targets, for example, a carbon target (J-PARC E70) and a lithium target (J-PARC E75), will be performed [4]. We have chance to take X-ray data in parallel, while the acceptance of the S-2S spectrometer will limit X-ray yields. The first experiment with the S-2S (J-PARC E70) will be performed in 2023 with a carbon target. In this experiment, the experimental target is Active Fiber Target (AFT) which consists of scintillating fibers including carbon. AFT's hit information will be used for energy loss correction. In addition, the AFT's hit information also help to identify Ξ^- stop events, leading to a good signal to noise ratio for Ξ-atomic X-ray spectroscopy, while a low density of AFT will limit the Ξ^- stop probability. 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. We are working on optimization of the detector setup considering interference between AFT and the Ge detectors. Ξ-atomic X-ray data for a wide mass range of nuclei should be taken in future measurements. We will try X-ray spectroscopy for carbon and other light target nuclei in the S-2S experiments. X-ray data for Ξ^- Fe atoms will be reported from J-PARC E03. X ray data for heavy Br and Ag will be reported from J-PARC E07 after the emulsion analysis. Furthermore, PANDA group at FAIR facility is planning an X-ray spectroscopy experiment covering a heavier Pb target.

5. Summary

X-ray spectroscopy of hadronic atoms is a powerful tool to investigate strong interaction between the hadron and nuclei. No experimental data for Ξ-atomic X ray exists at present. Aiming for the world-first detection of the X rays, we have conducted two experiments, J-PARC E07 and J-PARC E03. Preliminary reports from these experiments were shown, but further analysis is necessary to finalize these results. As a part of the future plans of Ξ-atomic X-ray spectroscopy experiments at J-PARC, we are planning an experiment for Ξ-atomic X rays with C and Li nuclei, employing the S-2S spectrometer.

References

[1] E. Friedman, A. Gal, the International School of Physics Enrico Fermi (2007).

[2] S.H. Hayakawa *et al*., Phys. Rev. Lett. 126 (2021) 6, 062501.

[3] M. Yoshimoto *et al*., PTEP 2021 (2021) 7, 073D02.

[4] T. Nagae *et al*., AIP Conf. Proc. 2130 (2019) 1, 020015.

[5] C. J. Batty, E. Friedman, and A. Gal, Phys. Rev. C59 (1999) 295.

[6] H. Takahashi *et al*., Phys. Rev. Lett. 87 (2001) 212502.

[7] T. Koike, private communication.