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Progress in *p*-shell Λ hypernuclear spectroscopy*

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Abstract The strangeness nuclear physics is an important branch of nuclear physics. The spectroscopic study of Λ hypernuclei has been used as a tool for investigating the Λ-N interaction as well as probing the nuclear interior structure. In this paper some high-lights and open questions in the spectroscopic study of *p*-shell Λ hypernuclei are presented.

Key words hypernuclei, spectroscopy, *p*-shell

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1 Introduction

Strangeness nuclear physics as one of the forefronts in nuclear physics extends the study of the strong interaction between nucleons which are composed of u and d quarks to that between baryons involving s quarks, such as Λ,Σ,Ξ etc. Due to the Λ-nucleon interaction the insert of a Λ hyperon in a nucleus will interfere with the structure of both the Λ particle and the nucleus. Because the Λ hyperon dosn't suffer from the Pauli blocking by the other nucleons, it can sit deep inside of the nucleus, and serves as a probe to reveal some new features of the hypernuclear structure.

Since the first observation of a Λ hypernucleus in a balloon experiment[1] nearly 50 Λ hypernuclei have been identified in laboratories mainly with (K^-,π^-) and (π^+,K^+) reactions. Abundant information on the structure of *p*-shell hypernuclei has been acquired by means of the electromagnetic spectrometer and the Hyperball γ-ray spectrometer[2]. While good agreement between the experimental results and the shell model description on the level structure of the *p*-shell Λ hypernuclei was achieved in most cases, some discrepancies remain. Both experimental studies and theoretical investigations are wanted. The aim of this paper is to provide a summary of the current status of the *p*-shell Λ hypernucleus study.

2 Production mechanism

In principle, hyprenuclei can be produced through a variety of hadronic reactions induced by mesons, protons and heavy ions, as well as through electromagnetic reactions by electron beams. In practice, most experiments performed so far used (K^-,π^-) reactions with K^- beams at CERN and BNL, or (π^+,K^+) reactions with π^+ beams at AGS of BNL and PS of KEK. Moreover, the $(e,e'K^+)$ reactions have been successfully used in producing $^{12}_{\Lambda}B$ with electron beams at CEBAF of the J-Lab[3]. In the strangeness exchange reaction (K^-,π^-), an s quark in the incident K^- exchanges with a d quark in a neutron of the target nucleus resulting in a π^- and a Λ hypernucleus. In the associate production reaction (π^+,K^+) as well as the electro production $(e,e'K^+)$, an $s-\bar{s}$ pair is created associately, resulting in a K^+ and a Λ hypernucleus. The hypernuclei produced by the strangeness exchange reaction with K^- prefer to populate substitutional states. This kind of reaction has high cross sections and low momentum transfer. Hypernuclei produced by the associate production reaction with π^+ prefer to populate stretched states and high spin states, while with electrons preferably spin flip and unnatural parity states are populated. Although the latter two kinds of reactions have low cross sections, the intense π^+ and electron beams available can make the production rate comparable with the

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K^- induced reactions.

3 Main results from electromagnetic spectroscopy

The SKS spectrometer at K6 beam line of KEK has an energy resolution of 1.5—2 MeV and is the most productive machine so far. In the E336(KEK) experiment[4], the s_Λ and the p_Λ states as well as the core excitations of $^{12}_{\Lambda}$C have been clearly observed. An intriguing result is that the 1^-_3 level has an excitation energy of 6.1 MeV which is in contradiction with the week coupling of the Λ to the core nucleus ^{11}C in the form of ^{11}C(4.8 MeV)$\otimes s_\Lambda$, and in disagreement with theoretical calculations[5, 6] (see Fig. 1).

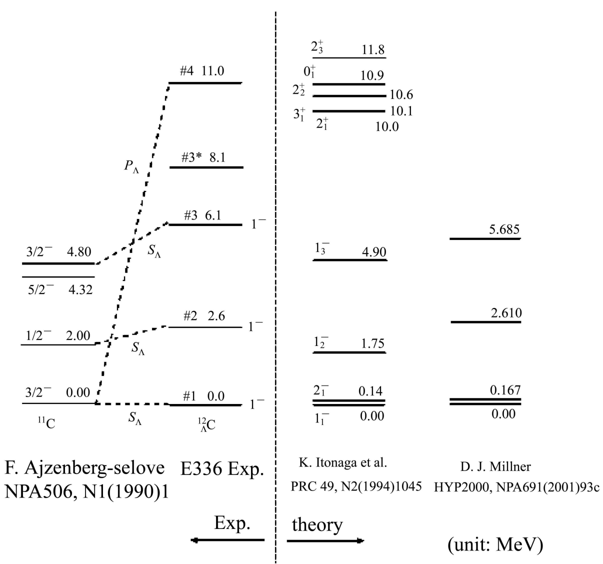

Fig. 1. Comparison of the experimental energy levels and the theoretical calculations for the $^{12}_{\Lambda}$C. (from Fig. 11 of Ref. [2]).

The $^{7}_{\Lambda}$Li excitation spectrum has been measured with ^{7}Li(π^+,K$^+$)$^{7}_{\Lambda}$Li reactions in the E336 experiment. The observed Λ binding energy, $B_\Lambda = 5.22$ ±0.08 (stat) ±0.36 (syst) MeV, agrees well with the emulsion data, $B_\Lambda = 5.58\pm0.03$ MeV[7]. Besides this, four peaks were identified as excited states with excitation energies 2.05, 3.88, 5.61 and 7.99 MeV. According to the theoretical calculations the ground state and the first excited state have configurations of [^{6}Li(1^+) $\otimes\Lambda s_{1/2}$]$1/2^+$, $T=0$ and [^{6}Li(3^+) $\otimes\Lambda s_{1/2}$]$5/2^+$, $T=0$, respectively. The shell model and cluster model calculations predicted the 3.88 and 5.61 MeV level to have $T=1$.

In the $^{9}_{\Lambda}$Be missing mass spectrum from the E336 experiment eight peaks have been found. The first four excitations have energies of 2.93±0.07, 5.80±0.13, 9.52±0.13 and 14.88±0.10 MeV. The most interesting structure observed in $^{9}_{\Lambda}$Be is the so called "supersymmetric states" first pointed out by Dalitzor[8] or the "genuine hypernuclear states" predicted by Bando et al. with a cluster model calculation[9]. In that model, the $^{9}_{\Lambda}$Be is considered to have a configuration of 2α+Λ, with the two α particles forming the ^{8}Be core. Three band structures $[(\alpha\alpha)\otimes\Lambda s_{1/2}]_{K=0^+}$, $[(\alpha\alpha)\otimes p^{\parallel}_{\Lambda}]_{K=0^-}$, and $[(\alpha\alpha)\otimes p^{\perp}_{\Lambda}]_{K=1^-}$, are shown in Fig. 2.

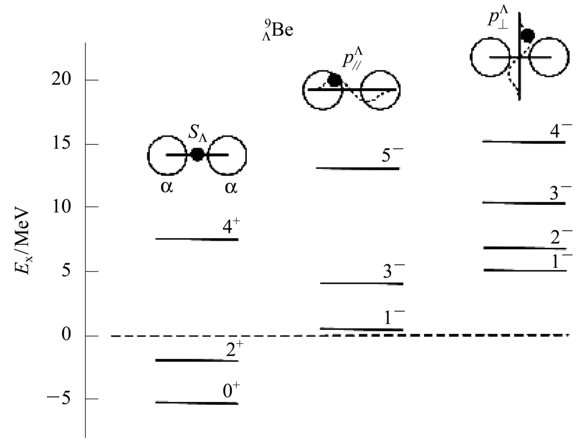

Fig. 2. Calculated energy levels of $^{9}_{\Lambda}$Be for three cluster configurations. A band corresponding to genuine hypernuclear states appears as an $\alpha-\alpha-\Lambda(p_\Lambda)$ configuration. (from Fig. 14 of Ref. [2]).

The second one represents the genuine states, where an Λ sits in the p orbit parallel to the (α+α+n) configuration. According to the theoretical calculation, the states of $E_x = 0$ and 2.93 MeV correspond to configurations of a Λ in the s orbit coupled to ^{8}Be(0^+) and ^{8}Be(2^+), while the excited states of 6 and 10 MeV are the "genuine hypernuclear" states, which correspond to configurations of a Λ in a $p^{\parallel}_{\Lambda}$ orbit coupled to ^{8}Be(1^-) and ^{8}Be(3^-) states. The 15 MeV level can be interpreted as an α cluster excitation of the ^{8}Be core based on cluster calculations[10]. Despite of the successful interpretation of the spectrum structure, the $^{9}_{\Lambda}$Be binding energy of 5.99 ±0.07(stat) ±0.36(syst) MeV determined from the experiment disagrees with that from emulsion data: 6.71 ± 0.03 MeV[7]. So far there is no reasonable interpretation for the disagreement.

Four peaks were identified in the $^{10}_{\Lambda}$B spectrum measured in the E140a experiment[11]. The three excited states are considered to have configurations of a Λ in the s orbit coupled to the excited states of the ^{9}B core nucleus at 2.4($5/2^-$), 7.1($7/2^-$) and 11.5($7/2^-$) MeV. Previously, using a configuration-mixing shell model, Itonaga et al.[5] have obtained four pronounced peaks ($2^-_1, 3^-_1, 3^-_2$ and 3^-_4) in the $^{10}_{\Lambda}$B spectrum below $E_X \approx 10$ MeV, which are in accord with observation.

Seven peaks were observed in the ${}^{13}_{\Lambda}$C spectrum from the E336 experiment. Those peaks can be assigned to a Λ hyperon in the s_Λ or p_Λ state coupled to a ^{12}C core at different excitation states. The measured energy levels can be well reproduced by the theoretical calculations with the shell model[5, 6] as well as the cluster model[12].

In the ${}^{16}_{\Lambda}$O spectrum measured in the E336 experiment four peaks were identified. The theoretical calculation with the configurations $[\nu p^{-1}_{1/2} \otimes \Lambda s_{1/2}]1^-_1$, $[\nu p^{-1}_{3/2} \otimes \Lambda s_{1/2}]1^-_2$, $[\nu p^{-1}_{1/2} \otimes \Lambda p_{3/2,1/2}]2^+_1, 0^+_1$ and $[\nu p^{-1}_{3/2} \otimes \Lambda p_{3/2,1/2}]2^+_2, 0^+_2$ agrees well with the experimental spectrum. The excitation energy of the 2^+_1 state determined from the E336 (π^+,K$^+$) spectrum is 10.57±0.06±0.14 MeV, while the energy of the ls partner 0^+_1 state from the CERN (K$^-$,π^-) in-flight spectrum[13] is 10.61±0.28 MeV. The small difference (0.04±0.32 MeV) in the energies between the 2^+_1 and 0^+_1 states leads to the conclusion that the spin–orbit splitting of the p orbit is quite small.

4 Results from γ-ray spectroscopy

The spin dependent terms in the shell model description of the Λ-N interaction in Λ hypernuclei, the impurity effect due to a Λ presenting in a nucleus, and the modification of the properties of the Λ particle in the nuclear medium can be best investigated by hypernuclear γ-ray spectroscopy due to its high energy resolution (2—3 keV compared to ∼2 MeV of the electromagnetic spectrometer).

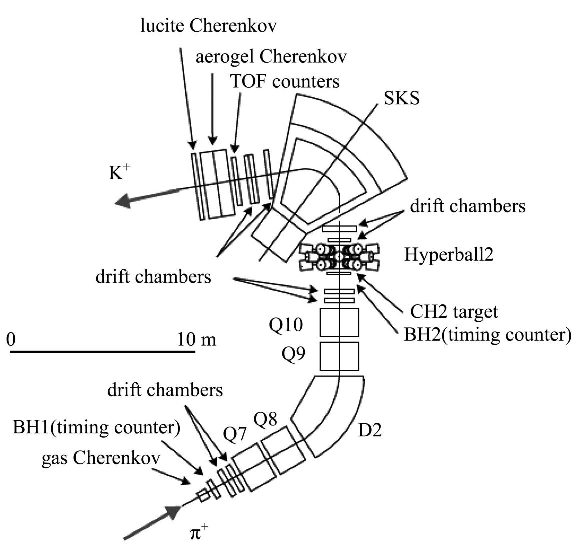

Fig. 3. The set-up for the γ-ray spectroscopy experiment of ${}^{12}_{\Lambda}$C with Hyperball (from Fig. 1 of Ref. [14]).

A Hyperball γ-ray spectrometer has been successfully used in the study of the p-shell hypernucei, such as ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{10}_{\Lambda}$B, ${}^{11}_{\Lambda}$B, ${}^{15}_{\Lambda}$N, ${}^{12}_{\Lambda}$C, ${}^{13}_{\Lambda}$C and ${}^{16}_{\Lambda}$O. Fig. 3 shows a sketch of the set-up for the γ ray spectroscopy experiment of ${}^{12}_{\Lambda}$C with Hyperball[14].

For p-shell hypernuclei, the two-body ΛN interaction potential can be expressed asc

$$V_{\Lambda N} = V_0(r) + V_\sigma(r)(s_\Lambda \cdot s_N) + V_\Lambda(r)(l_{\Lambda N} \cdot s_\Lambda) + V_N(r)(l_{\Lambda N} \cdot s_N) + V_T(r) S_{12} \ , \quad (1)$$

where $l_{\Lambda N}$ is the relative orbital angular momentum, while s_Λ and s_N are the Λ spin and nucleon spin operators, respectively, and S_{12} is the tensor interaction operator

$$S_{12} = 3(\sigma_N \cdot \hat{r})(\sigma_\Lambda \cdot \hat{r}) - \sigma_N \cdot \sigma_\Lambda \ , \quad (2)$$

with $r = |\boldsymbol{r}_N - \boldsymbol{r}_\Lambda|$. The radial integrals corresponding to each of the five terms on the right side of Eq. (1) are denoted (from left to right) as $\bar{V}, \Delta, S_\Lambda, S_N$ and T. From the ${}^{7}_{\Lambda}$Li($3/2^+$, $1/2^+$)(E419 KEK), ${}^{9}_{\Lambda}$Be($3/2^+$, $5/2^+$)(E930 BNL) and ${}^{16}_{\Lambda}$O(1^-, 0^-)(E930 BNL) spin doublet spacing, the shell model parameters Δ, S_Λ, and T were determined to be 0.34 MeV, −0.01 MeV, and 0.03 MeV, respectively. The parameter $S_N = -0.4$ MeV was determined by the spacing of the ${}^{7}_{\Lambda}$Li core excitation ($5/2^+$, $1/2^+$). However, the recent γ-ray spectroscopy experiment E566(KEK) with ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C found that the transition energies 1481.7 keV ($1/2^+, 5/1^+$) and 261.6 keV ($7/2^+, 5/2^+$) of ${}^{11}_{\Lambda}$B are significantly different from the values predicted by the shell model using the Δ and S_N determined from the ${}^{7}_{\Lambda}$Li data.[14]

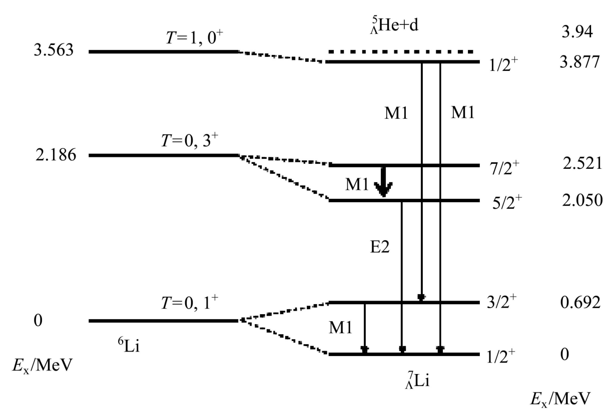

Fig. 4. The level scheme of ${}^{7}_{\Lambda}$Li (from Fig. 1 of Ref. [19]).

The glue-like effect of the Λ particle in a nucleus has been calculated by different models[15—17]. In the E419(KEK) experiment, the shrinkage of the ${}^{7}_{\Lambda}$Li was determined by measuring the life time of the (E2;

$5/2^+ \rightarrow 1/2^+$) transition with the Doppler shift attenuation method. A shrinkage factor S is introduced to quantify the size of shrinkage:

$$S=\left[\frac{9}{7}\frac{B(\mathrm{E2};{}^{7}_{\Lambda}\mathrm{Li}5/2^+\rightarrow 1/2^+)}{B(\mathrm{E2};{}^{6}\mathrm{Li}3^+\rightarrow 1^+)}\right]^{1/4}. \qquad (3)$$

A value of $S = 0.81$ corresponding to 19% of the shrinkage was extracted from the experiment[18]. This value agrees with the results of Motoba's $\alpha + \mathrm{d} + \Lambda$ cluster model (16%)[15] and Hiyama's $\alpha + \mathrm{p} + \mathrm{n} + \Lambda$ four body cluster model (22%)[17].

A first complete level scheme in the bound region has been constructed for ${}^{7}_{\Lambda}$Li (see Fig. 4).

5 Conclusion

The spectroscopic investigation of p-shell Λ hypernuclei with both electromagnetic spectroscopic and γ-ray spectroscopy technics has produced important information on the Λ-N interaction. Some features of the hypernuclear levels, such as the core excitation, the Λ particle in the p-shell excitation, the genuine state which can only be found in hypernuclei etc.. The shell model spin dependent Λ-N interaction parameters have been determined. The first experimental evidence of the shrinkage of hypernuclei due to the glue-like effect of a Λ particle in the 0_s state was discovered in ${}^{7}_{\Lambda}$Li.

With the new accelerator facility of J-PARC, p-shell hypernuclei will be further investigated. Especially, the possible modification of the Λ particle embedded in nuclear matter will be studied by measuring the B(M1) of the spin-flip M1($3/2^+ \rightarrow 1/2^+$) transition of ${}^{7}_{\Lambda}$Li at 692 keV, some inconsistency between the experimental results and the theoretical calculations needs to be clarified, and the Λ-N spin-dependent interaction parameters should be further studied as a cross check.

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