Study of Spin-Orbit Splitting in ${}^{13}_{\Lambda}$C

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Abstract

AGS/E929 experiment is a dedicated experiment for the study on the spin-orbit splitting of the Λ particle in hypernuclei. Basic idea of the experiment is an excitation energy measurement of spin-orbit doublets with better energy resolution and small systematic errors by detecting decay γ-rays from hypernuclei. Details of the experimental setup is shown. The sensitivity of the spin-orbit splitting in the experiment is estimated to be 0.1 MeV.

1 Introduction

Overall feature of the nuclear level scheme is well explained with models by considering the central, spin-dependent and isospin-dependent potentials, since the independent-particle picture and the isospin symmetry are quite well in nuclei. In hypernuclei, another degree of freedom of the Λ particle is introduced, and one interesting question is how the independent-particle picture or the shell model is still good for the Λ particle in hypernuclei. Recent experimental data of the (π^+, K^+) reaction demonstrated clear evidences

of the shell structure of the Λ single particle state in hypernuclei [1, 2]. The shell structure of the Λ particle is observed from the lowest s-orbit to almost Fermi-level orbits of normal nuclei. Together with the observation of the shell structure in the wide range of orbits, relatively simple level structure of the hypernuclei indicates a small spin-dependent potential for the Λ particle and weak residual interaction between Λ particle and nucleons.

The spin-orbit splitting (LS splitting) of a Λ particle in hypernuclei, which is one of the spin-dependent interaction, has been studied extensively [3, 4, 5, 6, 7]. From the experiments, the LS splitting seemed to be smaller than 1 MeV (for p-shell), but no conclusive result has been obtained yet due to the small LS splitting and finite energy resolution in the experiments. Most of the experiments except for Ref.[7] were spectrometer experiments. In the spectrometer experiments, the LS splitting was examined as the difference of excitation energies of LS doublets, and the precision of estimations of the LS splitting was limited by the excitation energy resolutions of the spectrometers, those were typically 2 MeV or worse.

To obtain conclusive result on the LS splitting, we need new experiments dedicated for the subject. Better resolution of the excitation energy is essential [8] and efforts to keep systematic errors in the LS splitting estimation small are needed. Excitation energy determination by a measurement of decay γ-rays from excited states in hypernuclei is one of methods to achieve the better energy resolution. In this presentation, we describe a new experiment for the LS splitting measurement based on a detection of γ-rays from $1\hbar\omega$ transition between the excited states, $p_{3/2-}(\Lambda)$ and $p_{1/2-}(\Lambda)$, and the ground state, $s_{1/2+}(\Lambda)$, in the ${}^{13}_{\Lambda}$C hypernucleus.

2 Basic ideas of new experiment

We study the LS splitting of the Λ particle in the p-shell orbit in the ${}^{13}_{\Lambda}$C hypernucleus by measuring decay γ-rays from the excited LS doublets to the ground state (see Fig.1). The reasons of the selection of the hypernucleus for the LS splitting study are (1) relatively simple structures of LS doublets, ${}^{12}C_{g.s.} + p_{j-}(\Lambda)$, and the ground state, ${}^{12}C_{g.s.} + s_{1/2+}(\Lambda)$, which is a merit to extract information of the LS splitting from the level separation of the doublets, (2) high energy decay γ-rays, $E_\gamma \sim 10 MeV$, those are relatively free from instrumental and physical backgrounds, (3) and previous observation of the decay γ-rays in the ${}^{13}_{\Lambda}$C hypernucleus ($1/2^-$ to g.s.) reported by the AGS/E781 collaboration [9]. We are planning to detect the decay γ-rays by arrays of NaI(Tl) detectors [10]. The energy resolution of the NaI(Tl) detectors are known to be better than 0.7 MeV (FWHM) even for the 10 MeV γ-rays, which is considerably better than that of magnetic spectrometers. The precision of the excitation energy measurement is determined by the intrinsic energy resolution of the NaI(Tl) detectors and also number of decay γ-rays to be detected. From the view point of the yield of γ-rays, the NaI(Tl) detector is a good choice, since it is easy

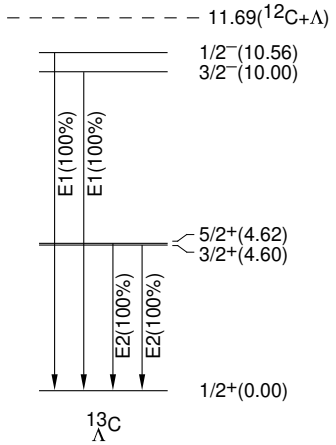

Figure 1: Level scheme of the $^{13}_{\Lambda}$C hypernucleus. Excitation energies are coming from a theoretical calculation.

to obtain more than 10 % overall efficiency (including solid angle) with arrays of NaI(Tl) detectors for the 10 MeV γ-rays.

Theoretically expected value of the LS splitting for a Λ particle in p-shell ranges from 0 MeV to 1 MeV. Even with the better energy resolution of the NaI(Tl) detectors, direct separation of energies of decay γ-rays from the LS doublets is not easy. Fortunately, we can measure the energies of the decay γ-rays almost separately by using the angular dependence of the differential cross section for the (K^-, π^-) reaction at the beam energy near the recoil-less condition. As well know, the substitutional states, $((l_j(\nu))^{-1}(l_j(\Lambda)))_{0+}$, are strongly populated by the (K^-, π^-) reaction at 0 degree near the recoil-less beam energy. In the $^{13}_{\Lambda}$C case, the $1/2^-$ state is one of the substitutional states, $^{13}C_{g.s.(1/2-)} + ((p_{1/2-}(\nu))^{-1}(p_{1/2-}(\Lambda)))_{0+}$, the state can be populated strongly by detecting the π^- at small angle ($\theta_{\pi^-} < 7$ degrees), and the decay γ-ray from the $p_{1/2-}(\Lambda)$ to the ground state dominates. The recoil-less condition breaks at large π^- scattering angle ($\theta_{\pi^-} > 10$ degrees), the ΔL=2 angular-momentum transfer is much more favored than the ΔL=0 in the (K^-, π^-) reaction, and the decay γ-ray from the $p_{3/2-}(\Lambda)$ to the ground state dominates. So, we can estimate the LS splitting of the $^{13}_{\Lambda}$C hypernucleus from the peak energy shift of the decay γ-rays as changing the detection angle of π^-. Figs.2 and 3 show the angular dependence of the differential cross section for the (K^-, π^-) reaction at the beam energy near the recoil-less condition (p_{K^-}=0.9GeV/c), and γ-ray energy spectra coincidence with π^- at small and large angles, respectively. Practically, we should measure the π^- from the (K^-, π^-) reaction at small and large angles at the same time to minimize the systematic error in the γ-ray energy measurement, and it is possible by using a large acceptance spectrometer.

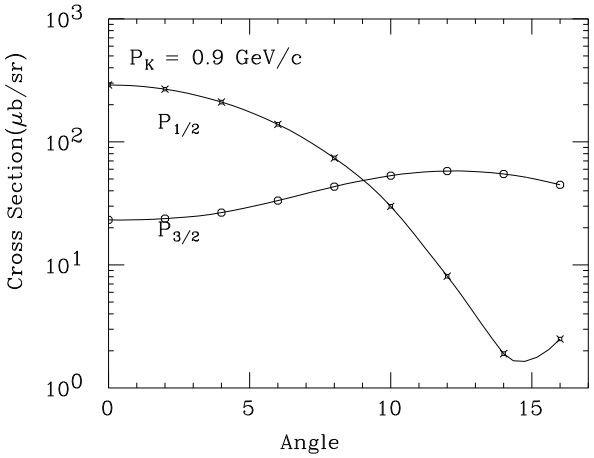

Figure 2: Angular dependence of the differential cross sections of the $^{13}C(K^-,\pi^-)^{13}_{\Lambda}C$ reaction at p_{K^-}=0.9GeV/c from a theoretical calculation. The cross sections for the $1/2^-$ (cross) and the $3/2^-$ (circle) states are plotted.

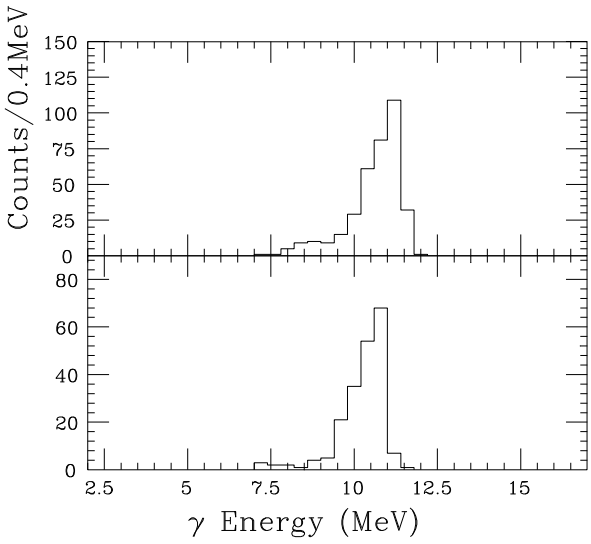

Figure 3: Energy spectra of decay γ-rays coincidence with π^- at small (top) and large (bottom) angles calculated by a Monte Carlo simulation. Doppler broadening, energy resolution and response of NaI(Tl) detectors are included.

3 AGS/E929 experiment

The AGS/E929 experiment is proposed for a dedicated study of the LS splitting in the $^{13}_{\Lambda}$C hypernucleus [11], and is in the preparation stage. 0.9 GeV/c K^- beam from the AGS D6 beam line is used, typical beam intensity is expected to be $10^5 K^-$/spill at 10^{10} proton/spill primary beam intensity, and $K^-/(e^-\mu^-\pi^-)$ ratio is well better than 1. A large acceptance 48D48 spectrometer is used to measure π^- from the (K^-,π^-) reaction. The spectrometer has an angular coverage from 2 to 16 degrees, and typical solid angles are 8 msr and 12 msr at 3 and 13 degrees, respectively.

Fig.4 shows schematic side view of detector setup at the target region. A plastic scintillation counter (BS) is used for beam defining and triggering. ^{13}C enriched benzene is used for the ^{13}C target, and kept in 4 glass cells with a size 60mm(W)×17mm(H)×32mm(T). The thickness of the target is about 9 g/cm^2. By adding wavelength shifter, the target benzene works as a scintillator and the light output is measured with photo multiplier tubes attached to the both ends of the glass cell (Live Targets). Since the in-flight K^- decays ($K_{\mu 2}$ and $K_{\pi 2}$ decays) are the strongest backgrounds, the light output information is used to reduce the backgrounds. Fig.5 shows π^- spectra obtained in a test experiment with a normal benzene scintillator target. Contribution from the K^- decay in-flight is seen as loci in the top plot of Fig.5. After selecting events with large energy deposit in the

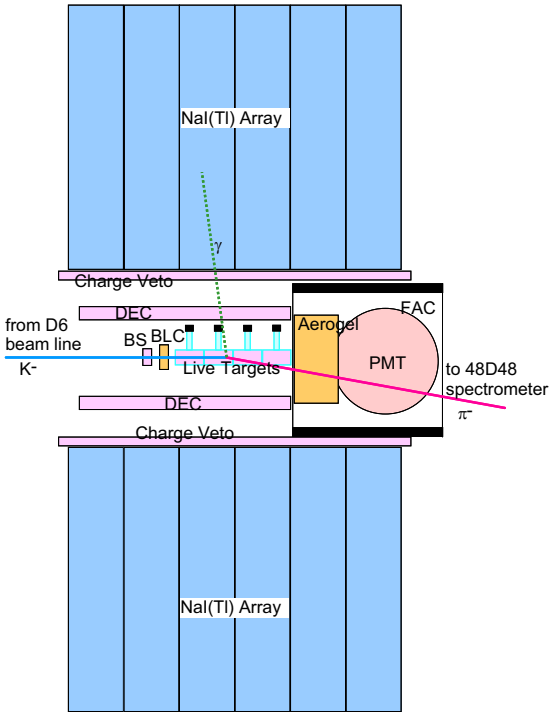

Figure 4: Schematic side view of experimental setup at the target region. See text for more detail.

Figure 5: Scattering angle (horizontal) vs momentum (vertical) plots of π^- from K^- induced reactions on ^{12}C target without (top) and with (bottom) event selection by the light output of the benzene scintillator. See text for more detail.

benzene target which corresponds to 1 MIP energy deposit plus additional energy deposit by the decay of hypernuclei, we can see clearly the contribution of π^- from the formation of hypernuclei (events $p_{\pi^-} < 0.75$ GeV/c). The efficiency of the decay tagging by the target scintillator is estimated to be 30 %, and the inefficiency of the rejection of the K^- decay in-flight events is less than 0.2 %. Decay particle counters (DEC) make additional tagging of the decay of hypernuclei by detecting decay charged particles. Two Čerenkov detectors are placed in the beam line at the upstream (BLC) and the downstream (FAC) of the target to clearly identify K^- and π^-, respectively. This additional particle identification reduces the contribution of the background of the K^- decay in-flight. BLC is a total-reflection type Lucite Čerenkov detector and FAC is a threshold type aerogel Čerenkov detector.

As the γ-ray detectors, two 6×6 arrays of NaI(Tl) detectors are placed 10 cm from the K^- beam above and below the target. Each NaI(Tl) detector module has a dimension 2.5"×2.5"×12". The segmentation of the NaI(Tl) detector system is necessary to keep the single rate of the NaI(Tl) detector modules low, then keep deterioration of the energy resolution of the detector negligible. The energy gains of the NaI(Tl) detector modules

are calibrated relatively by an online LED monitoring system, and calibrated absolutely with conventional γ-ray sources and high energy γ-rays from the ^{58}Ni(n,γ) reaction before and after the beam time. Charge Veto counters are placed in front of each NaI(Tl) array to reject charged particle hits in the NaI(Tl) detectors. Yield of γ-rays from the decay of $1/2^-$ and $3/2^-$ states is estimated to be 300 and 120, respectively, after 300 hours running at 10^{10} proton/spill primary beam intensity. With the γ-ray yields, the experiment is expected to have a sensitivity of the level spacing between the $1/2^-$ and the $3/2^-$ states down to 0.1 MeV.

4 Summary

The LS splitting of the Λ particle in hypernuclei is a longstanding problem to be studied. Clear estimation of the LS splitting is possible only by dedicated experiments with more better excitation energy resolution, and efforts to keep systematic errors small are essential. We presented a proposal of a dedicated experiment for the LS splitting study, AGS/E929 experiment, by measuring decay γ-rays from the excited states in the $^{13}_{\Lambda}$C hypernucleus. The sensitivity of the LS splitting in the experiment is expected to be 0.1 MeV, and beam-time is scheduled at AGS D6 beam line in June and July 1998.

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