Measurement of the Λ Spin-flip $B(M1)$ Value in Hypernuclei


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A hypernuclear γ-ray spectroscopy experiment (E13) will be performed using $K^-$ beam at the K1.8 beam line of the J-PARC Hadron Experimental Facility in 2015. In this experiment, we will determine the $B(M1)$ value of the Λ spin-flip transition of the ground state doublet in $^{19}$F to investigate the magnetic moment of a Λ hyperon in nuclei. In order to check the performance of the whole spectrometer system of E13, a commissioning run was performed at the K1.8 beam line in 2013. We confirmed that the E13 setup is almost ready for the next beam time in 2015. In particular, new detectors for suppressing events from the two main $K^-$ decay modes in the on-line and off-line analyses are installed. As a result, the signal to noise ratio of gamma spectra is drastically improved, and the sensitivity to the $B(M1)$ measurement is expected to increase.

KEYWORDS: Hypernuclei, γ ray spectroscopy, medium effect of hadron
1. Introduction

Properties of hadrons in nuclear matter such as the magnetic moment of a Λ hyperon in hypernuclei may be different from those in free space. Such nuclear medium effects on hadrons are expected to be caused mainly by partial restoration of the chiral symmetry in QCD vacuum. The \( g \)-factor of a Λ in nuclei can be derived indirectly by measuring a reduced transition probability between spin-doublet states \([\Lambda \text{ spin-flip } B(M1)]\) in hypernuclei. Figure 1 shows a schematic illustration of the spin-doublet states of a hypernucleus and a Λ spin-flip M1 transition.

![Spin-doublet states of a hypernucleus and a spin-flip M1 transition](image)

**Fig. 1.** Spin-doublet states of a hypernucleus and a spin-flip M1 transition

The \( B(M1) \) value of such a Λ spin-flip M1 transition can be expressed as [1],

\[
B(M1) = (2J_{up} + 1)^{-1} | \langle \psi_{low} | \mu | \psi_{up} \rangle |^2 = \frac{3 \times 2J_{low} + 1}{2J_c + 1} (g_c - g_\Lambda)^2
\]

\[
= \frac{9}{8\pi} \frac{1}{E_\gamma^3} \frac{1}{\tau}
\]  

(1)

where \( g_c \) and \( g_\Lambda \) denote the \( g \)-factors of the core nucleus and Λ, respectively. \( J_c \) and \( J_{low} \) are the spins of the core nucleus and of the lower state of the spin doublet, while \( E_\gamma \) is a M1 transition energy, as shown in Fig. 1. The \( B(M1) \) value can be derived from the lifetime \( \tau \) of the upper state of the spin doublet. The lifetime \( \tau \) can be measured by analyzing a partly Doppler-broadened γ ray peak shape measured with Ge detectors.

The energy spacings of spin doublets of hypernuclei are typically several hundred keV, but sometimes of a few ten keV. Therefore, We need to use Ge detectors with an excellent energy resolution to resolve the spin doublet.

The recoil momentum of a hypernucleus produced via the \((K^-, \pi^-)\) reaction is in the range of 0.1–0.6 GeV/c for \( p_K = 1.8 \) GeV/c. When a γ ray is emitted from the recoil hypernucleus in motion in the target material, the γ ray energy is shifted according to the recoiling velocity due to the Doppler effect. The de-excitation lifetime can be extracted by comparing the γ ray spectral shape between the experimental data and a simulation. This method is called the Doppler shift attenuation method (DSAM), which is applicable when the lifetime of the γ-transition and the stopping time of the hypernucleus are of the same order of magnitude.

Several γ-ray spectroscopy experiments using a Ge detector array have revealed strengths of the \( \Lambda N \) spin-dependent interactions from precise measurements of the energy levels of \( p \)-shell hypernuclei [2]. They successfully determined the values of parameters in the effective \( \Lambda N \) interaction [4]. On the other hand, the \( g \)-factor of a Λ in nuclei is yet to be measured due to restriction in the stopping time of the recoiling hypernucleus determined by the target density and the recoil momentum as well as a need for large statistics. In the E13 experiment at J-PARC, γ-ray spectroscopy study of \(^{19}\)F hypernucleus via the \((K^-, \pi^-)\) reaction will be performed to investigate the effective \( \Lambda N \) spin-spin interaction in \( sd \)-shell hypernuclei. In this experiment, the Λ spin-flip \( B(M1) \) value of \(^{19}\)F will also be obtained.
The $M1$ transition energy of $^{19}\Lambda F(3/2^+ \rightarrow 1/2^+)$ and the lifetime of the $3/2^+$ state are predicted to be $300$ keV [4] and $6$ ps, respectively. The yield of $^{19}\Lambda F(3/2^+ \rightarrow 1/2^+)$ is expected to be maximum at $p_{K^-} = 1.8$ GeV/$c$ [6]. Carbon tetrafluoride (CF$_4$) ($\rho = 1.6$ g/cm$^3$) is planned to be used as a hypernuclear production target. In these conditions, DSAM can be applied because the stopping time of $^{19}\Lambda F$ in the target is estimated to be $\sim 2.4$ ps by the SRIM code [5].

2. E13 Experiment

The E13 experiment will be performed at the K1.8 beam line [7] using the Superconducting Kaon Spectrometer (SKS) [8] in the spectrometer configuration called SksMinus together with a large-acceptance Ge detector array (Hyperball-J). These spectrometers are shown in Fig. 2. Each incident $K^-$ is momentum-analyzed by the K1.8 beam line spectrometer and irradiated on a CF$_4$ target (20 g/cm$^2$). The outgoing $\pi^-$ is analyzed by SksMinus. These mesons are identified by aerogel Čerenkov counters with a refractive index is 1.03 installed around the target. Production of a $^{19}\Lambda F$ hypernucleus is identified in the missing mass spectrum. In coincidence with the $(K^-; \pi^-)$ reaction, rays are measured by Hyperball-J installed surrounding the target.

$K^-$ decay events in the target region via $K^- \rightarrow \mu^- \bar{\nu}$ and $K^- \rightarrow \pi^- \pi^0$ cannot be discriminated from $(K^-, \pi^-)$ reaction events with the aerogel counters. They produce a huge number of fake triggers and remain in the missing mass spectrum at the most significant background even after the offline analysis. In order to suppress those $K^-$ decay events, the Muon Filter (SMF) and $\pi^0$ veto counter (SP0) are designed and used. SMF consists of hodoscope counters and iron. The decay $\mu^-$ is detected after passing the iron blocks. SP0 consists of lead plates and plastic scintillators and installed at the entrance of the SKS magnet. High energy $\gamma$ rays produced from $\pi^0$ decay are detected as an electromagnetic shower in SP0. The detection efficiencies for $K^- \rightarrow \mu^- \bar{\nu}$ and $K^- \rightarrow \pi^- \pi^0$ decays are 99% and 60%, respectively. The detection efficiency of $K^-$ decay products is 80%. This is the first time to use such beam-decay suppression counters for hypernuclear $\gamma$ ray spectroscopy.

The E13 commissioning data were taken in order to check the performance of the detector system under a realistic $K^-$ beam condition (300 k/spill, beam spill occurs every 6 s) at the K1.8 beam line from March to May, 2013. Figure 3 shows a missing mass spectrum (left) and a $\gamma$ spectrum (right) for the $(K^-, \pi^-)$ reaction on a CH$_2$ target. Spectra after taking anti-coincidence with the background suppressors are also shown. The signal to noise ratio of both spectra is drastically improved. In the $\gamma$ spectrum, background level is reduced to 30% at around 300 keV, which improves the S/N ratio in the $\gamma$ spectrum by 3.3 times.
3. Summary and Future Plans

The hypernuclear γ-ray spectroscopy experiment (E13) will be performed at the K1.8 beam line at J-PARC in 2015, where we will produce $^{19}$F hypernuclei via the $(K^-,\pi^-)$ reaction with 1.8 GeV/c $K^-$ beam to measure the $B(M1)$ value of $^{19}$F($3/2^+\rightarrow1/2^+$). The E13 commissioning was performed at the K1.8 beam line in 2013 to check the performances of all the spectrometers and detectors. The E13 setup is almost ready for physics run in the next beam time in 2015.

References