Hypernuclear gamma-ray spectroscopy: summary and future prospect

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Abstract. The present status and prospects of hypernuclear γ-ray spectroscopy are summarized. In particular, 4-body hypernuclear γ-ray spectroscopy, the recent result of ${}^{4}_{\Lambda}$He and the future plan of ${}^{4}_{\Lambda}$H and charge symmetry breaking in the ΛN interaction are presented. In addition, future plans to measure the Λ-spin-flip $B(M1)$ values of ${}^{7}_{\Lambda}(3/2^+ \to 1/2^+)$ and ${}^{12}_{\Lambda}$C$(2^- \to 1^-)$ transitions are introduced. They aim to study the g-factor of Λ in the nuclear medium.

1 Introduction

The γ-ray spectroscopy experiments of *s*-, *p*- and *sd*-shell hypernuclei have been carried out via the (K^-, π^-) and (π^+, K^+) reactions at KEK-PS, BNL-AGS and J-PARC since 1998. The γ-ray energies were measured using a series of germanium detector arrays, Hyperball, Hyperball-2, and Hyperball-J, which were developed particularly for high counting rate and high energy deposit environment for the hypernuclear experiment using secondary hadron beams.

Precise level structures of hypernuclei measured by the γ-ray spectroscopy give various information about the ΛN interaction. Accumulation of such data is important. In addition, the lifetime of the state which is deexcited by the Λ-spin-flip M1 transition contains information on the Λ g-factor at the nuclear density. However, such a lifetime measurement has not been successful yet.

2 Gamma-ray spectroscopy of light hypernuclei

2.1 4-body hypernuclear structure and charge symmetry breaking in the ΛN interaction

Charge symmetry is a basic concept in the NN interaction. It is expected to hold also in the ΛN interaction and Λ hypernuclei. Therefore the Λ binding energies (B_Λ) between a pair of mirror hypernuclei such as ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He should be identical under this symmetry. However, the old emulsion experiment data reported the charge symmetry breaking (CSB) in the ΛN interaction from a large difference between the B_Λ values of those ground 0^+ states to be $\Delta B_\Lambda = 350$ keV [1]. Theoretical efforts have been made since the 1960s, but have failed to give such a large ΔB_Λ value. Since the B_Λ difference for the excited 1^+ states may provide

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additional important information on the spin dependent CSB, an experiment to measure the ${}^{4}_{\Lambda}\mathrm{He}(1^+ \to 0^+)$ γ-ray energy was performed as J-PARC E13 at J-PARC K1.8 beam line. The γ-ray energy was measured using a germanium detector array, Hyperball-J.

Figure 1 shows the result of the J-PARC E13 experiment. (A) shows the missing mass spectrum measured in the ${}^{4}\mathrm{He}(K^-,\pi^-)$ reaction and (B) shows the γ-ray spectrum with event-by-event Doppler shift correction after gating the peak region in the mass spectrum. As shown in the γ-ray spectrum, a γ-ray peak energy corresponding to the ${}^{4}_{\Lambda}\mathrm{He}(1^+ \to 0^+)$ transition was determined to be 1.406 ± 0.002 ± 0.002 MeV [2].

Combined with the emulsion data of $B_\Lambda(0^+)$, the E13 result and ${}^{4}_{\Lambda}\mathrm{H}(1^+,0^+)$ energy measured by NaI, level schemes of the A=4 mirror hypernuclei are obtained (Fig. 2). Comparing the ΔB_Λ values of the 1^+ and 0^+, the CSB effect is suggested to be strongly spin dependent.

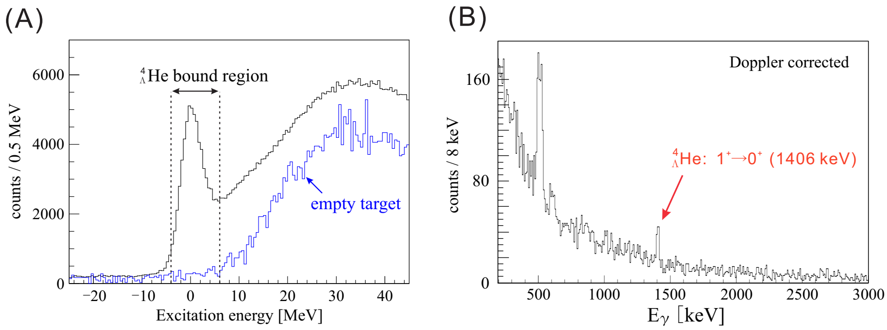

Figure 1. Result of the J-PARC E13 experiment for ${}^{4}_{\Lambda}\mathrm{He}$ γ-ray spectroscopy [2]. (A) Missing mass spectrum measured in the ${}^{4}\mathrm{He}(K^-,\pi^-)$ reaction. (B) γ-ray spectrum with event-by-event Doppler shift correction after gating the peak region in the mass spectrum.

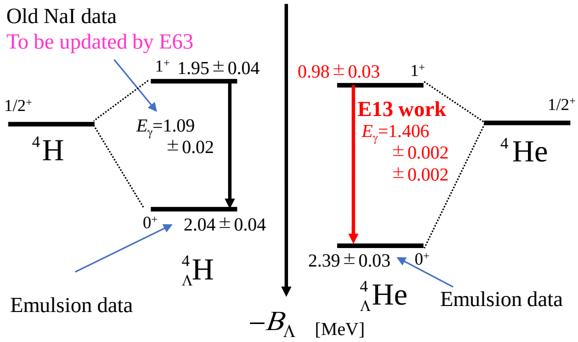

Figure 2. Level schemes of the A=4 mirror hypernuclei. The binding energies of both ground states are determined by old emulsion data [1]. The ${}^{4}_{\Lambda}\mathrm{H}(1^+ \to 0^+)$ transition energy is the average value of three independent experiments measured by NaI counters[3–5].

The ${}^{4}_{\Lambda}\mathrm{H}(1^+ \to 0^+)$ transition energy of 1.09 ± 0.02 MeV in Fig. 2 is the world average of the values reported by three old experiments using NaI detectors, 1.04 ± 0.04 MeV [3], 1.09 ± 0.03 MeV [4], and 1.114 ± 0.015 ± 0.015 MeV [5]. To measure this value precisely by Hyperball-J, a new experiment was proposed and accepted as a part of J-PARC E63[6]. Since ${}^{4}_{\Lambda}\mathrm{H}(1^+)$ cannot be produced by a non-charge exchange reactions. Therefore it was propose to produce ${}^{4}_{\Lambda}H$ as a secondary hypernucleus in the ${}^{3}\mathrm{He}$ emission decay of the ${}^{7}_{\Lambda}\mathrm{Li}$ highly excited unbound states, as shown in Fig. 3. This experiment will be perfomed at K1.1 beam line via the (K^-,π^-) reaction on the lithium target using a $p_K = 0.9$ GeV/c beam.

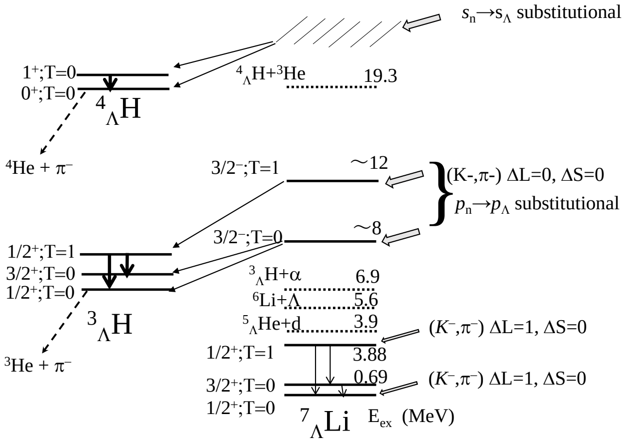

Figure 3. Level scheme of the ${}^{7}_{\Lambda}$Li and the particle emission decay from the highly excited state of the ${}^{7}_{\Lambda}$Li.

2.2 Search for the γ deexcited state of hypertriton

${}^{3}_{\Lambda}$H is the lightest hypernucleus which has a bound state. The GSI data reported the ${}^{3}_{\Lambda}n$ is bound [7]. If so, excited state of ${}^{3}_{\Lambda}$H(1^+,T=1) is also below the $N + N + \Lambda$ threshold. Figure 4 shows the level schemes of the NN and $NN\Lambda$ systems in the case that ${}^{3}_{\Lambda}n$ is bound. Since the excited state of ${}^{3}_{\Lambda}$H(1^+,T=1) cannot decay to the d+Λ channel due to the isospin conservation, it decays to the T=0 ground state doublet by the γ transitions. On the other hand, the JLab data reported the negative result for the existence of the ${}^{3}_{\Lambda}n$ bound state [8]. Even if ${}^{3}_{\Lambda}n$ is not bound, the ${}^{3}_{\Lambda}$H(1^+,T=1) is expected to be very close to the $N + N + \Lambda$ threshold to have a finite γ transition probability.

Search for the γ rays from the ${}^{3}_{\Lambda}$H(1^+,T=1) state is to be performed as a by-product of the ${}^{4}_{\Lambda}$H($1^+ \to 0^+$) measurement (J-PARC E63). As shown in Fig. 3, the ${}^{3}_{\Lambda}$H(1^+,T=1) state can be also produced in the α emission decay from the ${}^{7}_{\Lambda}$Li highly excited unbound states.

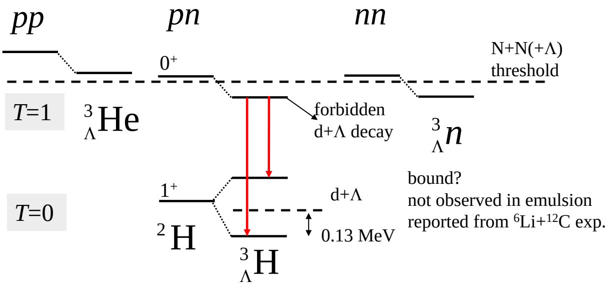

Figure 4. Level schemes of the NN and $NN\Lambda$ systems in case of the ${}^{3}_{\Lambda}n$ is bound as reported in the GSI data[7].

3 B(M1) measrurement of Λ spin-flip M1 transitions

3.1 g-factor of Λ in the nuclear medium

Magnetic moment of a Λ hyperon in the nuclear medium may be different from that in the free space. However the direct measurement of g-factor of hypernuclei is extremely difficult.

When the core nucleus has non-zero spin (J_c), the hypernuclear level splits into the spin-doublet state ($J_c \pm 1/2$) as shown in Fig. 5. The uppler level of the doublet decays to the lower level by the Λ-spin-flip M1 transition. In the weak coupling limit between Λ and the core nucleus, the reduced transition probability $B(M1)$ can be expressed as [9]

$$\begin{aligned} B(M1) &= (2J_{up}+1)^{-1}| < \phi_{low}||\boldsymbol{\mu}||\phi_{up} > |^2 \\ &= \frac{3}{8\pi}\frac{(2J_{low}+1)}{(2J_c+1)}(g_c - g_\Lambda)^2 = \frac{9}{16\pi}\frac{1}{E_\gamma^3}\frac{B.R.(M1)}{\tau_{up}}, \end{aligned} \quad (1)$$

where g_c and g_Λ denote effective g-factors of the core nucleus and Λ, $\mathbf{J}_c$ and $\mathbf{J}_\Lambda$ denote their spins, respectively, $\mathbf{J} = \mathbf{J}_c + \mathbf{J}_\Lambda$ is the spin of the hypernucleus, τ_{up} denotes the lifetime of the upper state of the spin doublet and $B.R.(M1)$ denotes the branching ratio of the M1 transition.

Table 1 shows the experimentally determined Λ-spin-flip M1 transition energies of hypernuclear ground state doublets and the calculated M1 decay widths. Except for the ${}^{12}_{\Lambda}$C case, the branching ratios of the M1 transitions are almost 100% due to their much shorter lifetimes than the typical hypernuclear lifetime to be ~ 200 ps.

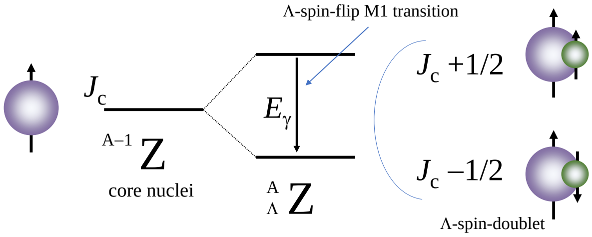

Figure 5. Schematic drawing of the hypernuclear spin-doublet states and the Λ-spin-flip M1 transition.

Table 1. Measured Λ-spin-flip M1 transitions between hypernuclear ground-state doublets and calculated M1 decay widths.

	g.s. doublet J_{up}, J_{low}	E_γ [keV]	Core g-factor [μ_N]	Calculated $1/\Gamma_{M1}$ [ps]
${}^{4}_{\Lambda}$He	$1^+, 0^+$	1406	−4.2552	0.1
${}^{7}_{\Lambda}$Li	$3/2^+, 1/2^+$	692	0.8220	0.5
${}^{11}_{\Lambda}$B	$7/2^+, 5/2^+$	262	0.6002	9
${}^{12}_{\Lambda}$C	$2^-, 1^-$	160	−0.643	440
${}^{19}_{\Lambda}$F	$3/2^+, 1/2^+$	316	0.849(Calc.)	6

3.2 B(M1) of the ${}^{7}_{\Lambda}$Li ground-state doublet by Doppler shift attenuation method

When the stopping time of the recoiling excited hypernucleus in the target material is of the same order as the lifetime of the γ-emitting excited state, the lifetime can be obtained by analyzing a partly Doppler-broadened γ-ray peak shape, which is called the Doppler Shift Attenuation Method (DSAM). To measure the lifetimes precisely by DSAM, matching between the lifetime and the stopping time is essential. In our simulation, the ${}^{7}_{\Lambda}$Li ($3/2^+ \rightarrow 1/2^+$) using a lithium oxide (Li_2O) crystal with a density of 2.01 g/cm^3 is found to be the best candidate for the lifetime measurement applying DSAM.

To measure the B(M1) of the ${}^{7}_{\Lambda}$Li ($3/2^+ \rightarrow 1/2^+$), a new experiment was proposed and accepted as a part of J-PARC E63 [6].

This experiment will be performed at K1,1 beam line using the (K^-, π) reaction on a Li_2O target. K^- beam momentum will be determined after taking a pilot data for 0.9 GeV/c and 1.1 GeV/c momenta to maximize the lifetime sensitivity.

3.3 B(M1) of the ${}^{12}_{\Lambda}$C gound-state doublet by gamma-weak coincidence method

When the lifetime of the upper level of the spin-doublet is of the same order as of the hypernuclear weak decay (~ 200 ps), the lifetime can be determined by measuring the timing of the particles such as π^- emitted by weak decays. The branching ratio of the M1 transition can be measured by the yield of the M1 γ ray. To apply this technique, ${}^{12}_{\Lambda}$C is the best candidate.

Figure 6 shows the level scheme of the ${}^{12}_{\Lambda}$C bound states. Excitation energies were measured in the Hyperball project [10]. The weak decay lifetime of the ${}^{12}_{\Lambda}$C was measured to be 212^{+7}_{-6} ps [11]. This measured lifetime value is slightly affected by the weak decay of 2^- state and feeding from the slow $2^- \rightarrow 1^-$ M1 transition. Expected lifetime and M1 branching ratio of the M1($2^- \rightarrow 1^-$) is calculated to be ~140 ps and 0.32, respectively.

Figure 7 shows the conceptual design to measure the weak decay lifetime and γ rays of ${}^{12}_{\Lambda}$C. In this figure, to measure the timing of the weak decay particles, employment of the dipole magnet and time projection chamber of the type used in J-PARC E42 [12] is assumed. Comparing the lifetimes accompanying γ_1 or γ_2 and γ_3 events, the lifetime of the 2^- can be determined. Further more, the 2^- lifetime can be measured directly using a fast response scintillation counter as a γ-ray detector. For this purpose, $CeBr_3$ scintillator of 17 ps decay constant is to be developed. R&D of this counter and realistic simulation is now undergoing. This experiment is planned to be performed at K1.1 or K1.8BR beam line using a $p_K = 0.9$ GeV/c beam.

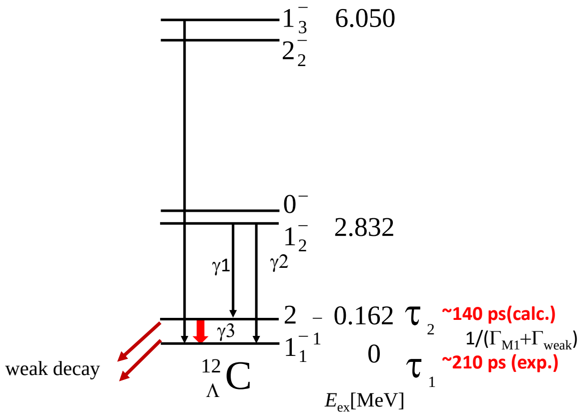

Figure 6. Level scheme of ${}^{12}_{\Lambda}$C bound states. The excitation energies are measured in the Hyperball project [10].

4 Summary

The γ-ray spectroscopy of ${}^{4}_{\Lambda}$He confirmed the existence of large CSB and its spin dependence in the ΛN interaction. Further study of CSB in hypernuclei, precise γ-ray spectroscopy of ${}^{4}_{\Lambda}$H

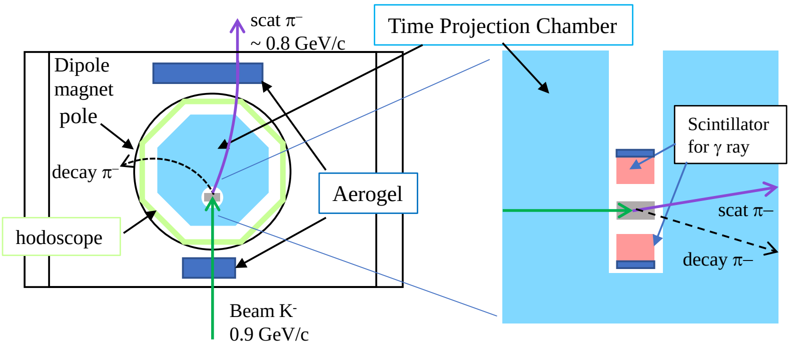

Figure 7. Conseptual design of the hypernuclear γ-weak coincidence experiment to measure the lifetime of the state in which the γ decay and the weak decay are competing. Dipole magnet and time projection chamber are assumed as the type of J-PARC E42 ones[12].

is to be performed via the (K^-, π^-) reaction on the lithium target. As the by-product, search for the ${}^{3}_{\Lambda}$H γ ray transition is also to be performed. In addition, measurement the Λ-spin-flip $B(M1)$ values of ${}^{7}_{\Lambda}(3/2^+ \rightarrow 1/2^+)$ and ${}^{12}_{\Lambda}\mathrm{C}(2^- \rightarrow 1^-)$ transitions will be perfomed to study the g-factor of a Λ in the nuclear medium.

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