# Structure of $^{13}_{\Lambda}$C hypernucleus studied by the ($K^-$,$\pi^-\gamma$) reaction

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The BNL-AGS/E929 experiment was carried out to study energy levels of the $^{13}_{\Lambda}$C hypernucleus by a gamma-ray spectroscopy. Energy splitting of the spin-orbit doublets, $1/2^-$ and $3/2^-$ states, was estimated precisely. The excitation energy of the 1st $3/2^+$ state was also measured. We discuss the symmetric and the anti-symmetric spin-orbit interactions between a $\Lambda$ particle and a nucleon from the measurement.

## 1. INTRODUCTION

Hypernuclear physics is one of interesting fields of nuclear physics because we can examine an extension of the nucleon-nucleon interaction to the nucleon-hyperon and hyperon-hyperon interactions by a help of the flavor SU(3) symmetry. Due to short lifetimes of hyperons, hyperon-nucleon scattering measurements are quite difficult to obtain high-

precision data, and we have to rely on spectroscopic data of hypernuclei to discuss the hyperon-nucleon and hyperon-hyperon interactions. For such spectroscopic studies, a determination of hypernuclear energy levels with high-precision is necessary.

Recently, such high-precision data became available by several gamma-ray spectroscopic studies on $\Lambda$ hypernuclei [1–3]. In this talk, we BNL-AGS/E929 Collaborating report a measurement of the $^{13}$C(K$^-$,$\pi^-\gamma$)$^{13}_{\Lambda}$C reaction and discuss the $\Lambda$-nucleon spin-orbit interaction. The spin-orbit interaction between hyperon and nucleon has two contributions. One is the symmetric spin-orbit interaction, $V_{LS}$, and another is the anti-symmetric spin-orbit interaction, $V_{ALS}$. The latter does not contribute to the nucleon-nucleon interaction in normal nuclei. When the orbital angular momentum between $\Lambda$ and nucleon, $\vec{L}$, couples to the nucleon spin, $\vec{S}_N$, the interaction, $U_{LS}(N)$, is written with a summation of the two spin-orbit interactions, $U_{LS}(N) = u_{LS}(N)\vec{S}_N \cdot \vec{L} = (V_{LS} + V_{ALS})/2$. On the other hand, another interaction, $U_{LS}(\Lambda)$, is written with a difference of the spin-orbit interactions, $U_{LS}(\Lambda) = u_{LS}(\Lambda)\vec{S}_\Lambda \cdot \vec{L} = (V_{LS} - V_{ALS})/2$, when $\vec{L}$ couples to the $\Lambda$ spin, $\vec{S}_\Lambda$. As we will mention later, the $^{13}_{\Lambda}$C hypernucleus is suitable to estimate the two spin-orbit interactions.

## 2. EXPERIMENTAL SETUP

The AGS/E929 experiment was carried out at the D6 beam line of the alternating-gradient-synchrotron (AGS) facility at the Brookhaven National Laboratory (BNL). The D6 beam line provided a good quality of intense negative kaon beam. The kaon beam momentum was set to 0.93 GeV/c, and the typical beam intensity was $8 \times 10^4$ kaons/spill at the $^{13}$C benzene target for primary beam intensity of $5 \times 10^{12}$ protons/spill. To measure the (K$^-$,$\pi^-$) reaction, a beam-line spectrometer system (K$^-$ measurement) and a so-called 48D48 magnetic spectrometer system ($\pi^-$ measurement) were used. The $^{13}$C benzene target was prepared also as a scintillation detector by adding laser dyes, and the light output information was used to enrich formation events of the hypernucleus in the off-line analysis [4]. To detect nuclear and hypernuclear gamma-rays coincidence with the (K$^-$,$\pi^-$) reaction, two sets of 6×6 array of NaI(Tl) scintillation detector modules were mounted above and below the $^{13}$C target. The size of each NaI(Tl) detector module was 2.5"×2.5"×12", and the distance from the $^{13}$C target center to the surfaces of the NaI(Tl) arrays was 10.5 cm. More details of the experimental procedure were given in ref. [1].

## 3. RESULTS AND DISCUSSIONS

Figure 1 shows the typical gamma-ray energy spectrum coincident with the (K$^-$,$\pi^-$) reaction. We see several peaks of gamma-rays from normal nuclei as indicated with arrows of broken lines in the figure. Observation of most of the nuclear gamma-ray peaks is consistent with excitation of levels of normal nuclei (mainly $^{12}$C) by the quasi-free n(K$^-$,$\pi^-$)$\Lambda$ reaction. We can see also two other peaks of gamma-rays from $^{13}_{\Lambda}$C hypernucleus indicated with arrows of solid lines in the figure. One is a peak around 11 MeV and it corresponds to a mixture of gamma-ray transitions from $1/2^-$ and $3/2^-$ states (Ex∼11MeV) to the ground $1/2^+$ state. Another is a peak at 4.9 MeV and corresponds to a transition from $3/2^+$ state (Ex∼4.9MeV) to the ground state.

The $1/2^-$and $3/2^-$ states have major configuration of $^{12}C_{g.s.} \otimes p_{1/2\Lambda}$ and $^{12}C_{g.s.} \otimes p_{3/2\Lambda}$,

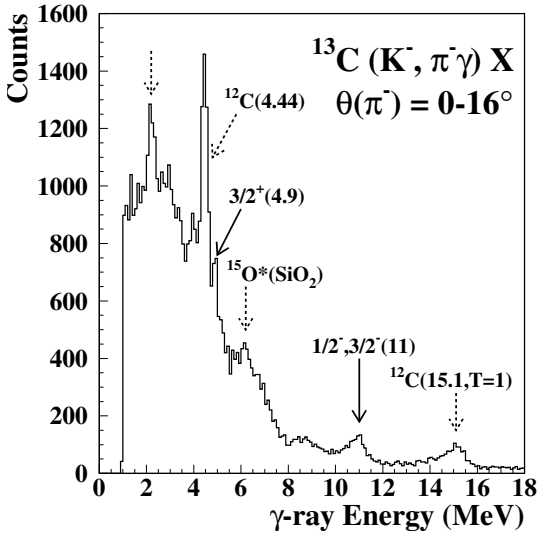


Figure 1. The typical gamma-ray energy spectrum coincidence with the ($K^-$,$\pi^-$) reaction. See text for more details.

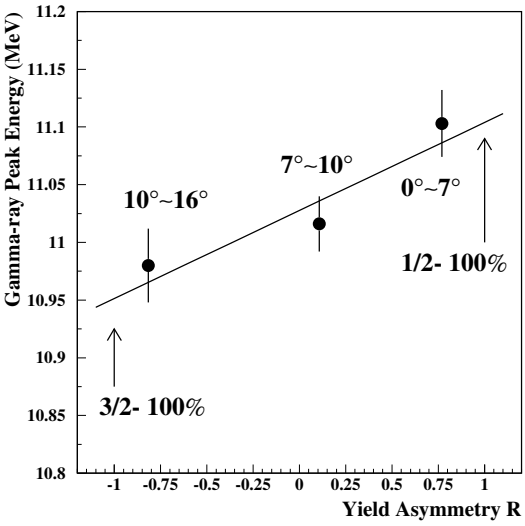


Figure 2. The $\pi^-$ scattering angle dependence of the gamma-ray peak energy at around 11 MeV.

respectively, and these are the $\Lambda$ spin-orbit partners in the p-shell. Estimation of the spin-orbit interaction between a $\Lambda$ particle and $^{12}$C nucleus is possible if we can measure the gamma-ray energies of the two transitions separately. Since the spin-orbit splitting was too small to observe the gamma-ray transitions as separate peaks even with the energy resolution of the NaI(Tl) detectors (about 350 keV at 11 MeV), we studied the $\pi^-$ scattering angle dependence of the peak energy. The result of a PWIA calculation of the ($K^-$,$\pi^-$) reaction on the $^{13}$C target [5] tells the population of the $1/2^-$ state is dominant at $\theta^{\pi^-}_{lab} < 9°$ and the population of $3/2^-$ state is dominant at $\theta^{\pi^-}_{lab} > 9°$. The difference of the population cross sections results in a shift of the peak energy of the $1/2^-$ and $3/2^-$ combined gamma-ray peak as a function of the $\pi^-$ scattering angle, and the amount of the shift depends on the energy splitting of the spin-orbit doublets.

Figure 2 shows the $\pi^-$ scattering angle dependence of the gamma-ray peak energy. To make a quantitative estimation of the energy splitting between the $1/2^-$ and $3/2^-$ states, we introduced the yield asymmetry $R$ which was defined as follows: $R$=($N(1/2^-) - N(3/2^-)$)/($N(1/2^-) + N(3/2^-)$), where $N(1/2^-)$ and $N(3/2^-)$ were yields of $1/2^-$ and $3/2^-$ states, respectively, and were estimated by the PWIA calculation. The horizontal axis of Figure 2 shows the yield asymmetry, and the data points were fitted with a linear function to estimate the energy difference between the $1/2^-$ and $3/2^-$ states. From the fitting, we obtained the value of the level splitting between the two states as follows: $\Delta E$=$Ex(1/2^-)$−$Ex(3/2^-)$=152 ± 54($stat$) ± 36($syst$) keV, where the systematic error mainly came from the ambiguity of the theoretical yield estimation (errors in $N(1/2^-)$ and $N(3/2^-)$). In simple mind, the small level splitting told that the spin-orbit interaction for the $\Lambda$ particle in the hypernucleus, $U_{LS}(\Lambda) = (V_{LS} - V_{ALS})/2$, was quite small. The indication of the smallness of the spin-orbit interaction was consistent with

the experimental result on ${}^{9}_{\Lambda}$Be hypernucleus [3].

The excitation energies of the individual states were estimated as $10.982 \pm 0.031(stat) \pm 0.056(syst)$ MeV and $10.830 \pm 0.031(stat) \pm 0.056(syst)$ MeV for the $1/2^-$ and $3/2^-$ states, respectively. In the excitation energy estimation, a correction on the absolute gamma-ray energies was applied since a systematic energy shift was observed in known nuclear gamma-ray peaks. The estimated value of the excitation energy of the $1/2^-$ state was consistent with the result of the previous gamma-ray measurement, $Ex$=$10.95 \pm 0.1 \pm 0.2$ MeV [6].

The level energy of the $3/2^+$ state was also estimate by a peak fitting of the gamma-ray energy peak around 4.9 MeV, and we obtained the excitation energy $4.880 \pm 0.010(stat) \pm 0.017(syst)$ MeV. The estimated value was consistent with the results previously measured by a magnetic spectrometer at KEK/PS, $4.89 \pm 0.07$ MeV [7], and the precision was considerably improved. Since the $3/2^+$ state has a major configuration of $[{}^{12}C_{2^+} \otimes s_{1/2\Lambda}]_{3/2}$, the shift of the excitation energy from the core ${}^{12}$C excitation energy (4.439 MeV) comes from interactions between the $\Lambda$ particles and the core nucleus, and the amount of the shift is considerably large: $Ex(3/2^+;{}^{13}_{\Lambda}C) - Ex(2^+;{}^{12}C) = 441 \pm 10 \pm 17$ keV. By a theoretical estimation [8], the major part of the shift comes from the contribution of the spin-orbit interaction $U_{LS}(N) = (V_{LS} + V_{ALS})/2$.

These results told the absolute values of the two spin-orbit interactions, $V_{LS}$ and $V_{ALS}$, were almost same and the signs of the interactions were same. This result was suggested in several quark-based hyperon-nucleon interaction models [9,10]. The $\Lambda$ binding energies of the spin-orbit doublets we studied were quite close to zero, $B_\Lambda$=0 at $Ex$=11.69 MeV. In such a loose binding case, a theoretical estimation suggests that the threshold effect reduces the energy difference between the spin-orbit partners [11]. The author of ref. [8] also suggested a possibility of a cancellation of the spin-orbit interaction with the tenser interaction. So, systematic studies on the level structures of the p-shell hypernuclei are still necessary to establish a clear picture on the $\Lambda$-nucleon interactions.

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