Recent data from E929 experiment at BNL

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The AGS-E929 experiment at BNL was performed to investigate the p-shell Λ spin-orbit interaction of hypernuclei by measuring the level splitting between the spin-orbit doublet, $1/2^-$ and $3/2^-$, of the ${}^{13}_{\Lambda}$C hypernucleus. Almost one order of magnitude better resolution than that in the past experiments was achieved in estimating the energy splitting by measuring the decay gamma-ray energies from the doublet. The level splitting between the doublet was estimated to be Ex($1/2^-$)-Ex($3/2^-$) = 152$\pm$54(stat.)$\pm$36(sys.) keV.

1. INTRODUCTION

Since the discovery of the Λ hypernuclei, the Λ-nucleus interaction has been investigated from the Λ binding energies, the information of hypernuclear structure, experimental data on Λ-nucleon scattering, etc. A pioneering study on the Λ spin-orbit interaction was performed by the Heidelberg-Saclay-Strasbourg Collaboration at CERN-PS by a measurement of the (K^-,π^-) reaction [1]. The experimental result indicated that the spin-orbit splittings of the ${}^{12}_{\Lambda}$C and ${}^{16}_{\Lambda}$O hypernuclei were, at least, one order of magnitude smaller than that of normal nuclei [1,2], and the result was immediately supported by another

pioneering work at BNL-AGS for the ${}^{12}_{\Lambda}$C and ${}^{13}_{\Lambda}$C hypernuclei [3,4]. The estimated spin-orbit splittings (ΔE) were ΔE$\leq$0.3MeV [1] and ΔE=0.7$\pm$0.7MeV [2] from the CERN-PS experiment, and ΔE$\leq$0.82MeV (or $\leq$0.42MeV depending on assumptions on cross sections) and ΔE=0.36$\pm$0.3MeV for the ${}^{12}_{\Lambda}$C and ${}^{13}_{\Lambda}$C hypernuclei, respectively, from the BNL-AGS experiment. Due to limited momentum resolution of magnetic spectrometers used in these experiments, the smallness of the Λ spin-orbit interaction was discussed with an accuracy of about 0.5 MeV.

After the reports of the pioneering experiments, Dalitz, Davis, Tovee and Motoba reported results of a re-analysis of an emulsion experiment [5], and suggested a possibility of slightly larger Λ spin-orbit splitting of ${}^{12}_{\Lambda}$C (ΔE$\sim$0.8MeV) and ${}^{16}_{\Lambda}$O (ΔE=1.56$\pm$0.12 MeV). The E336 experiment at KEK-PS measured the ^{13}C(π^+,K$^+$)${}^{13}_{\Lambda}$C reaction, and made a speculation of a relatively large Λ spin-orbit splitting of ${}^{13}_{\Lambda}$C hypernucleus, ΔE=1.03 $\pm$ 0.23 $\pm$ 0.7MeV [6].

All experimental results are indicating the smallness of the Λ spin-orbit splitting compared with the nucleon spin-orbit splitting of normal nuclei, but the absolute value of the splitting is not conclusive, yet. To estimate the Λ spin-orbit splitting more accurately, we performed a new experiment E929 at BNL-AGS [7]. The precision we tried to achieve in estimating the Λ spin-orbit splitting energy was about 30 keV, which was almost one order of magnitude better than that in the past counter experiments. In this paper we will show results of the analysis of the E929 experiment data.

2. EXPERIMENTAL IDEA

The AGS-E929 experiment studied the Λ spin-orbit interaction in the ${}^{13}_{\Lambda}$C hypernucleus. Figure 1 shows a theoretically predicted level scheme of ${}^{13}_{\Lambda}$C. The levels around 11 MeV

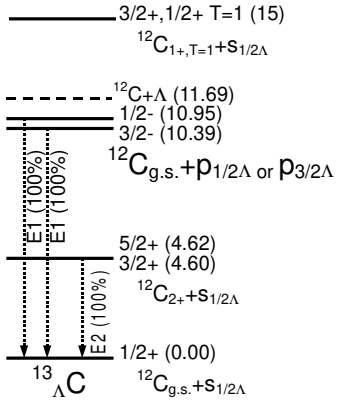

Figure 1. Theoretically predicted level scheme of the ${}^{13}_{\Lambda}$C hypernucleus.

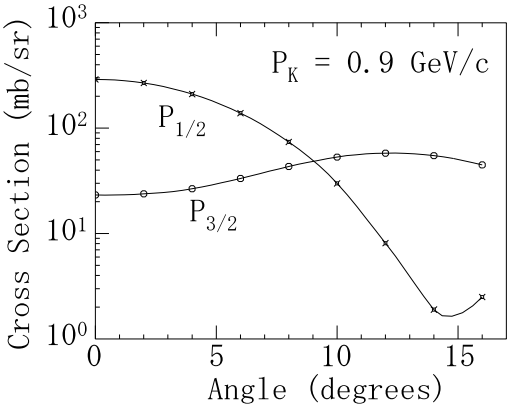

Figure 2. Theoretical differential cross sections of the ^{13}C(K$^-$,π^-)${}^{13}_{\Lambda}$C reaction.

are the spin-orbit doublet, $1/2^-$ and $3/2^-$ states, to be studied. These levels are believed to have major configurations of ^{12}C$_{g.s.}$(0$^+$)+p$_{1/2\Lambda}$ and ^{12}C$_{g.s.}$(0$^+$)+p$_{3/2\Lambda}$, respectively. If we can measure the energy splitting of the doublet, we can investigate the spin-orbit

interaction of Λ particle in the p-shell orbit. In principle, we can estimate the energy splitting of the doublet by measuring the excitation energies of the residual hypernucleus in the (K^-,π^-) or (π^+,K^+) reaction by a magnetic spectrometer, but practically the finite energy resolution, typically 3 MeV (FWHM), makes it difficult to estimate the splitting precisely.

A clever method to utilize the difference of angular dependences of the production cross section of the (K^-,π^-) reaction for different states was proposed and examined already in the pioneering counter experiment [4]. The population of the $1/2^-$ state by the ^{13}C(K^-,π^-)$^{13}_{\Lambda}$C reaction requires zero angular momentum transfer (ΔL=0) since the spin-parity of the target ^{13}C nucleus is $1/2^-$. The differential cross section of the (K^-,π^-) reaction for the $1/2^-$ state dominates over other states around the 11 MeV excitation region when pion is detected at zero degree, like the isobaric-analogue transition in normal nuclei. The differential cross section for the $1/2^-$ state falls off rapidly with the increase of the pion detection angle, and the population of the $3/2^-$ state dominate over the $1/2^-$ state. Figure 2 shows the theoretical cross-over of the cross sections at around 9 degrees [8]. The selective population of the doublet makes it possible to estimate the energy splitting of the doublet quite accurately even if we do not have enough resolution to see the doublet as separate peaks in the excitation energy spectrum.

In ref. [4], the method was used and a sensitivity of about 0.3 MeV was achieved in estimating the energy splitting of the spin-orbit doublet by the magnetic spectrometer measurement. To improve the sensitivity, we performed a measurement of the ^{13}C(K^-,$\pi^-\gamma$) reaction by using NaI(Tl) as gamma-ray detectors. The particle decay threshold of the $^{13}_{\Lambda}$C hypernucleus is estimated to be 11.69 MeV (see Figure 1) from the binding energy of the hypernucleus [9]. The 11 MeV levels are believed to be stable against particle decays, and decay with gamma-ray emissions to the ground state. One of the gamma-ray transitions, the $1/2^-$ to ground state transition, has already been measured by May *et al.* [10]. By measuring the energies of the gamma-rays, we can estimate the energy splitting of the spin-orbit doublets more accurately since the energy resolution of a NaI(Tl) detector at around 11 MeV is usually about one order of magnitude better than that of currently available magnetic spectrometers.

The measurement of the (K^-,$\pi^-\gamma$) reaction had another advantage of a small systematic error. In our experiment, the population of the spin-orbit doublet was controlled by the selection of the magnetic spectrometer angle which detected the π^- from the (K^-,π^-) reaction, and the estimation of the excitation energies of the doublet was done by the gamma-ray detectors. Since the spectrometer and the gamma-ray detectors were almost independent, we could reduce a systematic error due to a correlation between the π^- angle and the excitation energy which was inevitable in an experiment with only measurement by the magnetic spectrometer. Further, we used a large acceptance magnetic spectrometer, and a measurement of the (K^-,π^-) reaction at various angles at a time contributed to reduce the systematic error.

3. EXPERIMENTAL SETUP

We used the D6 beam-line at the Alternating-Gradient-Synchrotron (AGS) of Brookhaven National Laboratory (BNL). The beam-line provided a clean and intense negative kaon

beam. Typical beam intensity was 10^5 particle/s, and the K^-/π^- ratio was better than one. The beam momentum was set at 930 MeV/c to maximize the population of the spin-orbit doublet. Data were collected with about 21×10^9 negative kaons on the target.

^{13}C enriched benzene was used as the ^{13}C target, and the total target thickness was about 10 g/cm^2. The target also worked as a liquid scintillation detector by adding laser dyes as wave-length shifters [11]. The signal from the target scintillation detector was used to discriminate signal events from events of the kaon decay in-flight which was the major background in the ^{13}C(K^-,π^-) reaction measurement.

We used the so-called 48D48 magnetic spectrometer to measure the π^- particle from the (K^-,π^-) reaction [12]. The spectrometer had the ability of a clear particle identification, and had a large angular acceptance, from -8 to 8 degrees horizontally and from -17 to 0 degrees vertically. A typical momentum resolution was 12 MeV/c (FWHM). The momentum resolution was not so fancy, but was enough to select the particle bound region in the excitation energy of the $^{13}_{\Lambda}$C hypernucleus.

Figure 3 shows schematic view of the detectors around the target. A beam defining

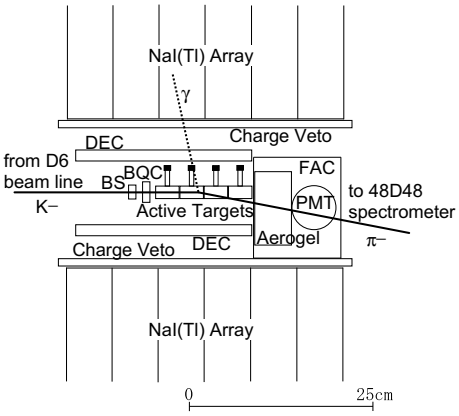

Figure 3. Schematic view of the detectors around the target.

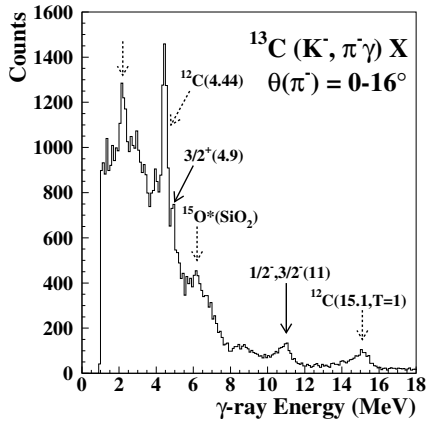

Figure 4. Gamma-ray energy spectrum coincidence with the ^{13}C(K^-,π^-) reaction.

plastic scintillation counter (BS) and a quartz beam Čerenkov detector (BQC) were installed upstream the ^{13}C target (Active Target), and an aerogel Čerenkov detector (FAC) was installed downstream the target. Plastic scintillation detectors to detect decay particles (DEC) were placed above and below the target, and used to discriminate the signal and background events as in the case of the active targets.

Two 6×6 arrays of NaI(Tl) gamma-ray detector modules were placed above and below the target. Each array had plastic scintillation counters for charged particle veto (Charge Veto) at the front surface. The central 4×4 arrays out of 6×6 were used for gamma-ray detection, and one surrounding layer of NaI(Tl) modules was used to collect energy leak from each central array. All NaI(Tl) modules had a size of 2.5"×2.5"×12". In terms of energy resolution, we had two kinds of NaI(Tl) modules. 16 modules had fine energy resolutions of about 8% for the ^{137}Cs gamma-rays (0.662 MeV), and were arranged in the

central regions of the detector arrays. Other modules had energy resolutions of 13% in average. In this analysis, we used events in which the major energy deposits of gamma-rays were in the 16 modules with the fine energy resolutions.

Since we used segmented NaI(Tl) detectors, the relative and absolute energy calibrations were necessary. Short and long term relative calibrations were done with a LED pulsing on all modules and ^{22}Na gamma-rays on several modules, respectively, during the data taking. Absolute energy calibrations were regularly done with the gamma-rays (0.511 MeV and 1.275 MeV) of the ^{22}Na decay, and high energy gamma-rays created by the ^{58}Ni(n,γ) (8.999 MeV) and ^{13}C(α,nγ)^{16}O (6.129 MeV) reactions.

4. ANALYSIS RESULTS AND DISCUSSIONS

Figure 4 shows gamma-ray energy spectrum measured with the NaI(Tl) detector arrays in coincidence with the ^{13}C(K$^-$,π^-) reaction. There are several peaks which correspond to gamma-ray transitions of normal nuclei and hypernuclei. Candidates of the normal nuclear gamma-rays are indicated with dashed arrows. We see prominent gamma-rays from the 2^+ (4.44 MeV) and 1^+;T=1 (15.1 MeV) states of the ^{12}C nucleus. It is known that the single neutron pickup by the (p,d) reaction from the ^{13}C nucleus leaves ^{12}C in the 0^+ (g.s.), 2^+ (4.44 MeV), 1^+ (12.7 MeV), 1^+;T=1 (15.1 MeV) and 2^+;T=1 (16.1 MeV) states. Among these states, the 2^+ and 1^+;T=1 states decay with gamma-ray emissions. So, it is quite likely these gamma-rays from normal nuclei are the result of a strong population of these states by the quasi-free (K$^-$,π^-) reaction.

There are other peaks of hypernuclear gamma-ray candidates at 4.9 MeV and 11 MeV. The 11 MeV gamma-rays are the gamma-rays we wished to measure to estimate the energy splitting of the spin-orbit doublet of the $^{13}_{\Lambda}$C hypernucleus. The origin of the gamma-rays can be investigated by looking at the excitation energy spectrum measured by the magnetic spectrometer. Figure 5 shows the excitation energy spectrum in coincidence with the 11 MeV gamma-rays (slid histogram) together with a typical background shape (dashed histogram), and the spectrum has a clear peak at the 11 MeV region of the excitation energy of $^{13}_{\Lambda}$C. It indicates a direct population of either or both levels of the spin-orbit doublet around the 11 MeV excitation region, and a subsequent gamma decay to the ground state.

From the identified normal nuclear gamma-ray transitions, we could estimate the overall energy resolution of the gamma-ray detector system. For this purpose, we used the 4.44 MeV gamma-rays from ^{12}C. Figure 6 shows a gamma-ray energy spectrum around the 5 MeV region. We see two clear peaks in the spectrum. One of the peaks at the lower energy corresponds to the 4.44 MeV gamma-ray from the 2^+ state of ^{12}C, and another corresponds to the 4.9 MeV gamma-ray from the excited state of $^{13}_{\Lambda}$C ($3/2^+$). The energy spectrum around the two peaks was fitted by two Gaussian and a linear functions. The fitting result gave about 220 keV (FWHM) resolution for the 4.44 MeV gamma-rays. An estimated energy resolution for 11 MeV gamma-rays was about 350 keV (FWHM) by a simple extrapolation of the energy resolution to higher energy ($\propto$E$^{1/2}$). The estimated energy resolution is used in the following analysis. From the peak fitting, the excitation energy of the $3/2^+$ states of $^{13}_{\Lambda}$C was estimated to be 4.915$\pm$0.013 MeV. The error is statistical only. The result is consistent with the result reported by the KEK-E336 experiment

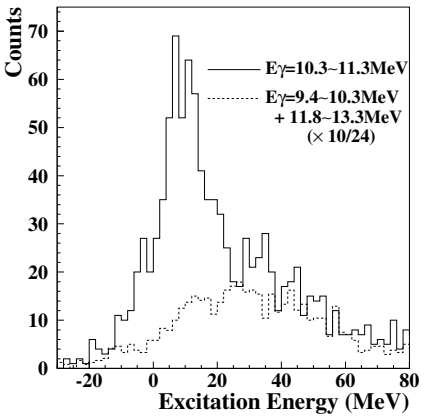

Figure 5. Excitation energy spectrum of $^{13}_{\Lambda}$C in coincidence with the 11 MeV gamma-rays (solid histogram).

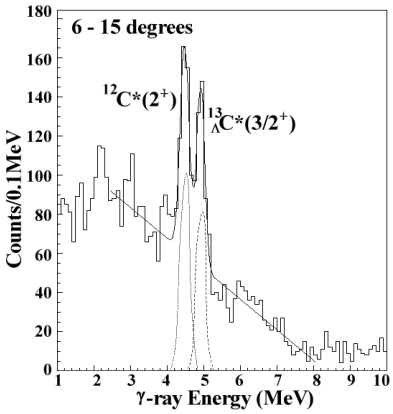

Figure 6. Gamma-ray energy spectrum in the 5 MeV region. Two clear peaks were observed.

within errors [6], and the precision is much improved from the old experiment.

To estimate the energy splitting of the spin-orbit doublet, we divided the experimental data into three subsets by cuts on the pion emission angle: $0°<\theta_\pi<7°$, $7°<\theta_\pi<10°$ and $10°<\theta_\pi<16°$. For each subset, the gamma-ray energy spectrum was created as shown in Figure 7. The 11 MeV peaks in the gamma-ray energy spectra were fitted by a full-energy peak, a single-escape peak, a Compton scattering component, which were generated by a Monte Carlo simulation calculation, and a simple exponential background function. As the result of the peak fitting, gamma-ray energies, E_γ, were obtained as follows: $E_\gamma(0°<\theta_\pi<7°) = 11.103\pm0.029$ MeV, $E_\gamma(7°<\theta_\pi<10°) = 11.016\pm0.024$ MeV and $E_\gamma(10°<\theta_\pi<16°) = 10.980\pm0.032$ MeV. We also estimated a ratio R = (N(1/2$^-$)-N(3/2$^-$))/(N(1/2$^-$)+N(3/2$^-$)), we called it "yield asymmetry", for each subset, where N(1/2$^-$) and N(3/2$^-$) were the detected numbers of gamma-rays from the 1/2$^-$ and 3/2$^-$ states, respectively, estimated from the theoretical differential cross sections and the knowledge of the magnetic spectrometer acceptance. We obtained values of the yield asymmetry, R, as follows: $R(0°<\theta_\pi<7°) = 0.769$, $R(7°<\theta_\pi<10°) = 0.107$ and $R(10°<\theta_\pi<16°) = -0.816$.

Figure 8 shows the gamma-ray energy, E_γ, as a function of the yield asymmetry, R. The data points are fitted by a linear function. The points R=1 and -1 corresponds to the 100% population of the 1/2$^-$ and 3/2$^-$ states, respectively. So, the energy difference at the R=1 and -1 points gives the value of the energy splitting of the spin-orbit doublet: Ex(1/2$^-$)-Ex(3/2$^-$) = 152±54(stat.)±36(sys.) keV. The estimated energy splitting is extremely small in comparison with the spin-orbit splitting of normal nuclei [13], and the level order of the spin-orbit doublet is the same as that of normal nuclei; i.e., 1/2$^-$ is higher than 3/2$^-$ in the excitation energy.

The absolute values of the excitation energies for the spin-orbit doublet were estimated as follows after a re-calibration of the gamma-ray energy scale by using the peak energies of known gamma-rays from normal nuclei: Ex(1/2$^-$) = 10.98±0.03 MeV (preliminary) and Ex(3/2$^-$) = 10.83±0.03 MeV (preliminary). The obtained excitation energy for the

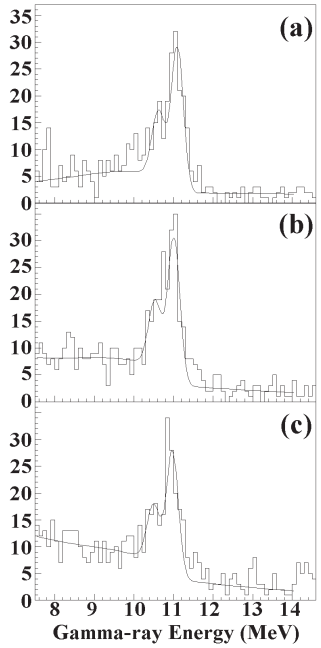

Figure 7. Gamma-ray energy spectra for the three data subsets. Angular cuts for the spectra were (a) $0°<\theta_\pi<7°$, (b) $7°<\theta_\pi<10°$ and (c) $10°<\theta_\pi<16°$.

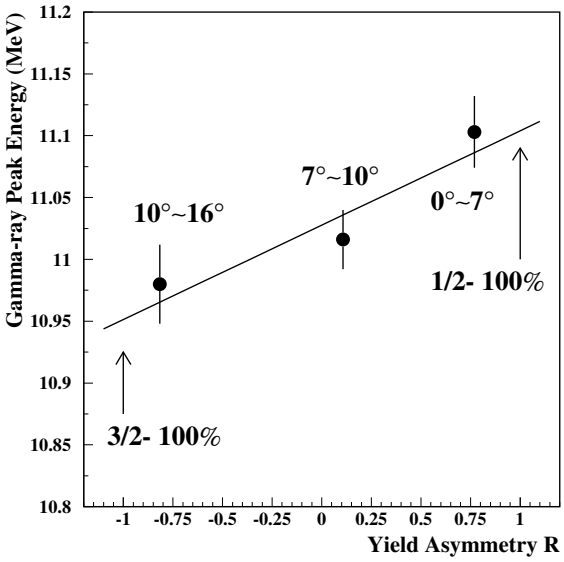

Figure 8. The gamma-ray energy was plotted as a function of the yield asymmetry, R.

$1/2^-$ state is consistent with the result reported in ref. [10].

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