Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)
JPS Conf. Proc. **26**, 031016 (2019)
https://doi.org/10.7566/JPSCP.26.031016

The Ξ^- Atom X-ray Spectroscopy at J-PARC

Manami Fujita[1], Ryotaro Honda[1], Kenji Hosomi[2], Yuji Ishikawa[1], Honoka Kanauchi[1], Takeshi Koike[1,3], Hirokazu Tamura[1], Mifuyu Ukai[4], Takeshi O. Yamamoto[4] for the J-PARC E07 collaboration †

[1]*Department of Physics, Tohoku University, Sendai 980-8756 Japan*
[2]*Advanced Science Research Center (ASRC), Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan*
[3]*Institute for Excellence in Higher Education, Tohoku University, Sendai 980-8576 Japan*
[4]*Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[†]*Full author list is same as this archive. arXiv:1811.07726.*
E-mail: fujita@lambda.phys.tohoku.ac.jp

(Received January 18, 2019)

Studying hyperon-nucleon interactions is important for more general understanding of nuclear force. We can extend the NN interaction with the isospin SU(2) symmetry to the baryon-baryon interactions under the flavor SU(3) symmetry. However, experimental data for the S=−2 sector, particularly on the ΞN interaction, are very limited. One way to obtain such information is a measurement of X rays from Ξ^- atoms by obtaining energy shifts of the atomic levels from those precisely calculated based purely on electromagnetic interaction. From the shifts, information on the ΞN potential can be extracted. In 2016 and 2017, we measured X rays from Ξ^- atoms with a Germanium (Ge) detector array, Hyperball-X, at J-PARC using a hybrid emulsion method for the first time. The current analysis status of the Hyperball-X data is reported.

KEYWORDS: strangeness, Ξ^- atom, X-ray spectroscopy

1. Introduction

Investigation on double-Λ hypernuclei and Ξ^- atoms with Strangeness =−2 is important to understand baryon-baryon interactions. X-ray spectroscopy of Ξ^- atom is one way to get information on ΞN interaction. Since a Ξ^- particle has a negative charge, it can form a Ξ^- atom after stopping in material. The produced Ξ^-atoms are highly excited states and deexcite to lower states with X-ray emission before absorbed by nuclei via the strong interaction processes. The atomic energy levels may shift and broaden because of the strong interaction between Ξ^- and nucleon, or Ξ^--N [1]. In order to measure this energy shift, we performed a Ξ^--atomic X-ray spectroscopy experiment at J-PARC.

2. J-PARC E07

The J-PARC E07 experiment — measure of X rays from Ξ^- atom and search for double-Λ hypernuclei using nuclear emulsion — was performed at the K1.8 beam line of the J-PARC hadron experimental facility in 2016 and 2017 [2]. This is the first experiment of Ξ^- atomic X-ray spectroscopy.

Ξ^- particles are produced in a diamond target via the quasi-free $p(K^-, K^+)\Xi^-$ reaction. They slow down inside the target and travel through a nuclear emulsion module located downstream of the target. Some stop in the emulsion module and are captured by atoms contained in emulsion material, such as Ag and Br. The expected X-ray energies just before the Ξ^- absorption for Ξ^- Ag and Ξ^-

Table I. The theoretically predicted shift and width. Case 1 is the result for the t_ρ potential [4] and case 2 is for the Nijmegen D potential [5] .

$Z(n, l)$	E [keV]	shift [keV]	width [keV]
Ag (8,7)→ (7,6)			
case 1	370.45	0.28	0.15
case 2		3.3	0.79
Br (7,6)→ (6,5)			
case 1	315.5	0.73	0.44
case 2		5.5	1.74

Br atoms are 370 keV and 316 keV, respectively, if the strong interaction is ignored. According to a theoretical calculation, the energy shift is expected to be from a few hundreds of eV to a few keV [3]. Results calculated with two types of potential that are the t_ρ potential [4] and the Nijmegen D potential [5] are shown in Table I.

The experimental setup consists of mainly three detector parts as shown in Figure 1. Firstly, two reaction spectrometers were used in order to identify the (K^-, K^+) reaction events. Incident K^- particles of 1.8 GeV/c momentum was analyzed by a beam line spectrometer consisting of QQDQQ magnets, hodoscopes, a fiber tracker, Aerogel Cherenkov detectors, and drift chambers. On the other hand, a scattered K^+ was analyzed by the KURAMA spectrometer consisting of a dipole magnet, hodoscopes, Aerogel Cherenkov detectors, and drift chambers. Secondly, a nuclear emulsion module was located downstream of the diamond target. The event in which Ξ^- stopped in the emulsion module will be called a "Ξ^--stop event" in this text. Ξ^--stop events were observed as two kinds of image in emulsion. One is one or more tracks of charged particles. This is defined as "σ-stop". The other is no track of charged particles except for Auger electrons. This is defined as "ρ-stop". For the σ-stop events, the observed particle should be Ξ^-. On the other hands, the ρ-stop events contain some protons being as background. In addition to the spectrometers, using information from the silicon strip detectors (SSD) located just upstream of the emulsion module, we can track Ξ^- to the point where it stops in the emulsion module. Combining a track determined by an SSD and emulsion makes the time shorter to analyze Ξ^- tracks in emulsion and is called a hybrid emulsion method. Thirdly, a Ge detector array, called Hyperball-X, was located around the target in order to detect X rays. Events that Ξ^- decays inflight become backgrounds for the X-ray spectrum. We can select stopped Ξ^- events and classify them into "σ-stop" and "ρ-stop" from emulsion analysis. By selecting these events, all the background events can be almost removed.

3. Hyperball-X

Hyperball-X consists of six sets of a Ge detector and BGO counters as shown in Figure 1. The energy resolution of each Ge detector was 2 keV in FWHM at 300 keV. Each Ge detector was surrounded by BGO scintillation counters. Backgrounds as Compton scattering and high-energy γ rays can be removed by taking coincidence between the Ge detector and the BGO counters. The measured efficiency of Hyperball-X was 0.73 %.

1.0×10^{11} K^- particles were exposed to 118 emulsion modules in total. 1.0×10^{4} Ξ^- are expected to be the stopped in the emulsion modules. X-ray yield estimate is given as

$$yield = Y_{\Xi capture} \times P_{\Xi(n,l)} \times BR_{\Xi(n,l)\to(n-1,l-1)} \times \epsilon_{Ge}, \tag{1}$$

where $Y_{\Xi capture}$ is the number of Ξs captured in atoms, $P_{\Xi(n,l)}$ the probability that the stopped Ξ reaches the (n, l) atomic state, and BR the branching ratio of the transition. For the Ag(8,7)→(7,6) transition, the predicted ratio is 0.88. For the Br(7,6)→(6,5) transition, the ratio is 0.73 [3]. ϵ_{Ge} is an efficiency of Hyperball-X. The predicted yields of X rays from the last transition of Ag and Br Ξ^- atoms are 13 and 8 counts, respectively.

To be noted, a new energy calibration system consisting of LSO counters and ^{22}Na sources was introduced for energy calibration with high accuracy. They were installed around the diamond target as shown in Figure 1. Two γ rays, 202 keV and 307 keV from LSO scintillators and 511-keV γ ray from ^{22}Na sources, were used as the reference γ rays. The β-γ and γ-γ coincidence between the Ge detectors and LSO counters made continuous in-beam calibration data taking possible. From the in-beam study of energy calibration, the calibration error for the individual Ge detector is reduced to less than ±50 eV over the interpolated energy region between 200 keV and 400 keV.

4. Current analysis

Based on the data analysis of the spectrometers and the SSD, all events were categorized according to different criteria 1, 2 and 3. The criteria 1 event is expected to contain a Ξ^--stop event with high probability. It is expected that 80% of all the Ξ^- stop event will be included in the data set of the criteria 1. Having the highest priority, emulsion scanning with the criteria 1 is being conducted. X rays from Ξ^- atom may be observed in Ge energy spectrum for the σ- and ρ- stop events. The energy spectra corresponding to these events are shown in the Figure 2. The upper one shows the spectrum for the σ-stop events, and the lower one for the σ- and ρ- stop events. By October 2018, 900 σ-stop events have been observed, which correspond to 1500 Ξ^- -stop events. Clear peak structure has yet to be found in the current analysis.

5. Summary

In order to understand baryon-baryon interaction, investigating double-Λ hypernuclei and Ξ^- atom is important. X-ray spectroscopy of Ξ^- atom is one of the essential ways to obtain information on the ΞN interaction. The first experiment of X-ray spectroscopy was performed at the J-PARC K1.8 beam line in 2016 and 2017. The energy shift of X rays from Ξ^- Ag atom and Ξ^- Br atom are measured by the Ge detector array, called Hyperball-X. Using the information of the spectrometers and the SSD to reconstruct Ξ^- tracks, the so-called hybrid emulsion method, Ξ^--stop events in emulsion modules are searched efficiently. The data taking has been completed in 2017, and the emulsion image analysis is on-going. Since X-rays for Ξ^- stop events are selected for the analysis of Hyperball-X, a spectrum of good signal to noise ratio is expected. At the present analysis, 900 σ-stop events (corresponding to 1500 Ξ^- stop-events) were found by emulsion analysis. However, no clear peak structure is observed at the moment in the energy spectrum of Hyperball-X while the analysis is on-going.

References

[1] C. J. Batty, E. Friedman and A. Gal, Phys. Rev. C**59**, 295 (1999).
[2] K. Imai, K. Nakazawa and H. Tamura, J-PARC Proposal E07, `https://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p07-Nakazawa`
[3] E. Friedman and A. Gal, private communication (2001).
[4] C.J. Batty, E. Friedman, and A. Gal, Phys. Rep. **287**, 385 (1997).
[5] M.M. Nagels, T.A. Rijken, and J.J. de Swart, Phys. Rev. D **15**, 2547 (1977).

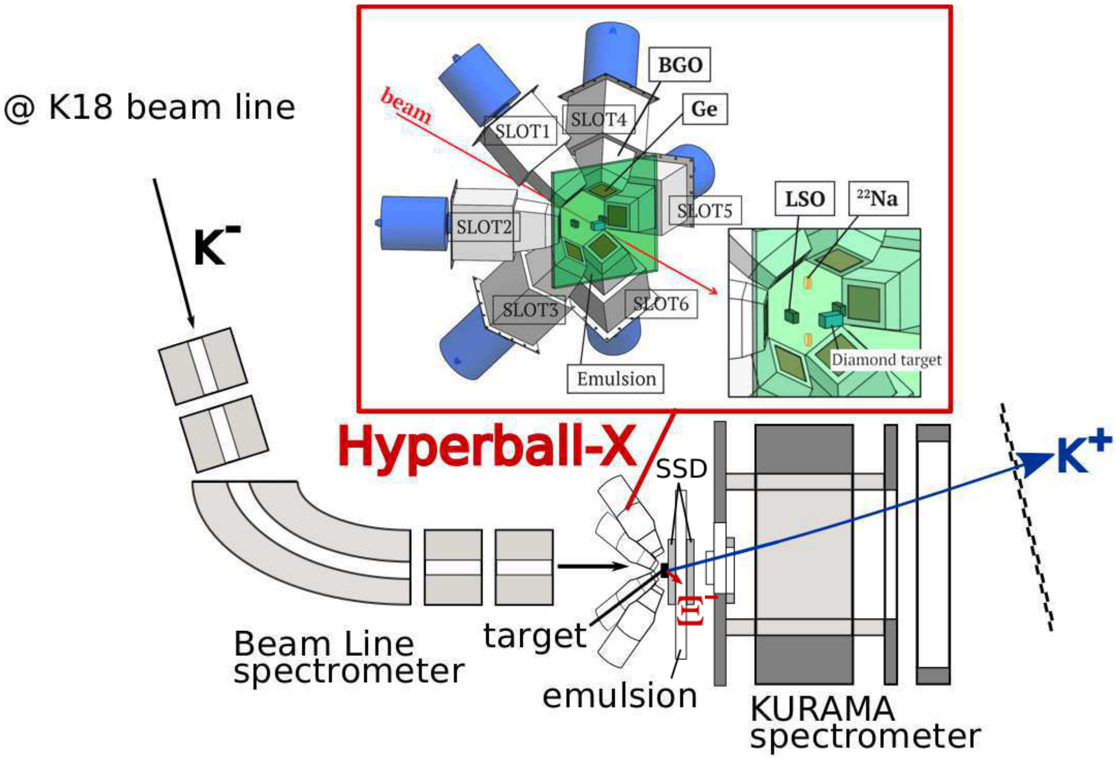

Fig. 1. A schematic drawing of the setup for J-PARC E07 and Hyperball-X system. See text for details.

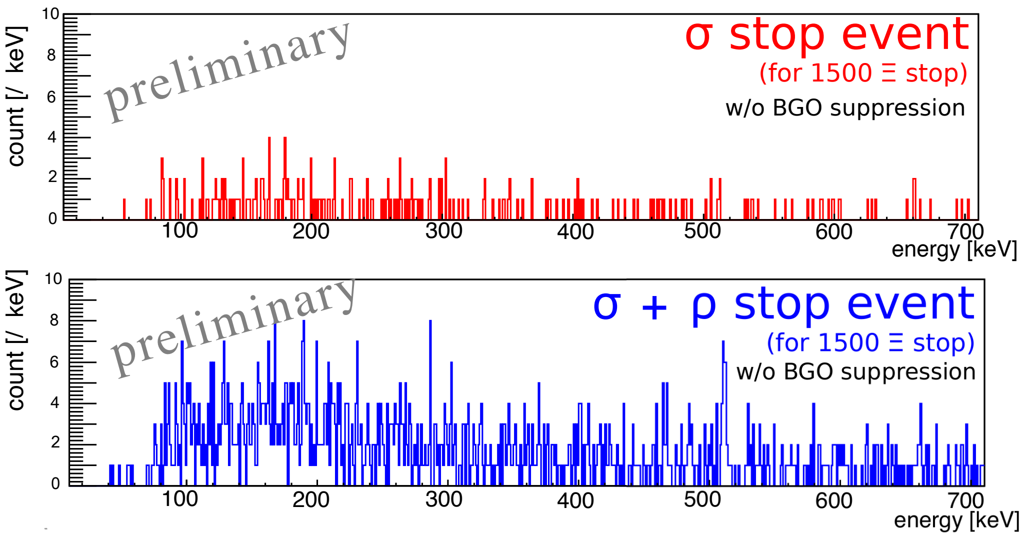

Fig. 2. The energy spectra detected by the Ge detectors. The upper spectrum is for σ-stop events, and the lower one for σ- and ρ-stop events. These numbers of events correspond to the 1500 Ξ^--stop events. For these spectra background suppression by BGO counters is yet to be applied.