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Status report on E566: Hypernuclear γ spectroscopy on ^{12}C target

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1 Introduction

The E566 experiment investigates structures of $^{12}_{\Lambda}$C and $^{11}_{\Lambda}$B hypernuclei by means of high-precision γ-ray spectroscopy technique developed by our group. The $^{12}_{\Lambda}$C and $^{11}_{\Lambda}$B hypernuclei were produced by the (π^+,K^+) reaction on ^{12}C target, in which $^{11}_{\Lambda}$B was produced through proton emission of unbound excited states of $^{12}_{\Lambda}$C. We measured the missing mass of hypernuclear production employing the K6 beam line and the Superconducting Kaon Spectrometer (SKS), and detected their γ rays by using the germanium (Ge) detector array "Hyperball2", the upgraded version of Hyperball with a doubled efficiency.

One of the purposes of the experiment is to produce $^{11}_{\Lambda}$B($7/2^+$) from the p_Λ states of $^{12}_{\Lambda}$C(2^+) and to measure the reduced transition probability $B(M1)$ of the Λ-spin-flip transition $^{11}_{\Lambda}$B($7/2^+ \rightarrow 5/2^+$) with the Doppler shift attenuation method, for the purpose of extracting an effective g-factor of a Λ in a nucleus and investigating a possible modification of the magnetic moment of a Λ. The other purpose is to investigate the ΛN interaction, including the effect of ΣN-ΛN coupling force, from the $^{12}_{\Lambda}$C and $^{11}_{\Lambda}$B level energies. From our previous experiment (BNL E930), the $^{10}_{\Lambda}$B($1^-, 2^-$) spacing was found to be less than 100 keV from non-observation of the $1^- \rightarrow 2^-$ transition [1]. This result gives the spin-spin interaction strength of $\Delta < 0.3$ MeV (see Sect. 3.1), which seems to contradict to the value of $\Delta = 0.43$ MeV derived from the $^{7}_{\Lambda}$Li($3/2^+$,$1/2^+$) spacing [2]. The new data on $^{11}_{\Lambda}$B and $^{12}_{\Lambda}$C will help us solve this "puzzle".

The experiment was carried out in November in 2005. We irradiated 2×10^{12} pions on a 18.6 g/cm^2 olyethylene target. The new apparatus, Hyperball2, showed a good performance as expected through the experiment. The data analysis is in the final stage. We will obtain the final results in a few months. Preliminary results have been published in Ref. [3].

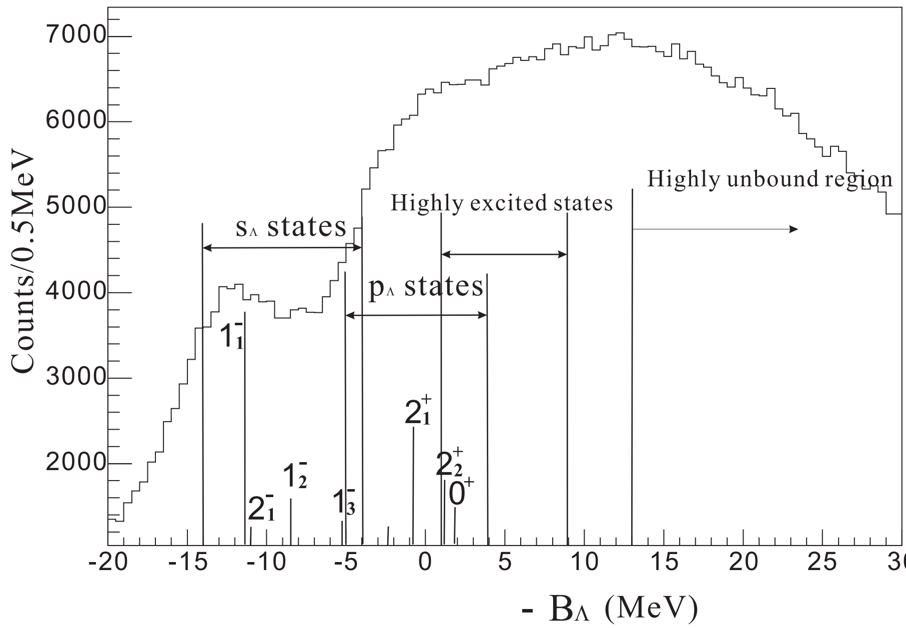

Figure 1: Missing mass sepctrum of ^{12}C(π^+,K^+) reaction plotted in the scale of binding energy of Λ in $^{12}_{\Lambda}$C (preliminary). Theoretically calculated $^{12}_{\Lambda}$C level energies and yields are shown together.

2 Preliminary results

Figure 1 shows the obtained missing mass sepctrum of the ^{12}C(π^+,K^+) reaction. Considering the target thickness, the spectrum shape is consistent with the previous ^{12}C(π^+,K^+)$^{12}_{\Lambda}$C spectrum.

When the bound-state region of $^{12}_{\Lambda}$C ($-14 < -B_{\Lambda} < -4$ MeV) is selected, we observed a γ-ray peak at 2667.3 ± 2.8 keV (preliminary) after Doppler shift correction (see Fig. 2 (a)). This is assigned to the $^{12}_{\Lambda}$C($1^-_2 \rightarrow 2^-$) transition as shown in Fig. 3, because the γ-ray energy is consistent with the excitation energy of $^{12}_{\Lambda}$C(1^-_2) (2.6 MeV) measured in the previous ^{12}C(π^+,K^+)$^{12}_{\Lambda}$C experiment [4] and this transition is expected to have the largest yield in $^{12}_{\Lambda}$C.

When the p_{Λ}-state region of $^{12}_{\Lambda}$C ($-5 < -B_{\Lambda} < 4$ MeV) is selected, we observed a γ-ray peak at 261.6 ± 0.24 keV (preliminary), as shown in Fig. 2 (b). It is uniquely assigned to the spin-flip $M1$ transition between the $^{11}_{\Lambda}$B ground-state doublet, $^{11}_{\Lambda}$B($7/2^+ \rightarrow 5/2^+$) (see Fig. 3), because the energy of the $p_{\Lambda}(2^+)$ state of $^{12}_{\Lambda}$C allows the decay only to the ground state doublet of $^{11}_{\Lambda}$B. The $^{11}_{\Lambda}$B($1/2^+ \rightarrow 5/2^+$) transition at 1482 keV, which was identified in the previous ^{11}B(π^+,K^+) experiment [5], was also observed in this experiment when a higher excitation energy region was selected.

As a result, we determined the level schemes of $^{12}_{\Lambda}$C and $^{11}_{\Lambda}$B as shown in Fig. 3.

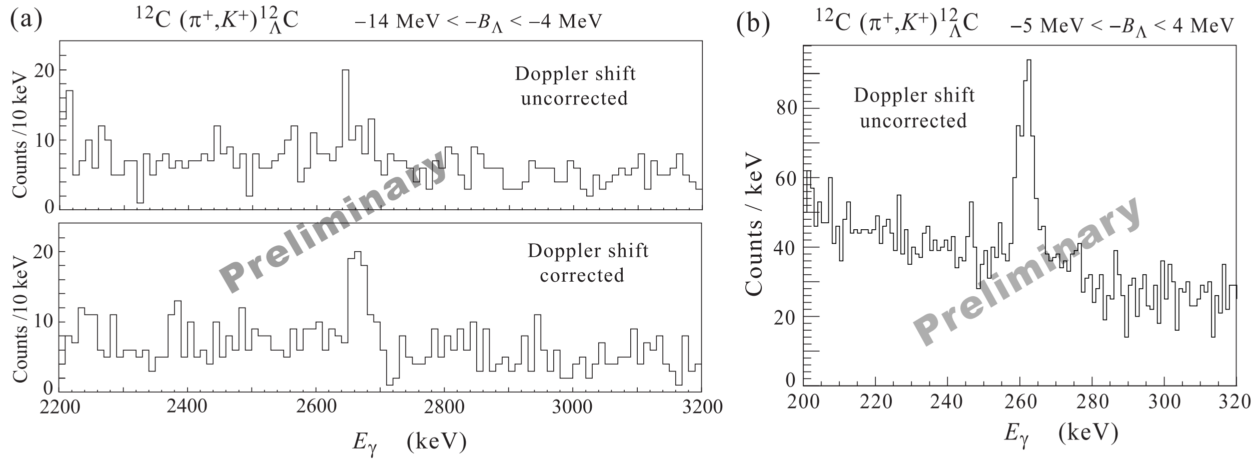

Figure 2: γ-ray spectrum of $^{11}_{\Lambda}$B and $^{12}_{\Lambda}$C measured by the ^{12}C(π^+,K^+) reaction at KEK (E566). (a) shows the spectra when the s_Λ state region of $^{12}_{\Lambda}$C (-14 MeV $< -B_\Lambda < -4$ MeV) is selected and before (top) and after (bottom) Doppler shift correction is applied. The γ ray observed at 2667.3$\pm$2.8 keV (preliminary) is assigned to the transition of $^{12}_{\Lambda}$C($1^- \to 2^-$). (b) shows the spectrum when the $p_\Lambda(2^+)$ state region of $^{12}_{\Lambda}$C (-5 MeV $< -B_\Lambda <$ 4 MeV) is selected. The observed γ-ray peak is assigned to the $^{11}_{\Lambda}$B($7/2^+ \to 5/2^+$) transition after $^{12}_{\Lambda}$C(2^+) $\to$ $^{11}_{\Lambda}$B + p decay.

3 Discussion

3.1 ΛN interaction

From previous data of the Hyperball experiments, all the ΛN spin-dependent interaction strengths have been determined as [6]

$$\Delta = 0.43 \text{ MeV}, \quad S_\Lambda = -0.01 \text{ MeV}, \; S_N = -0.4 \text{ MeV}, \quad T = 0.03 \text{ MeV}. \tag{1}$$

Here, the strength parameters are radial integrals with the $s_\Lambda p_N$ wave function for the spin-spin term $V_\sigma(r)$, the Λ-spin-dependent spin-orbit term $V_\Lambda(r)$, the nucleon-spin-dependent spin-orbit term $V_N(r)$, and the tensor term $V_T(r)$, respectively, of the effective ΛN interaction [7, 8]:

$$V^{eff}_{\Lambda N}(r) = V_0(r) + V_\sigma(r)\, \boldsymbol{s}_\Lambda \boldsymbol{s}_N + V_\Lambda(r)\, \mathbf{l}_{\Lambda N} \boldsymbol{s}_\Lambda + V_N(r)\, \mathbf{l}_{\Lambda N} \boldsymbol{s}_N + V_T(r)\, [3(\boldsymbol{\sigma}_\Lambda \hat{\mathbf{r}})(\boldsymbol{\sigma}_N \hat{\mathbf{r}}) - \boldsymbol{\sigma}_\Lambda \boldsymbol{\sigma}_N] \tag{2}$$

The parameters Δ, S_Λ, S_N, and T were already determined from the level spacings of $^{7}_{\Lambda}$Li($3/2^+, 1/2^+$) [2], $^{9}_{\Lambda}$Be($3/2^+$, $5/2^+$) [9, 1], $^{7}_{\Lambda}$Li($5/2^+, 1/2^+$) [2], and $^{16}_{\Lambda}$O($1^-, 0^-$) [10], respectively.

This parameter set also explains most of the other data of p-shell hypernuclei obtained in the recent Hyperball experiments [11]. However, all the $^{11}_{\Lambda}$B and $^{12}_{\Lambda}$C level energies measured in the present experiment are significantly deviated from the predicted values from the parameter set 1. According to a shell model calculation by Millener, the $^{11}_{\Lambda}$B ground-state doublet ($7/2^+$,$5/2^+$) spacing is described as [6]

$$E(7/2^+, 5/2^+) = 1.025\Delta + 2.467 S_\Lambda + 0.027 S_N - 2.259 T + \Sigma\Lambda(55 \text{ keV}),$$

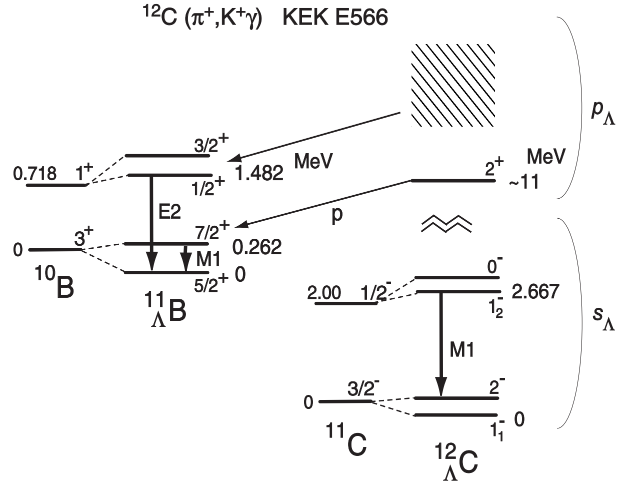

Figure 3: Observed γ transitions and level schemes of ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C determined in this experiment.

where $\Sigma\Lambda$ stands for the effect of ΣN-ΛN coupling force estimated with the Nijmegen hyperon-nucleon interaction model NSC97f. From this equation, the observed energy gives Δ =0.33 MeV, being smaller than the value of Δ = 0.43 MeV extracted from the ${}^{7}_{\Lambda}$Li(3/2$^+$,1/2$^+$) spacing. The recent data of ${}^{16}_{\Lambda}$O $(2^-, 1^-)$ spacing from BNL E930 [12], which are also sensitive only to Δ, corresponds to $\Delta = 0.33$ MeV. Therefore, we may conclude that the Δ value determined to be 0.43 MeV from ${}^{7}_{\Lambda}$Li should be slightly reduced to 0.33 MeV for heavier ($A \geq$10) p-shell hypernuclei [6]. This result partly solves the puzzle of the small ${}^{10}_{\Lambda}$B$(1^-, 2^-)$ spacing giving $\Delta < 0.3$ MeV.

The ${}^{12}_{\Lambda}$C ground-state doublet (1^-_1, 0^-) spacing, which is expected to provide a clue to extract the ΛNN three-body force effect, has not been determined in the present data analysis. We aimed at detecting both $1^-_2 \to 1^-_1, 0^-$ transitions but one of them ($1^-_2 \to 1^-$) was not observed because of lower statistics than expected as well as a possible small branching ratio.

The observed ${}^{11}_{\Lambda}$B$(1/2^+, 5/2^+)$ spacing (1482 keV) and the ${}^{12}_{\Lambda}$C$(1^-_2, 2^-)$ spacing (2667 keV) gives $S_N = -0.9$ and -0.7 MeV, respectively. It is significantly different from the value of $S_N = -0.4$ MeV, which reproduces most of the other hypernuclear data. The contribution of the S_N term is sensitively affected by the wave functions of core nuclei. This discrepancies in the middle of the p-shell may be caused by inaccuracy of the wave functions of core nuclei in the shell model.

3.2 B(M1) measurement

Since the ${}^{11}_{\Lambda}$B$(7/2^+ \to 5/2^+)$ transition energy (262 keV) was found to be much smaller than expected (450 keV) because of the deviation of the Δ value, the lifetime of the $7/2^+$ state, being proportional to $1/E_\gamma^3$, is much longer than expected. Therefore, Doppelr shift attenuation method cannot be applied to this transition. Actually, the $7/2^+ \to 5/2^+$ γ-ray peak was not broadened by Doppler effect and the information of the lifetime cannot be extracted.

4 Future prospects at J-PARC

We will continue our studies of hypernuclear γ-ray spectroscopy at J-PARC, where we employ the (K^-,π^-) reaction using intense K^- beams from the K1.8 or K1.1 beam lines. We are constructing a larger Ge detector array, Hyperball-J [13], which is featured by newly developed techniques necessary to tolerate higher counting rates, such as a mechanical cooling method, background suppression counters with PWO scintillator, and a waveform readout method.

The first experiment titled "γ spectroscopy of light hypernuclei" [14] obtained a stage-2 approval as one of the Day-1 experiments. The purposes of this experiment are (1) B(M1) measurement in ${}^{7}_{\Lambda}$Li($3/2^+ \rightarrow 1/2^+$), (2) detailed studies of ΛN interaction from ${}^{10}_{\Lambda}$B and ${}^{11}_{\Lambda}$B, (3) investigation of charge symmetry breaking in ΛN interaction and production of spin-flip states from ${}^{4}_{\Lambda}$He, and (4) study of ΛN interaction in sd-shell hyeprnuclei from ${}^{19}_{\Lambda}$F. After the E13 experiments, we are planning to perform various experiments on a wide range of hypernuclei up to ${}^{208}_{\Lambda}$Pb, neutron-rich hypernuclei such as ${}^{7}_{\Lambda}$He, B(M1) measurements of various hypernuclei to study isospin and nuclear density dependence of g_Λ value.

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