Study of ΛN Interaction via the γ-ray Spectroscopy of $^4\Lambda$He and $^{19}\Lambda$F (E13-1st)


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(Received October 14, 2014)

A γ-ray spectroscopy experiment via the $(K^-,\pi^-)$ reaction (J-PARC E13-1st) will be performed at the J-PARC Hadron Experimental Facility using a newly developed Ge detector array, Hyperball-J. Spin-dependent ΛN interactions will be studied through the precise measurement of the structure of hypernuclei, $^4\Lambda$He and $^{19}\Lambda$F. In May 2013, commissioning of whole detector system was carried out and calibration data were taken. In particular, production cross sections of $\Sigma^+$ and $^{12}\Lambda$C via the $(K^-,\pi^-)$ reaction on the CH$_2$ target for $p_K = 1.5$ and 1.8 GeV/c were obtained.

**KEYWORDS:** Λ hypernuclei, γ-ray spectroscopy, J-PARC

1. Introduction

Investigation of the ΛN interaction plays an important role in understanding the baryon-baryon interactions as an extension of the nucleon-nucleon interaction by introducing the strangeness quantum number. The effective potential of the ΛN interaction is expressed as

$$V_{\Lambda N} = V_0(r) + V_{\sigma}(r)\sigma_N \cdot s_\Lambda + V_{\Lambda}(r)I_{NA} \cdot s_\Lambda + V_N(r)I_{NA} \cdot s_N + V_T(r)[3(\sigma_\Lambda \cdot \hat{r})(\sigma_N \cdot \hat{r}) - \sigma_\Lambda \sigma_N].$$
The spin-independent term of the \( \Lambda N \) interaction was well studied by the reaction spectroscopy experiments on various hypernuclei [1]. However, it is difficult to study the spin-dependent terms due to the small effect on the level structure of the hypernuclei. Their energy spacing is sometimes several tens of keV. \( \gamma \)-ray spectroscopy is a powerful tool to study the spin-dependent \( \Lambda N \) interactions through precise measurements of the level structures of hypernuclei by using germanium (Ge) detectors with an energy resolution of \( \sim 3 \) keV. Using this method, the structures of \( p \)-shell hypernuclei were previously measured at KEK and BNL [1], and the strengths of the spin-dependent terms of the \( \Lambda N \) effective interaction in the \( p \)-shell region were determined [2,3]. Figure 1 shows the level scheme of \( ^7 \Lambda Li \) reconstructed by these experiments. The strength of the spin-spin term was extracted from the energy spacing of the ground-state doublet \((3/2^+, 1/2^+)\), which comes from an interaction between the core nucleus of \( S(\text{total spin}) = 1, L(\text{total angular momentum}) = 0 \), and a \( \Lambda \) (spin=1/2) in \( s \)-orbit. Excitation energy of higher excited states also has an information of other spin-dependent terms. We plan to extend our knowledge of the interactions to \( s \)- and \( s d \)-shell regions in the \( \gamma \)-ray spectroscopy experiment (J-PARC E13) using a newly developed Ge detector array, Hyperball-J [5], and high intensity \( K^- \) beam at the J-PARC facility [4].

**Fig. 1.** The level structure of \( ^7 \Lambda Li \) reconstructed by the \( \gamma \)-ray spectroscopy experiments at KEK and BNL [1].

**Fig. 2.** Expected level scheme of \( ^{19} \Lambda F \). The ground-state doublet splitting \((3/2^+-1/2^+)\) is estimated to be about 300 keV by Millener [8].

**Fig. 3.** Cartoon image of a radial dependence of spin-dependent interactions.
2. \(\gamma\)-ray Spectroscopy Experiment at J-PARC (E13-1st)

Several hypernuclei will be studied by the \(\gamma\)-ray spectroscopy experiment (J-PARC E13). In the first phase of E13, \(\gamma\)-ray spectroscopy of \(^4\Lambda\)He and \(^{19}\Lambda\)F will be performed at the K1.8 beam line in the J-PARC Hadron Experimental Facility [6, 7]. By measuring the \(^4\Lambda\)He \((1^- \rightarrow 0^+\) \(\gamma\) ray, existence of charge symmetry breaking in the \(\Lambda N\) interaction will be examined by comparing with the \(^4\Lambda\)H \((1^- \rightarrow 0^+)\) data. \(^{19}\Lambda\)F will be the first sd-shell hypernucleus to be studied by the \(\gamma\)-ray spectroscopy method. Figure 2 shows an expected level scheme of \(^{19}\Lambda\)F. The \(^{19}\Lambda\)F \((1/2^-)\) state will be most strongly populated by the \((K^-, \pi^-)\) reaction followed by cascade de-excitation. Information of the spin-spin term of the \(\Lambda N\) interaction will be extracted from an energy spacing of the ground-state doublet \((3/2^+, 1/2^+)\). The effect of the spin-dependent interaction on the hypernuclear level structure comes from the interaction between a \(\Lambda\), in the \(s\)-orbit for low-lying hypernuclear states, and the valence nucleons. Radial distances between the \(\Lambda\) in the \(s\)-orbit and the valence nucleons in the \(s\)-, \(p\)- and \(sd\)-orbit, corresponding to \(sd\)-shell hypernuclei, are different. Therefore, a radial dependence of the spin-dependent \(\Lambda N\) interactions can be investigated by comparing strengths of the spin-spin term in \(s\)-shell \((^4\Lambda\)He\), \(p\)-shell \((^7\Lambda\)Li\) and \(sd\)-shell \((^{19}\Lambda\)F\) hypernuclei as shown in Fig. 3. In addition, a possible change of \(\Lambda\)‘s magnetic moment in the nuclear medium will be studied by measuring a lifetime of the \(^{19}\Lambda\)F \((3/2^+)\) state.

\(^4\Lambda\)He and \(^{19}\Lambda\)F will be produced by the \((K^-, \pi^-)\) reaction with beam momenta of 1.5 and 1.8 GeV/c, respectively. Figure 4 shows a schematic view of the experimental setup. Incident \(K^-\) mesons and scattered \(\pi^-\) mesons are particle-identified and momentum-analyzed by the beam line spectrometer and the SksMinus spectrometer, respectively. On the other hand, \(\gamma\) rays are detected by Hyperball-J surrounding the target. Through a coincidence measurement between these spectrometer systems and Hyperball-J, \(\gamma\) rays from hypernuclei produced can be measured. Hyperball-J is a newly developed Ge detector array for the hypernuclear \(\gamma\)-ray spectroscopy. The array consists of 32 Ge detectors and PWO counters for the background suppression. The array can be used in a high intensity hadron beam condition by introducing mechanical cooling of a Ge detector [9]. The effect of radiation damage on a Ge detector can be restrained by keeping crystal temperature lower than 80 K. The PWO counters have a much shorter decay constant than conventional BGO counters. Liquid \(^4\)He and HF are chosen as the experimental target. The target systems are being developed.

The detector installation at the K1.8 beam line was started in summer, 2012. Commissioning of the detector system and a beam tuning were performed from March to May, 2013.
Fig. 5. Missing mass spectrum with the CH$_2$ target for the $p(K^-, \pi^-)X$ kinematics (left) and for the $^{12}$C($K^-, \pi^-)^{12}$C kinematics (right) with $p_K = 1.5$ GeV/c. The latter is plotted as a function of Λ binding energy, $B_{\Lambda}$.

3. Result of the E13 Commissioning Beam Time

In the commissioning beam time, data were taken for the CH$_2$ target (2.9 g/cm$^2$) and the CF$_2$ target (20 g/cm$^2$) with $p_K = 1.5$ and 1.8 GeV/c for a performance check of the detectors. Figure 5

Fig. 6. Obtained production cross section of the $p(K^-, \pi^-)\Sigma^+$ (left) and the $^{12}$C($K^-, \pi^-)^{12}$C ($s_{\Lambda}$ states) (right) with beam momenta of 1.5 (red) and 1.8 (black) GeV/c. The previous data for the $\Sigma^+$ production cross sections [10] are also shown in dotted lines. For the cross section of $^{12}$C, the angle dependence predicted by a DWIA calculation [11] are shown in dotted lines after scaled to the data.
Fig. 7. γ-ray energy spectrum obtained with the CF$_2$ target. A red line shows the spectrum applying background suppression with the PWO counters.

shows the obtained missing mass spectra with the CH$_2$ target for the $p(K^-,\pi^-)\Sigma^+$ reaction and for the $^{12}$C($K^-,\pi^-)_{\Lambda}^{12}$C reaction. The successful measurement of the $\Sigma^+$ and $^{12}$C productions confirmed sufficient performance of the detector system. The production cross sections of $\Sigma^+$ and $^{12}$C via the ($K^-\pi^-$) reaction were obtained as shown in Fig.6 as a function of the scattering angle ($\theta_{Kn}$). The obtained cross section of $\Sigma^+$ agreed with old data [10] shown in dotted lines. The hypernuclear production cross sections via the ($K^-\pi^-$) reaction were previously measured only for low momentum kaons ($p_K < 1 \text{ GeV}/c$). The obtained cross section data for $p_K = 1.5$ and 1.8 GeV/c will be used to test theoretical frameworks of hypernuclear production process via the ($K^-\pi^-$) reaction. For example, the angular distribution of the cross section predicted from DWIA calculations [11] and scaled to the data, which are shown in dotted lines in Fig.6 right, agree well with the data.

The reaction-γ coincidence system and the performance of Hyperball-J were checked with the CF$_2$ target irradiated with the $K^-$ beams, although Ge detectors were not fully mounted. Figure 7 shows a γ-ray energy spectrum obtained with the reaction-γ coincidence trigger. Target-originated γ-ray peaks, for example, 197 keV ($^{19}$F:5/2$^+ \rightarrow 1/2^+$) and 718 keV ($^{10}$B:1$^+ \rightarrow 3^+$), were observed. This shows that the coincidence system was working. The energy resolution was ~4 keV (FWHM) at 1 MeV. By applying background suppression with the PWO counters, the background counts were reduced by almost a half at around 1 MeV.

4. Summary

γ-ray spectroscopy using Ge detectors is a powerful tool to study the spin-dependent $\Lambda N$ interactions through a precise measurement of the level structures of hypernuclei. $^4\Lambda$He and $^{16}\Lambda$F will be studied in the 1st part of J-PARC E13 via the ($K^-\pi^-$) reaction. A radial dependence of the spin-spin interaction of the $\Lambda N$ interaction can be investigated by comparing s-, p- and sd-shell hypernuclei. Installation and commissioning of the detector system were performed. Data were taken for the CH$_2$ and the CF$_2$ target with $p_K = 1.5$ and 1.8 GeV/c for the performance check of detectors. The production cross sections of the $p(K^-,\pi^-)\Sigma^+$ and the $^{12}$C($K^-,\pi^-)_{\Lambda}^{12}$C were obtained. The reaction-γ
coincidence system was checked by measuring target-originated γ rays. The whole detector system has been checked and is ready for the physics run.

References

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