HYPERNUCLEAR STUDIES AT KEK AND BNL
– $\gamma$ SPECTROSCOPY OF $\Lambda$ HYPERNUCLEI

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Abstract

Recent experiments of hypernuclear $\gamma$ spectroscopy at KEK and BNL are described. By using a Ge detector array, Hyperball, we investigated level structure of $\Lambda^7$Li and $\Lambda^7$Be. We obtained information on the $\Lambda N$ spin-spin and spin-orbit forces. We also measured $B(E2)$ of $\Lambda^7$Li and confirmed shrinking effect of the hypernuclear size. The spin-orbit splitting of $\Lambda$ in $^{13}$C was also observed from $\gamma$ transitions detected with an NaI array. From those experiments, we have established a very small spin-orbit force of $\Lambda$.

1 Introduction

1.1 Hypernuclear $\gamma$ spectroscopy – significance and difficulty

Improvement of energy resolution is one of the most important issues in experimental nuclear physics. In hypernuclear physics, spectroscopy with the ($K^-,\pi^-$) and ($\pi^+,K^+$) reactions employing magnetic spectrometers has been used since 1970's. In this method, energy resolution is limited to 1.5 MeV (FWHM) at best, which is far from satisfactory for investigation of detailed structures of hypernuclei. This situation would be drastically improved by introducing $\gamma$ spectroscopy, particularly with germanium (Ge) detectors having a few keV resolution. In addition, $\gamma$-ray cascade enables us to investigate various excited states including those which cannot be populated by the direct reactions, such as spin-flip states of $\Lambda$. Electromagnetic moments and spin-parities can be also determined in $\gamma$ spectroscopy through transition probabilities and angular correlations.

In spite of these significances, hypernuclear $\gamma$ spectroscopy with Ge detectors was not pursued because of technical difficulties; a huge energy-deposit rate and a high counting rate from beam halo and scattered beam particles do not allow normal operation of Ge detectors at secondary meson beams.
Because of a small hypernuclear production yield, Ge detectors cannot be installed far enough from the target to avoid such beam background. Only five hypernuclear $\gamma$ transitions have been established so far, and all of them were observed with NaI counters.

In order to establish hypernuclear $\gamma$ spectroscopy, we need a Ge detector system with a higher efficiency (a large acceptance) and a less electronics dead time. After some technical studies, we constructed a large-acceptance Ge detector system dedicated to hypernuclear $\gamma$ spectroscopy, Hyperball, and started a series of experiments [1]. Hyperball is used for $\gamma$ rays up to several MeV energies. For higher energy ($\sim 10$ MeV) $\gamma$ rays expected for $E1(p_A \rightarrow s_A)$ transition in $^{13}$C for example, use of a large-volume NaI array is more effective.

1.2 Motivation of the project

The physics motivation of the Hyperball project is summarized as follows.

1. Baryon-baryon interactions

The spin-dependent $\Lambda N$ interactions (spin-spin, spin-orbit, and tensor interactions) can be investigated from detailed level structure of $\Lambda$ hypernuclei. Information on the $\Sigma$-$\Lambda$ coupling can be also obtained. From double $\Lambda$ hypernuclei, $\Lambda \Lambda$ interaction will be studied.

2. Impurity effects

Even a single $\Lambda$ particle added to a nucleus may drastically change nuclear properties such as size, shape and collective motions. Such effects can be investigated from detailed level structure and transition probabilities.

3. Medium effects

Since a $\Lambda$ particle can stay deeply in a nucleus but distinguishable from nucleons, it can be a probe to investigate possible modifications of baryons in nuclear matter.

In particular, the most important motivation at present is the study of baryon-baryon interactions. Detailed level structures of hypernuclei allow us to obtain information on the spin-dependent parts of the $\Lambda N$ interaction; in p-shell hypernuclei the strengths of the spin-spin term, the $\Lambda$-spin-dependent spin-orbit term, the nucleon-spin-dependent spin-orbit term, and the tensor term, denoted as $\Delta, S_A, S_N,$ and $T$, respectively, can be experimentally derived [2, 3]. As shown in Fig. 1, when a $\Lambda$ in $0s$ orbit is coupled to a core nucleus (spin $J \neq 0$), a doublet ($J-\frac{1}{2}, J+\frac{1}{2}$) appears of which energy spacing is determined by these spin-dependent terms. Since the spacings of such spin doublets called "hypernuclear fine structure" are expected to be small (typically less than 100 keV), high-resolution $\gamma$-ray spectroscopy with Ge detector is almost the only
Figure 1: Hypernuclear fine structure and γ spectroscopy. High-resolution of Ge detector is essential to resolve two levels (fine structure) split by ΔN spin-dependent interactions.

method to investigate them.

In $^4_\Lambda$H and $^6_\Lambda$He, the $M1$ transition between the ground state doublet ($0^+,1^+$) was detected with NaI counters [4]. This is the only observations of spin-flip $M1$ transitions between a hypernuclear fine structure. The observed energy (1.1 MeV) naively gives the strength of the $\Delta N$ spin-spin interaction. However, the three body $\Lambda NN$ force is expected to give a large contribution to the splitting in the $A = 4$ case. In addition, another experiment for $^{10}\Lambda$B gave a result on the spin-spin interaction contradictory to the $A = 4$ data [5]. Therefore, more data for level splittings of other $p$-shell hypernuclei have been awaited.

It has been long accepted that the $\Lambda N$ spin-orbit interaction is very small compared with that of $NN$, based on the $(K^-,\pi^-)$ spectra of $^{16}\Lambda$O and $^{13}\Lambda$C [6, 7], although a finite size of the spin-orbit splitting has not been measured. Recently, it is pointed out that some new experimental data imply much larger spin-orbit force of about $1/3-1/5$ of the nucleon case [8, 9]. This puzzling situation can be solved by γ spectroscopy of specific hypernuclei such as $^9\Lambda$Be and $^{12}\Lambda$C. Since quark models predict a very small spin-orbit force of $\Lambda$ due to cancellation between the symmetric and antisymmetric $LS$ forces [10], measurement of a finite size of the spin-orbit force is of particular interest.

1.3 Hyperball

Hyperball consists of fourteen sets of coaxial N-type Ge detectors (relative efficiency of 60% for each) equipped with fast electronics and BGO scintillation counters around each Ge crystal. The photo-peak efficiency for all the Ge de-
tectors is 2.5% at 1 MeV. The BGO counters were used not only for Compton suppression but for rejection of high-energy photons from $\pi^0$ and high-energy charged particles which cause serious background. More descriptions on Hyperball are found in Ref. [11, 12].

![Diagram of KEK-PS E419 setup and Hyperball setup around the target](image)

Figure 2: Left: setup of the $\gamma$ spectroscopy of $\bar{^7}$Li (KEK E419) with the K6 beam line and SKS at KEK. Right: side view around the target which is surrounded by Hyperball.

2 $\bar{^7}$Li: AN spin-spin force and $B(E2)$

The first experiment with Hyperball was performed in 1998 at KEK. We produced $\bar{^7}$Li bound states using the $\bar{^7}$Li($\pi^+, K^+$) reaction employing the K6 beam line and the SKS spectrometer, and measured $\gamma$ rays in coincidence. The setup of the experiment is shown in Fig. 2. In this experiment we succeeded in observing well-identified hypernuclear $\gamma$ transitions using Ge detectors for the first time. More descriptions are found in Refs. [11, 13, 12].

Figure 3 is the $\gamma$-ray spectrum when the bound-state region of $\bar{^7}$Li is selected. We observed four $\gamma$-ray peaks at $691.7\pm0.6\pm1.0$ keV, $2050.4\pm0.4\pm0.7$ keV, $3186\pm4\pm6$ keV, and $3877\pm5\pm7$ keV. The 692 keV peak is uniquely assigned as the spin-flip $M1(\frac{3}{2}^+\rightarrow\frac{1}{2}^+)$ transition, and the 2050 keV peak as the
Figure 3: γ-ray spectrum of $^7\Lambda$Li measured with Hyperball. Four hypernuclear transitions, $M1(\frac{3}{2}^+\rightarrow\frac{1}{2}^+)$, $E2(\frac{5}{2}^+\rightarrow\frac{1}{2}^+)$, $M1(\frac{1}{2}^+(T=1)\rightarrow\frac{3}{2}^+)$, and $M1(\frac{1}{2}^+(T=1)\rightarrow\frac{1}{2}^+)$, were observed. Right inset in the left figure shows the fitting of the $E2$ peak with the optimum lifetime, 5.8 ps.

$E2(\frac{5}{2}^+\rightarrow\frac{1}{2}^+)$ transition. The shapes of these peaks are consistent with Doppler broadening estimated from expected lifetimes of those states. The 692 keV peak becomes sharp after event-by-event Doppler-shift correction as shown in the left inset of Fig. 3 (left). The peaks at 3186 keV and 3877 keV, which were observed in the Doppler-shift corrected spectrum Fig. 3 (top-right), are assigned as the $M1$ transitions from the $\frac{1}{2}^+(T=1)$ state to the ground state doublet ($\frac{1}{2}^+,\frac{3}{2}^+$). We have thus established the level scheme of $^7\Lambda$Li as shown in Fig. 4 (top-left), where our observed transitions are shown in thick black arrows.

The energy spacing of the ground state doublet ($\frac{3}{2}^+,\frac{1}{2}^+$) is determined almost only by the $\Lambda N$ spin-spin interaction. By comparing the experimental data of 692 keV with a shell-model calculation by Millener [14], the observed $M1$ energy unambiguously gives the strength of the spin-spin interaction, $\Delta = 0.48$–0.50 MeV. This result gives a strong restriction on baryon-baryon interaction models.

As for the $E2(\frac{5}{2}^+\rightarrow\frac{1}{2}^+)$ transition at 2050 keV, which was previously observed at BNL with NaI counters [15], we have obtained the lifetime of the $\frac{5}{2}^+$ state with Doppler shift attenuation method (DSAM), and then derived $B(E2)$ to be $3.6\pm0.5^{+0.5}_{-0.4} \ e^2$fm$^4$. This result, compared with the $B(E2)=10.9\pm0.9 \ e^2$fm$^4$ of the core nucleus $^6$Li($3^+\rightarrow1^+$), indicates a significant shrinkage of the $^7\Lambda$Li size from the $^6$Li size. It is an evidence of the “glue-like role” of $\Lambda$ predicted
Figure 4: Level scheme and $\gamma$ transitions of several $p$-shell hypernuclei which are investigated in E419 and E930 for determination of all the spin-dependent interaction terms ($\Delta$, $S_{\Lambda}$, $S_N$, $T$).

by cluster-model calculations [16]. According to a recent cluster-model calculation by Hiyama et al. [17], our measured $B(E2)$ corresponds to a shrinkage of the distance between the $\alpha$ cluster and the center of mass of $p$ and $n$ by $19\pm4\%$. It is also noted that this is the first measurement of reduced transition probabilities of hypernuclei. See Ref. [13] for details.

3 $^{9}_{\Lambda}\text{Be}$: $\Lambda N$ spin-orbit force

In the next experiment with Hyperball, we studied $^{9}_{\Lambda}\text{Be}$ employing the $(K^-,\pi^-)$ reaction at 0.9 GeV/c utilizing a high intensity $K^-$ beam at BNL AGS (E930).
See Ref. [18] for details.

Figure 5 shows the γ-ray spectrum when the bound-state region in the $^9$Be($K^-,\pi^-)^0_\Lambda$Be spectrum is gated. We successfully observed a fine structure, twin peaks at 3029 keV and 3060 keV, in the $^9$Be γ-ray spectrum. They are assigned as the $E2(\frac{3}{2}^+\rightarrow\frac{1}{2}^+, \frac{3}{2}^+\rightarrow\frac{1}{2}^+)$ transitions shown in Fig. 4 (top-right). The observed structure was well fit by two peaks having partly Doppler-broadened shape expected from a simulation.

Since the ($\frac{3}{2}^+, \frac{1}{2}^+$) doublet corresponds to the $^8$Be($2^+$) state with a Λ in 0s orbit, their energy spacing is determined almost purely by the Λ-spin-dependent ΛN spin-orbit interaction ($S_\Lambda$). According to a shell-model calculation by Millener [14], the spacing is written as $-0.035\Delta - 2.465S_\Lambda + 0.936T$ (MeV). Although $T$ is unknown, it is expected to be small ($T \sim 0 - 0.1$ MeV). So our result of about 30 keV spacing suggests a very small spin-orbit term, of the order of $|S_\Lambda| \sim 0.01$ MeV. Recent cluster-model calculations by Hiyama et al. [19] using several versions of the meson-exchange baryon-baryon interaction models predicted a spacing of $80 - 200$ keV, which indicates that the present meson-exchange models have to be modified. Our observation thus confirmed a very small ΛN spin-orbit force which is much less than 1/10 of the N N spin-orbit force.

**E930 with Hyperball**

![E930 with Hyperball](image)

Figure 5: Measured γ-ray spectrum of $^9_\Lambda$Be. The twin peak structure was well fitted using a expected partly-Doppler-broadened peak shape. The two peaks are assigned as the $E2(\frac{3}{2}^+, \frac{3}{2}^+\rightarrow\frac{1}{2}^+)$ transitions.
4 \(^{13}\Lambda\)C: \(\Lambda\) spin-orbit splitting

It is also important to observe the spin-orbit splitting of single particle \(\Lambda\) states in hypernuclei to investigate the \(\Lambda N\) spin-orbit force and general properties of hypernuclear structure.

Another experiment (E929) was performed at BNL to measure the spin-orbit splitting of \((p_{1/2})_{\Lambda}\) and \((p_{3/2})_{\Lambda}\) from the \(E1\) transitions, \((p_{1/2})_{\Lambda} \rightarrow (s_{1/2})_{\Lambda}\) and \((p_{3/2})_{\Lambda} \rightarrow (s_{1/2})_{\Lambda}\). See Ref. [20] for details.

The experiment was carried out in 1998 before the \(^9\Lambda\)Be experiment with Hyperball with the same setup except for the \(\gamma\)-ray detectors. Here, a large-volume NaI array having much larger efficiency for 11 MeV \(\gamma\) rays was used. Bound states of \(^{13}\Lambda\)C were populated by 0.9 GeV/c \(^{13}\)C\((K^-,\pi^-)\) reaction.

The \(1/2^-\) \([p_{1/2}]_{\Lambda}\) state, which is a substitutional \((\Delta L = 0)\) state in the \(^{13}\)C\((K^-,\pi^-)\) reaction, is populated at very forward angles, while the \(3/2^-\) \([p_{3/2}]_{\Lambda}\) state with \(\Delta L = 2\) is populated at backward \((\theta \sim 10^5)\) angles. Using a magnetic spectrometer having a large angular acceptance from 0 to 12 degree, both of the \(1/2^-\) and \(3/2^-\) states were produced without changing the spectrometer setting.

A \(\gamma\)-ray peak was observed at 11 MeV. It was found that the peak energy slightly shifts as a function of the scattering angle, and the spin-orbit splitting was obtained to be \(152\pm54\pm36\) keV.

This result also confirmed a small spin-orbit force of \(\Lambda\). According to the cluster-model calculation by Hiyama et al., the meson-exchange interactions give 0.39–0.96 MeV, which is also several times larger than the observed splitting energy as in the \(^9\Lambda\)Be case. Both of the \(^9\Lambda\)Be and \(^{13}\Lambda\)C data have established a small but finite size of the \(\Lambda\) spin-orbit force, which cannot be explained from existing meson-exchange models of baryon-baryon interactions. These results will provide us with a clue to understand the origin of the nuclear spin-orbit interaction.

5 Near future plans with Hyperball

Figure 4 shows hypernuclear \(\gamma\) transitions which we have observed or need to observe in order to determine the strengths of all the spin-dependent terms of \(\Lambda N\) interaction. The next beam time for BNL E930 is scheduled in the summer in 2001, when we will study \(^{16}\Lambda\)O\((^{13}\)N\)), \(^7\)Li, \(^{12}\)C, etc. with Hyperball.

The purpose of the \(^{16}\)O experiment is to obtain information on the \(\Lambda N\) tensor force which is completely unknown at present. One pion exchange, which is responsible for the \(NN\) tensor force, is forbidden for \(\Lambda N\), but two pion exchange with \(\Lambda N\cdot\Sigma N\) mixing is expected to give a significant contribution to
the tensor force. Both of the \( M1 \) transitions from the 6 MeV 1\(^{-} \) state to both of the ground doublet states (0\(^{-} \), 1\(^{-} \)) will be separately detected with a few weeks’ beam time at BNL.

Then we will investigate \( ^7 \)Li again to observe the \( \frac{3}{2}^+ \rightarrow \frac{5}{2}^+ \) spin-flip \( M1 \) transition using 1.1 GeV/c \( (K^-,\pi^-) \) reaction which has a sizable cross section to produce the spin-flip state \( \frac{3}{2}^+ \). The spacing of the \( (\frac{3}{2}^+, \frac{5}{2}^+) \) doublet gives information on strengths of both of the spin-spin and spin-orbit forces \( (\Delta \text{ and } S_\Lambda) \). Consistencies with the \( ^7 \)Li ground doublet data for \( \Delta \) and the \( ^9 \)Be doublet data for \( S_\Lambda \) can be checked. The energy spacing between the weighted averages of the \( (\frac{3}{2}^+, \frac{5}{2}^+) \) doublet and the \( (\frac{3}{2}^+, \frac{1}{2}^+) \) doublet gives clear information on the nucleon-spin-dependent spin-orbit force \( (S_N) \), which enables us to determine both of the symmetric LS and the antisymmetric LS strengths. The ground doublet spacing of \( ^{12} \)C also has information on \( \Delta \) and \( S_\Lambda \). It will be measured from \( M1 \) transitions from the 2.6 MeV excited 1\(^{-} \) state to both of the ground doublet states \( (2^-, 1^+) \).

6 Summary

We started a project of hypernuclear \( \gamma \) spectroscopy. By using a Ge detector array, Hyperball, we investigated level structure of \( ^7 \)Li and \( ^9 \)Be. We observed four \( \gamma \) transitions in \( ^7 \)Li and obtained information on the \( \Lambda N \) spin-spin and force from the spin-flip \( M1 \) transition energy. We also measured \( B(E2) \) of \( ^7 \)Li and confirmed shrinking effect of the hypernuclear size. We also observed two \( E2 \) transitions in \( ^9 \)Be. The spin-orbit splitting of \( \Lambda \) in \( ^{12} \)C was observed from the \( E1 \) transitions \( (1/2^-, 3/2^- \rightarrow 1/2^+) \) detected with an NaI array. From those experiments, we have established a very small spin-orbit force of \( \Lambda \) which cannot be explained by existing meson exchange models of baryon-baryon interactions.

References

References


