MEASUREMENT OF SPIN-ORBIT SPLITTING IN $^{13}_{\Lambda}$C HYPERNUCLEUS

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An experiment, E929, has been carried out at BNL/AGS to estimate the spin-orbit splitting in the $^{13}_{\Lambda}$C hypernucleus by measuring $1\hbar\omega$ γ-ray transitions. About 250 events of $1\hbar\omega$ γ-ray transitions coincidence with the ^{13}C(K^-,π^-) reaction were obtained by analyzing about 50 % of the experimental data. Even though the energy calibration of the γ-ray detector is still primitive, overall energy resolution of about 550 keV at 11 MeV is obtained, and it corresponds to the sensitivity roughly down to 150 keV in estimating the spin-orbit splitting. Preliminary γ-ray energy spectra are shown.

1 Introduction

Spectroscopic study on the Λ hypernuclei has been done for many years. One of the interests in the study was the property of the Λ-nucleus interaction. How is it similar with and how is it different from the well known nucleon-nucleus interaction ? The single independent particle motion of Λ in the mean field of the nucleus was clearly demonstrated by the associated production reaction; i.e., the (π^+,K^+) reaction.[1,2] The simple shell structure of the heavy Λ hypernuclei viewed by the (π^+,K^+) reaction is telling the smallness of the Λ-nucleon residual interaction, which makes the escape and spreading widths wider for the particle unbound Λ shell-model states, and it is also telling smaller spin dependent interaction on the Λ particle in the nuclear medium than that on the nucleon. Experimentally, the smallness of the spin dependent interaction made the detailed study of the Λ-nucleus interaction difficult. Various attempts to determine the spin dependent interaction were not so successful and results were unclear with a few exceptions. On the other hand, theoretical studies on the Λ-nucleus interaction, based on the SU(3) flavour symmetry assumption with the microscopic nucleon-nucleon interaction, had a great progress in the recent years. Spin doublets in the Λ hypernuclei were discussed with the spin-spin, spin-orbit and tensor interactions, and effect of the Λ-Σ cou-

pling was estimated.[3] To catch up with the theoretical progresses, new experiments have been proposed. These new types of experiments necessarily attempt to be high resolution; i.e., sub-MeV resolution at least and a few keV resolution in the best case.

In this paper, we report preliminary results of the NaI(Tl) γ-ray detector experiment, AGS/E929, for the spin-orbit splitting measurement in the $^{13}_{\Lambda}$C hypernucleus attempting the sub-100keV sensitivity.

2 Basic Ideas of the Experiment

The measurement of the Λ $1\hbar\omega$ γ-ray transition by NaI(Tl) detectors was reported by May *et al.* at the first time for the $^{13}_{\Lambda}$C hypernucleus.[4] Among many excited states of the $^{13}_{\Lambda}$C hypernucleus, there are two excited states for which $p_{1/2\Lambda}$ and $p_{3/2\Lambda}$ couple to the $^{12}C_{g.s.}$ core, respectively. The γ-ray transition observed, E_γ=10.95$\pm$0.1$\pm$0.2 MeV, was the transition from the excited states to the ground state of the hypernucleus. Due to the limited yield of the decay γ-rays (about 15 events), most of the γ-rays corresponded to the $p_{1/2\Lambda}\rightarrow s_{1/2\Lambda}$ transition. An experiment with higher statistics makes it possible to measure both $p_{1/2\Lambda}\rightarrow s_{1/2\Lambda}$ and $p_{3/2\Lambda}\rightarrow s_{1/2\Lambda}$ transitions, and we can estimate the spin-orbit splitting between the $p_{1/2\Lambda}$ and the $p_{3/2\Lambda}$ states if a selective measurement of the two transitions is possible. A sub-100keV sensitivity is expected by γ-ray detectors with a 300 keV energy resolution at 11 MeV.

The selective excitation of the two states in $^{13}_{\Lambda}$C hypernucleus is possible by using the difference of the angular dependences of the differential cross section of the (K^-,π^-) reaction. Fig.1 shows the differential cross section of the ^{13}C(K^-,π^-)$^{13}_{\Lambda}$C reaction as a function of the π^- scattering angle at E_{K^-}=0.9GeV/c by a DWIA calculation.[5] Due to the small momentum transfer in the (K^-,π^-) reaction, the differential cross section of the $p_{1/2\Lambda}$ population (momentum transfer in the reaction ΔL=0) is forward peaking, and that of the $p_{3/2\Lambda}$ population (ΔL=2) is large at larger angle. By using the difference of the angular distribution of the cross sections, we can selectively populate either of the excited state by selecting the angular region of the scattered π^-. We wish to emphasize that this method of the spin-orbit splitting estimation is almost free from systematic errors because the π^- detection with the spectrometer system and the detection of γ-rays with the γ-ray detectors are almost independent. This is not the case for the experiment only with a spectrometer, since the momentum and scattering angle measured with a spectrometer usually have an instrumental correlation. A small residual correlation between the π^- scattering angle and the γ-ray energy comes from the Doppler-shift, but the effect is small and correctable.

More details of the ideas and design principle of the experiment are described in the experimental proposal.[6]

3 Experimental Setup

The experiment has been carried out at the D6 beamline of the AGS experimental facility in Brookhaven National Laboratory in June/July 1998. The beamline pro-

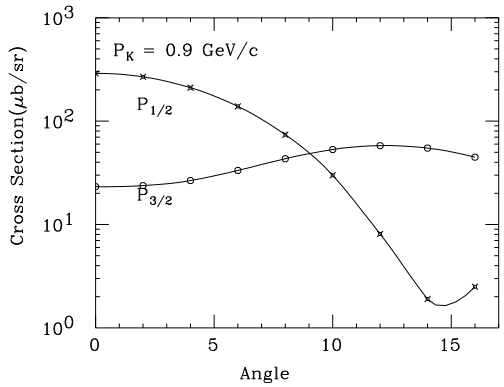

Figure 1: Differential cross section of the ^{13}C(K$^-$,π^-)$^{13}_{\Lambda}$C reaction as a function of the π^- scattering angle by a DWIA calculation.

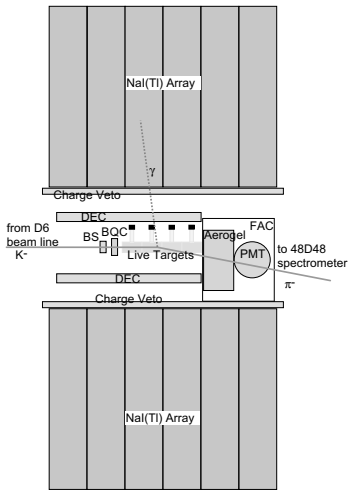

Figure 2: A schematic view of the detector setup around the target.

vided good quality of intense K$^-$ beam, and products of the (K$^-$,π^-) reaction were measured with the large acceptance spectrometer system, 48D48. Details of the D6 beamline and the 48D48 spectrometer can be found elsewhere.[7]

The nominal beamline momentum was set to 930 MeV/c which was optimized for the yield of the (K$^-$,π^-) reaction, typical beam intensity was 10^5 K$^-$/spill (1 spill $\sim$ 4 sec), and 21×10^9 K$^-$ beam bombarded on the target in total. The K$^-/\pi^-$ ratio was better than 1 by the electrostatic mass separator in the beamline, and clear identification of the K$^-$ beam particles was possible by the beam aerogel Čerenkov detector and the beamline TOF information in the trigger-level and in the off-line analysis, respectively. The π^- particles from the reaction were analyzed with the 48D48 spectrometer system. The aerogel Čerenkov detector and the TOF system in the spectrometer made the clear identification of π^- particles feasible. Typical missing mass resolution of the spectrometer system was 10 MeV/c^2 including the contribution from the beamline momentum analysis.

In addition to the standard detector setup of the D6 beamline and the 48D48 spectrometer system, new detectors were installed in the target region. Fig.2 shows a schematic view of the detector setup around the target. Our ^{13}C target consisted of 4 sets of ^{13}C benzene based liquid scintillator contained in glass cells (Live Targets). The scintillation light was read out by PM tubes attached to both ends of each glass cell through light guides. The information was used to positively identify the formation of the hypernuclei as described in Sec.4. In the upstream of the target, the beam defining plastic scintillation counter (BS) and the total reflection type quartz Čerenkov detector (BQC) were placed. In the downstream of the target, the aerogel Čerenkov detector (FAC) was placed. Since the most strong background

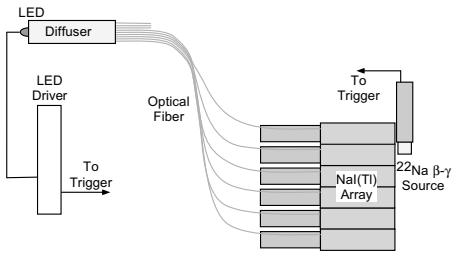

Figure 3: A schematic view of the energy calibration system for the NaI(Tl) detectors. See text for more detail.

in the measurement of the (K^-,π^-) reaction was the K^- decay in-flight, BQC and FAC information was used to minimize the decay region of K^-. The decay particle counters (DEC) were placed at the top and the bottom of the target, and detected charged particles from the target cell.

To measure the γ-rays coincidence with the (K^-,π^-) reaction, 6×6 arrays of NaI(Tl) detectors were placed above and below the target with charge veto plastic scintillation detector (Charge Veto). Each NaI(Tl) module had a 2.5"×2.5"×12" size. The distance from the target to the NaI(Tl) detector arrays was about 10 cm. For the energy calibration, the LED light signal driven by a pulser sent to each NaI(Tl) module through an optical fiber. The LED was pulsed about 5 times in a beam spill, and could be used for a monitoring of the detector energy gain. To make a continuous monitoring for the absolute energy calibration, a ^{22}Na γ-ray source was attached to the top NaI(Tl) array, and the 1.275 MeV γ-ray was monitored as a part of the data acquisition stream. Fig.3 shows a schematic view of the energy calibration system for the NaI(Tl) detectors. Absolute energy calibration was done for all NaI(Tl) modules by the ^{22}Na γ-ray source and γ-rays from the ^{58}Ni(n,γ) reaction (Eγ=8.54MeV and 9.00 MeV) about in every week and every month, respectively.

4 Data Reduction and Results

The recorded experimental data contained the (K^-,π^-) events, large amount of background events from the K^- decay in-flight between BQC and FAC, and mis-identified K^- elastic scattering events. The K^- elastic scattering events were removed by the mass-squared cut calculated from the momentum and TOF information in the 48D48 spectrometer. The energy deposit in the Live Targets for the background K^- decay in-flight events is essentially comparable with 1 MIP energy deposit. On the other hand, if the ^{13}C(K^-,π^-) reaction creates a Λ hypernucleus and it decays with non-mesonic process (proton-stimulated), the energy deposit in the Live Target at the reaction vertex is much higher than that of 1 MIP due to additional energy deposit by the decay proton. By selecting large energy deposit in one of the Live Target, we could efficiently select the formation of hypernuclei (efficiency $\sim$ 30%) and reject the K^- decay in-flight background (reduction $\sim$ a few 0.1% with a tight cut). DEC information was also useful to detect decay pro-

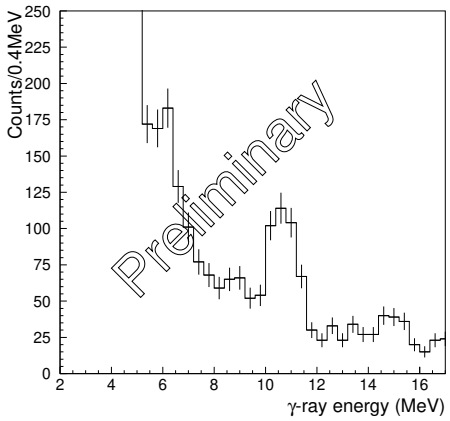

Figure 4: Energy spectrum of γ-ray coincidence with the (K^-,π^-) reaction. The peak around 11 MeV corresponds to the $p_\Lambda \rightarrow s_\Lambda$ $1\hbar\omega$ transition.

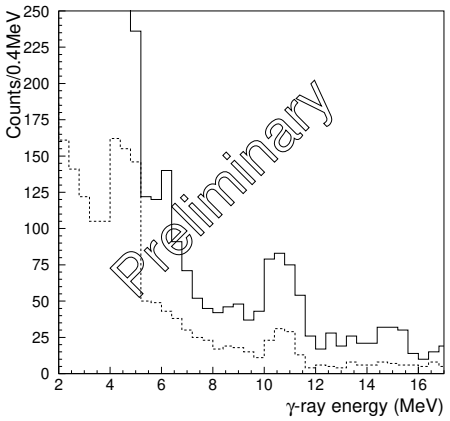

Figure 5: Same histograms as Fig.4 with cuts on the π^- scattering angle; $2^\circ \leq \theta_{\pi^-} \leq 9^\circ$ (solid line) and $9^\circ \leq \theta_{\pi^-} \leq 16^\circ$ (dashed line).

tons from the non-mesonic decays of hypernuclei, and improved the efficiency of the formation tagging of the hypernuclei.

After the reduction of the background, the missing mass was calculated by assuming the ^{13}C(K^-,π^-) kinematics. Since the spectrometer analysis was still preliminary and absolute momentum calibration of the spectrometer was not final, a loose cut on the excitation energy was set; i.e., the cut $0 \leq E_X \leq 50$ MeV was used. For the events selected by the excitation energy, the γ-ray energies measured by the NaI(Tl) arrays were accumulated as shown in Fig.4 for 50 % of total data. The peak around 11 MeV corresponds to the reported $1\hbar\omega$ γ-ray transition in the $^{13}_{\Lambda}$C hypernucleus. The γ-rays with energy around 11 MeV deposit energy in NaI(Tl) by several steps of interaction and has transverse spread of energy deposit which is larger than the size of our NaI(Tl) modules. The energy deposits in a 3×3 array of the NaI(Tl) modules were summed up to achieve a larger full-energy peak efficiency for the 11 MeV γ-rays. The yield of the γ-rays in the peak around 11 MeV was about 250 counts with 50 % of total data, which was almost consistent with the yield estimation in the experimental proposal. The energy calibration of the NaI(Tl) detector was still preliminary; i.e., only the weekly measured energy calibration data with the ^{22}Na calibration source were used to correct the gain drift of the NaI(Tl) detectors. The energy resolution of the NaI(Tl) detector arrays including the imperfection of the energy calibration was estimated with the 4.44 MeV γ-rays from the ^{12}C nucleus. The quasi-free (K^-,π^-) reaction, in which the Λ particles escape from the hypernuclei, leave the residual nuclei in their excited states. The γ-rays from the quasi-free events could be accumulated from the same dataset used for the hypernuclear γ-ray measurement. By a simple extrapolation of the γ-ray energy resolution from 4.44 MeV to 11 MeV, the resolution at 11 MeV was estimated to be 550 keV. This energy resolution roughly corresponds to 150

keV sensitivity in the spin-orbit splitting determination.

Fig.5 shows also the γ-ray energy spectra with different cuts on the π^- scattering angle; i.e., the forward angle $2^\circ \leq \theta_{\pi^-} \leq 9^\circ$ (solid line) and the backward angle $9^\circ \leq \theta_{\pi^-} \leq 16^\circ$ (dashed line) cuts. If our basic idea described in Sec.2 works well, the difference of the peak positions of the two histograms in Fig.5 tells the spin-orbit splitting for the $p_{1/2\Lambda}$ and $p_{3/2\Lambda}$ doublets in the ${}^{13}_{\Lambda}$C hypernucleus. Since the analysis is still preliminary and still in progress; e.g., the energy calibration of the γ-ray detectors, spectrometer analysis, effect of Doppler-shift, etc., we postpone the numerical evaluation of the spin-orbit splitting while it looks very small.

5 Summary

We carried out a high statistics γ-ray measurement coincidence with the ^{13}C(K^-,π^-) reaction to estimate the spin-orbit splitting between $p_{1/2\Lambda}$ and $p_{3/2\Lambda}$ states in the ${}^{13}_{\Lambda}$C hypernucleus. About 250 events of $p_\Lambda \rightarrow s_\Lambda$ γ-ray transition were obtained after analyzing about 50 % of the total data. We expect about 30 times improvement in statistics compared with the previous experiment after analyzing the full data, and it will make precise determination of the Λ spin-orbit splitting in sub-100keV level feasible. Currently obtained energy resolution for 11 MeV γ-ray was estimated to be 550 keV, and it means we already have the sensitivity of the spin-orbit splitting determination down to 150 keV. We expect an improvement of the energy resolution of the NaI(Tl) detectors down to 300 keV with more careful energy calibration of the γ-ray detectors.

Acknowledgments

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