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Cross-section measurement of virtual photoproduction of iso-triplet three-body hypernucleus, Λnn

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Abstract. Missing-mass spectroscopy with the ${}^{3}\mathrm{H}(e, e'K^{+})$ reaction was carried out at Jefferson Lab's (JLab) Hall A in Oct–Nov, 2018. The differential cross section for the ${}^{3}\mathrm{H}(\gamma^{*}, K^{+})\Lambda nn$ was deduced at $\omega = E_e - E_{e'} = 2.102$ GeV and at the forward K^{+}-scattering angle ($0^\circ \leq \theta_{\gamma^{*}K} \leq 5^\circ$) in the laboratory frame. Given typical predicted energies and decay widths, which are $(B_\Lambda, \Gamma) = (-0.25, 0.8)$ and $(-0.55, 4.7)$ MeV, the cross sections were found to be $11.2 \pm 4.8(\mathrm{stat.})^{+4.1}_{-2.1}(\mathrm{sys.})$ and $18.1 \pm 6.8(\mathrm{stat.})^{+4.2}_{-2.9}(\mathrm{sys.})$ nb/sr, respectively. The obtained result would impose a constraint for interaction models particularly between Λ and neutron by comparing to theoretical calculations.

1 Introduction

Existing data of binding energies of Λ hypernuclei and scattering experiments between Λ and proton lead to a prediction that three-body hypernuclei of the iso-spin triplet state, such as Λpp and Λnn, do not exist [1]. However, the HypHI collaboration at GSI identified events that may be interpreted as the bound states of Λnn and even a two-body system of Λn in invariant-mass spectra [2]. It is noted that the experiment at GSI measured decayed particles from weak-decay processes of hypernuclei, and essentially had sensitivity to only the bound state. The bound state of Λnn is hard to be theoretically explained maintaining consistency of energy levels of other hypernuclei [3–9]. On the other hand, some theoretical calculations support the existence of resonant state [7–14]. Experiments which can also investigate the resonant state should help in order to pin down the bound Λnn problem. The experiment at Jefferson Lab (JLab) which is described in the present article (JLab E12-17-003 Experiment) has sensitivity to both bound and resonant states because it measures the reaction at the strangeness production (missing-mass method). The data analysis is divided into three as follows: (i) Λnn-peak search with a count-base spectrum [20], (ii) measurement of the cross-section of ${}^{3}\mathrm{H}(\gamma^{*}, K^{+})\Lambda nn$ [21], and (iii) study of the final state interaction between Λ and n based on the shape analysis of quasi-free Λ spectrum [22]. The present article shows a part of result of the analysis (ii).

2 Λnn-search experiment by electron beam

We performed the experiment to investigate the Λnn state through the missing-mass spectroscopy with the reaction of ${}^{3}\mathrm{H}(e, e'K^{+})$ at JLab's Experimental Hall A in 2018. The continuous electron beam at $E_e = 4.32$ GeV with the rastered beam size of 2×2 mm^2 was impinged on a gaseous tritium target [23]. The typical beam intensity on the target was 1.4×10^{14} electrons per second (22.5μA). The scattered electron (e') and K^+ were measured by two HRSs [24] which are existing spectrometers at JLab Hall A. The central momenta measured by the HRSs were set to be 2.218 and 1.823 GeV/c for the e' and K^+, respectively. The acceptance of the K^+ scattering angle with respect to the virtual photon was about $0^\circ \leq \theta_{\gamma^* K} \leq 5^\circ$ in the laboratory frame. The beam energy on the target was well controlled, and total of its energy spread and fluctuation ($\Delta E_e / E_e$) was down to less than a few of 10^{-4} in FWHM. Momentum vectors of the e' and K^+ at a reaction point were reconstructed by the HRSs, and they were used to obtain the missing-mass spectrum. The Λ binding energy B_Λ is calculated once the missing mass $M_{\Lambda nn}$ is obtained as follows, $B_\Lambda = 2M_n + M_\Lambda - M_{\Lambda nn}$ where $M_{n,\Lambda}$ are the masses of neutron and Λ [15].

The momentum vectors of e' and K^+ were obtained by a backward transfer matrix (BTM) for each spectrometer [16]. The matrix elements were optimized by using data with sieve slits (SSs), a hydrogen target. The SSs are 2.54-cm thick tungsten plates that have specific patterns of holes, and we took special data with the SS attached to a first quadrupole magnet of each spectrometer. The elements of BTMs for the scattering angle were tuned so as to reproduce the 2-D images of SSs' hole patterns. As for the elements of the momentum, Λ and Σ^0 productions from the hydrogen target were used as references because the masses of Λ and Σ^0 are well known. The obtained mass resolution of Λ is $\sigma_\Lambda = 1.3 \pm 0.1$ MeV/c^2 which is consistent with the expectation by a Monte Carlo (MC) simulation based on Geant4 [17–19]. The MC simulation determined the expected mass resolution for the Λnn production to be $\sigma^{\text{pred.}}_{\Lambda nn} = 1.5 \pm 0.2$ MeV/c^2 when its decay width is assumed to be $\Gamma = 0$ MeV. In addition, the systematic uncertainty on the binding-energy measurement was found to be $|\Delta B^{\text{sys.}}_\Lambda| = 0.4$ MeV for the present analysis. Refer to Ref. [21] for details.

3 Analysis and result

Figure 1 shows the differential cross section for the ^{3}H(γ^*, K^+) reaction as a function of $-B_\Lambda$. In the present analysis, a momentum cut that allowed the particle distribution in the MC simulation to be consistent with that in the experimental data was applied to minimize the systematic error on the differential cross section due to the acceptance correction. It is noted that the momentum cut reduced the number of events by about 10–20%.

The background distribution of the accidental coincidence between e' and K^+ was obtained by mixed event analysis (MEA) as shown in Fig. 1. The MEA takes random combinations of e' and K^+ from the data sample to estimate the distribution with a much smaller statistical uncertainty. The MEA was used and proven to work well in the past hypernuclear experiments with the $(e, e'K^+)$ reaction [25–30]. On the other hand, the distribution of the quasi-free (QF) Λ production which rises at $-B_\Lambda = 0$ MeV is unknown. The QF-Λ distribution might be approximated as a linear function unless the considered range is not far from the threshold ($-B_\Lambda = 0$ MeV). Decent treatment of the final state interaction (FSI) between Λ and n (and nn) is necessary to be a closer estimate. However, no theory to estimate the QF-Λ distribution with FSI exists so far. Therefore, we assumed the QF-Λ distribution as the linear function in the present analysis.

Spectral fits were performed with the unbinned maximum likelihood (UBML). The fit function for the signal is a convolution of the experimental response and Breit-Wigner functions. The probability density function that we defined for the fit was composed of the signal function, linear function for the QF-Λ production, and the 4th-order polynomial function for the accidental coincidence background. Here, parameters for the 4th-order polynomial function were determined by using the accidental coincidence-background distribution obtained by MEA in advance of the UBML fit. Figure 2 shows results of the spectral fits assuming

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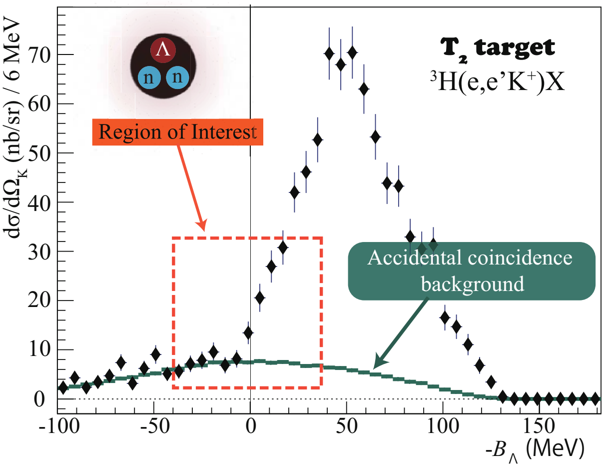

Figure 1. The differential cross section of the ${}^{3}\mathrm{H}(\gamma^{*}, K^{+})$ reaction as a function of $-B_{\Lambda}$. Distribution of the accidental coincidence between e' and K^{+} was obtained by mixed event analysis (MEA).

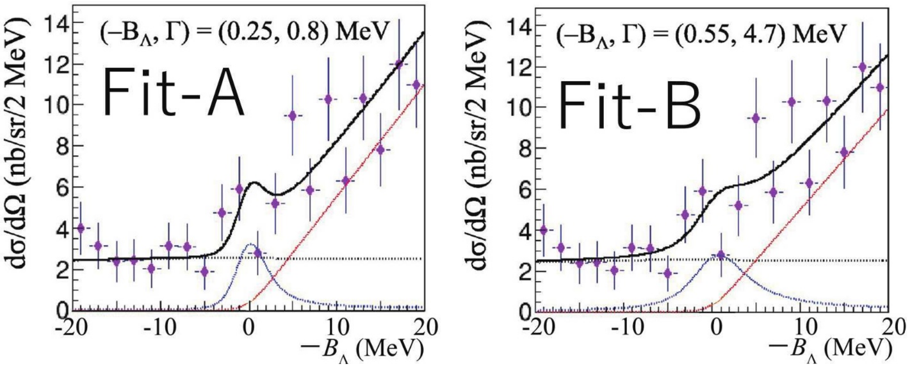

Figure 2. Results of the spectral fits by UBML assuming typical theoretical predictions of the energies and decay widths, $(-B_{\Lambda}, \Gamma) = (0.25, 0.8)$ [9] and $(0.55, 4.7)$ MeV [10], which are labeled Fit-A and Fit-B, respectively.

typical theoretical predictions $(-B_{\Lambda}, \Gamma) = (0.25, 0.8)$ [9] and $(0.55, 4.7)$ MeV [10]; the former (Fit-A) has a smaller decay width and the latter (Fit-B) has a larger one. It is noted that the Γ was taken into account in the Breit-Wigner function of the signal function.

The obtained cross sections for the signal were $11.2 \pm 4.8(\mathrm{stat.})^{+4.1}_{-2.1}(\mathrm{sys.})$ and $18.1 \pm 6.8(\mathrm{stat.})^{+4.2}_{-2.9}(\mathrm{sys.})$ nb/sr for Fit-A and Fit-B, respectively. There is surplus that could be attributed to the Λnn signal for both cases. However, the peak significance is less than three sigma which does not allow us to reach decisive conclusion about the Λnn state. Therefore, we also derived the upper limit of the differential cross section. A 2-D scan of the upper limit of the cross section was performed for $-20 \leq -B_{\Lambda} \leq 20$ MeV and $0 \leq \Gamma \leq 10$ MeV. The result of the cross-section upper limits is shown in Ref. [21].

4 Conclusion

We performed the experiment with the $^{3}\mathrm{H}(e, e'K^{+})$ reaction at JLab Hall A to investigate the Λnn state. The present article focuses on the data analysis of the differential cross section for the $^{3}\mathrm{H}(\gamma^{*}, K^{+})\Lambda nn$ reaction. Given typical predictions of the energies and decay widths, which are $(B_{\Lambda}, \Gamma) = (-0.25, 0.8)$ and $(-0.55, 4.7)$ MeV, the cross sections were obtained to be $11.2 \pm 4.8(\mathrm{stat.})^{+4.1}_{-2.1}(\mathrm{sys.})$ and $18.1 \pm 6.8(\mathrm{stat.})^{+4.2}_{-2.9}(\mathrm{sys.})$ nb/sr, respectively. The obtained result would impose a constraint for interaction models particularly between Λ and n. Theoretical calculations to be compared with the obtained result are awaited. In addition, the result has significant information that allows us to design a future experiment in which we would pin down the bound Λnn problem.

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