EPJ Web of Conferences **271**, 03005 (2022)
HYP2022
https://doi.org/10.1051/epjconf/202227103005

Results of the Ξ^- atomic X-ray measurement in J-PARC E07

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Abstract. Ξ^- atomic X-ray spectroscopy is one of the most useful methods for investigation of the Ξ-nucleus strong interaction. A serious problem in the measurement is the significant background coming from in-flight Ξ^- decay. For the first Ξ^- atomic X-ray spectroscopy experiment, a novel method of identifying stopped Ξ^- events using nuclear emulsion was developed to reject background photons from in-flight Ξ^- decay. We succeeded in reducing the background to 1/170 by this method employing coincidence measurements using the nuclear emulsion and X-ray detectors.

1 Introduction

The interaction between a Ξ hyperon and nucleons/nuclei is currently little understood due to the extremely limited experimental data. The Ξ hypernuclear missing mass spectroscopy has been studied [1, 2], but no clear Ξ hypernuclear peak was observed due to the low resolution. These data only suggest that the depth of the Ξ-nucleus potential is 10–20 MeV. On the other hand, the nuclear emulsion experiments have been conducted as well [3, 4], but no clear Ξ hypernuclear peak was observed due to the limited resolution. S (strangeness) = -2 systems of double Λ hypernuclei and twin Λ hypernuclei were observed. The KISO event identified as a Ξ-^{14}N bound system revealed that the Ξ-nucleus interaction is attractive [5].

In addition to the above two experimental methods, we have established a new approach, Ξ^- atomic X-ray spectroscopy. Since the Ξ^- hyperon has a negative charge, it forms a Ξ^- atom via the Coulomb interaction with the nucleus. The captured Ξ^- hyperon cascades down to the inner orbits by emitting X-rays or Auger electrons. Finally, the Ξ^- is absorbed by the nucleus via the strong interaction of $\Xi^- p \to \Lambda\Lambda$ in the “ last ” orbit where the strong interaction is dominant. Affected by the strong interaction between the Ξ^- and the nucleus, the energy levels of the Ξ^- atom shift and/or broaden compared to those calculated with the Coulomb interaction alone. The values of the energy shifts, ΔE, and the widths, Γ_{abs}, are determined from the Ξ atomic wave function and the potential. When the strong-interaction optical potential is denoted by $U = V + iW$, the measurement of the shifts and widths give

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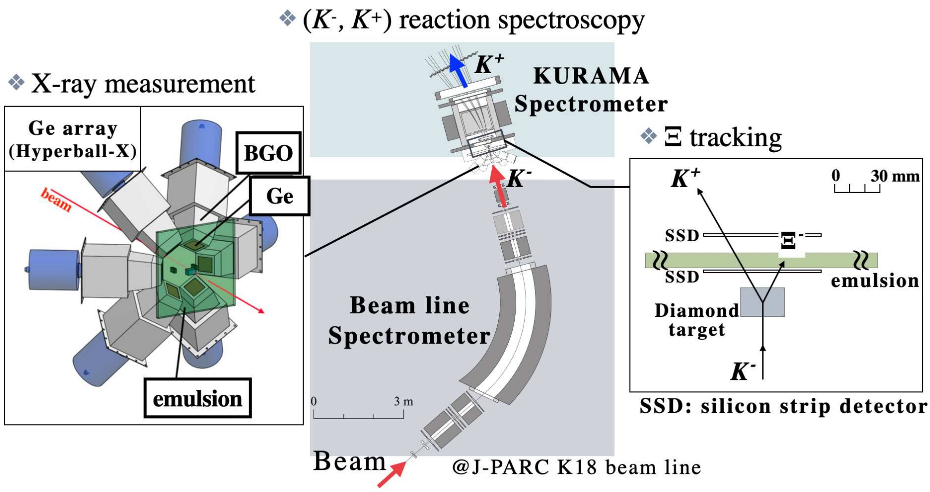

Figure 1. Experimental setup of the J-PARC E07 experiment.

information on the real (V) and imaginary (W) parts of the potential, respectively. In addition, the branching ratio of the last transition is useful to investigate the W potential.

2 Experiment

Since the lifetime of Ξ^- hyperons is as short as ~164 ps, most of them decay, before they stop and form Ξ^- atoms in matter. A serious difficulty in the measurement is that the high energy photons associated with the in-flight Ξ^- decay make a significant background in the X-ray spectra. In addition to selecting Ξ^- production events via the $p(K^+, K^+)\Xi^-$ reaction, it is necessary to identify the stopped Ξ^- events. We developed a novel method employing nuclear emulsion images for the Br and Ag Ξ^- atomic X-rays and carried out a measurement as the J-PARC E07 experiment alongside the experiment searching for $S = -2$ hypernuclei in nuclear emulsion.

The last transitions for Ξ^- Br and Ag atoms are predicted to be the Br($7I \rightarrow 6H$) and Ag($8J \rightarrow 7I$) transitions, and their X-ray energies without shifts are 316 keV and 370 keV, respectively. According to the theoretical calculations assuming the $t\rho$ potential, the shift and width values for the last transitions of the Ξ^- Ag atom are predicted as 0.28 keV and 0.15 keV, respectively [6, 7].

As shown in Fig. 1, a triple coincidence measurement was performed using three detectors: the two magnetic spectrometers for identifying the Ξ^- production reaction, the nuclear emulsion as a Ξ^- tracking detector, and the germanium (Ge) detector array, named Hyperball-X [8], for X-ray measurement. The silicon strip detectors (SSD) were installed upstream of the emulsion for Ξ^- track analysis, and the point where the Ξ^- hyperon reached the emulsion surface was predicted. Then, the emulsion image analysis was performed with a microscope, and the Ξ^- track was identified and followed to the end where the Ξ^- was stopped and absorbed or decayed in flight.

3 Analysis

Firstly, Ξ^- production events were identified by analysis of the $p(K^-, K^+)\Xi^-$ reaction; K^- and K^+ mesons were analyzed by the two magnetic spectrometers, and the events having the vertex of K^- and K^+ tracks within the reaction target were selected. In addition, the consistency between the Ξ^- track detected by SSD and the reconstructed missing momentum of the (K^-, K^+) reaction was checked. As a result, the number of the selected stopped Ξ^- events corresponds to 80% of the expected yield in simulation.

Secondly, the stopped Ξ^- events were identified in the emulsion. A total of 35438 Ξ^- tracks in all 118 emulsion modules were analyzed. The stopped Ξ^- hyperons were observed as one of the two types of images shown in Fig. 2. For the first case (I), classified as a "σ-stop" event, one or more charged fragments/particles are observed at the Ξ^- hyperon stopping point. For the second case (II), classified as a "ρ-stop" event, no charged particle tracks were observed at the stopping point. This happened when only neutral particles, including n, Λ, and π^0, were produced in the Ξ^- absorption process, or when heavy fragments were produced but their tracks were too short to be observed. The numbers of the observed σ- and ρ-stop events were 2208 and 9961, respectively. Assuming a ratio of σ- and ρ-stop events of 2:1 [9], the number of Ξ^- events in the ρ-stop events is estimated to be $\sim$ 1100, and the others are considered to be proton contaminations. Auger electrons associated with the de-excitation of Ξ^- atoms can be observed. To reject proton contamination, only ρ-stop events with Auger electrons were selected.

Finally, coincidence analysis of selected stopped Ξ^- events and X-ray data was performed. The energies of the Ge detectors were calibrated by a newly-developed in-beam energy calibration method [8].

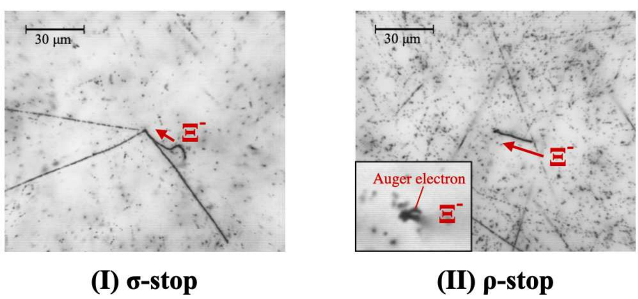

Figure 2. Emulsion images for (I) a σ-stop event and (II) a ρ-stop event

4 Results and discussion

The X-ray spectrum for the Ξ^- production events identified by the reaction analysis was obtained as shown in Fig. 3 (a). Several γ rays produced by the scattered beam or secondary particles/photons hitting the Ge detectors or surrounding materials were observed. Assuming that the signal is negligibly small compared to the background, the spectrum (a) was fitted with a linear function, and the background level was found to be 63.5 counts/keV at 370 keV. The spectrum for the σ-stop events and "ρ-stop with Auger electron" events was obtained as shown in Fig. 3 (b). For a peak search, the spectrum (b) was fitted by a Gaussian function plus a constant background. The spectrum (b) from 200 to 400 keV is shown at the top panel of Fig. 4, and the obtained peak significance values are plotted at the bottom. No evident peak with significance larger than 3σ was observed. By fitting spectrum (b) with a constant function, assuming that the signal is negligible, we found that the background level was 0.34 counts/keV in the region of 300–400 keV. The background level was successfully suppressed to 1/170 by employing the selection using emulsion images. The expected X-ray yield for the Ag(8J $\rightarrow$ 7I) transition is 2.2 counts, and the signal to noise ratio, $S/\sqrt{N}$, was estimated

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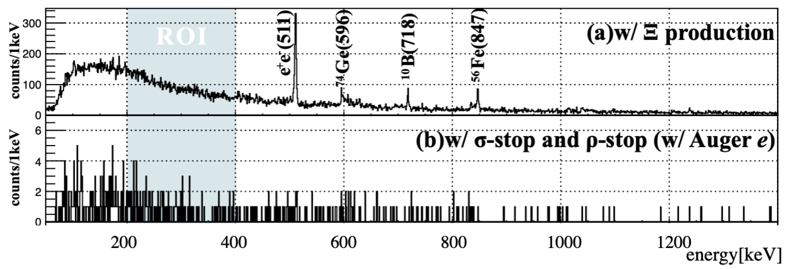

Figure 3. X-ray spectra (a) for the Ξ^- production events, and (b) for the σ-stop events and the "ρ-stop with Auger electron" events.

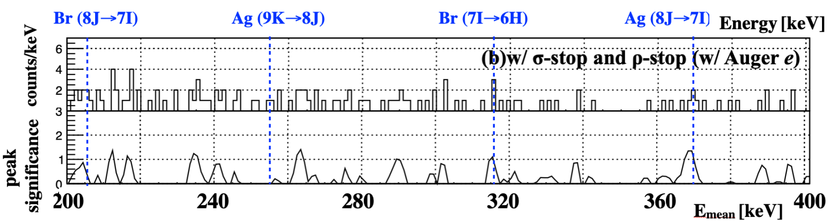

Figure 4. X-ray spectrum (top) and peak significance (bottom) for the spectrum (b) for the σ-stop events and the "ρ-stop with Auger electron" events. The dotted lines show the X-ray energies from Ξ^- Br and Ag atoms without shifts. The E_{mean} is the mean value of the Gaussian function.

to be 1.7. Thus, the Ξ^- Ag atomic X-ray peaks with a 3.8σ significance would be observed if five times more data are taken.

5 Summary

The first Ξ^- atomic X-ray spectroscopy experiment (J-PARC E07) was conducted at J-PARC K1.8 beam line to investigate Ξ-nucleus interaction by measuring the shift and width of the last transitions. To reject the significant background due to the in-flight Ξ^- decay, a novel method of identifying stopped Ξ^- events by a coincidence of magnetic spectrometers, nuclear emulsion, and X-ray detectors was employed. The X-rays of the last transitions of Ξ^- Br and Ξ^- Ag atoms were measured by the Ge detector array. Although no evident peak was observed, the background level was drastically reduced by employing the triple coincidence measurement. With five times higher statistics, successful identification of the Ξ^- atomic X-ray peaks would be possible in the future.

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