Observation of Spin-Orbit Splitting in Λ Single-Particle States

S. Ajimura,[1] H. Hayakawa,[1] T. Kishimoto,[1] H. Kohri,[1] K. Matsuoka,[1] S. Minami,[1] T. Mori,[1] K. Morikubo,[1] E. Saji,[1] A. Sakaguchi,[1] Y. Shimizu,[1] M. Sumihama,[1] R. E. Chrien,[2] M. May,[2] P. Pile,[2] A. Rusek,[2] R. Sutter,[2] P. Eugenio,[3] G. Franklin,[3] P. Khaustov,[3] K. Paschke,[3] B. P. Quinn,[3] R. A. Schumacher,[3] J. Franz,[4] T. Fukuda,[5] H. Noumi,[5] H. Outa,[5] L. Gan,[6] L. Tang,[6] L. Yuan,[6] H. Tamura,[7] J. Nakano,[8] T. Tamagawa,[8] K. Tanida,[8] and R. Sawafta[9]

[1]*Department of Physics, Osaka University, Toyonaka, Osaka, 560-0043, Japan*
[2]*Brookhaven National Laboratory (BNL), Upton, New York 11973*
[3]*Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[4]*University of Freiburg, Hermann-Herder-Strasse 3, D79104 Freiburg, Germany*
[5]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaragi, 305-0801, Japan*
[6]*Department of Physics, Hampton University, Hampton, Virginia 23668*
[7]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[8]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[9]*Department of Physics, North Carolina A&T State University, Greensboro, North Carolina 27411*

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The spin-orbit splitting of Λ single-particle states in ${}^{13}_{\Lambda}$C was measured. The ^{13}C$(K^-,\pi^-){}^{13}_{\Lambda}$C reaction was used to excite both the $1/2^-$ and $3/2^-$ states simultaneously, which have predominantly ^{12}C$(0^+) \times p_\Lambda$ configuration. γ rays from the states to the ground state were measured in coincidence with the π^-'s, by which ℓs splitting was found to be 152 ± 54(stat) ± 36(syst) keV. The value is 20–30 times smaller than exhibited by the ℓs splitting in the nuclear shell model. This value gives us new insight into the *YN* interaction.

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Observation of Λ single-particle states, first by the (K^-,π^-) reaction [1] and then later by the (π^+,K^+) reaction [2,3], clarified the gross structure of the Λ-nucleus interaction. The dominant central part is found to be roughly 2/3 that of nucleon. This is quantitatively reproduced by one boson exchange (OBE) models of the hyperon-nucleon (*YN*) interaction and qualitatively understood in quark models that the Λ is composed of *u*, *d*, and *s* quarks and the *s* (strange) quark contributes little to the nuclear force. On the other hand, little has been known about the spin-dependent interaction. Especially, spin-orbit (ℓs) splitting was found to be smaller than that for the nucleon [4–6] although no experiment has given a definite value so far. The ℓs splitting in the Λ*N* interaction has been a major goal in the study of hypernuclei.

The ℓs splitting is given by the energy difference of the single-particle states of $j = \ell - 1/2$ and $j = \ell + 1/2$. The ℓs splitting of single-nucleon states is as large as that of the major shell spacing and plays an essential role for the foundation of the nuclear shell model. The ℓs force in the Λ*N* interaction has an antisymmetric part $[\ell \cdot (\mathbf{s}_\Lambda - \mathbf{s}_N)]$ in addition to the usual ℓs force. These two forces tend to cancel in the Λ*N* interaction leading to a small ℓs splitting of single-Λ states although quantitative prediction depends on theoretical models. OBE models of the *NN* interaction have been extended to *YN* interactions with the help of flavor SU(3) symmetry [7]. Effective one-body hyperon-nucleus interactions have been constructed based on OBE models [8,9]. It reproduces the central part of the Λ-nucleus interaction and predicts small ℓs splitting. For instance, the ℓs splitting of single-Λ states in ${}^{13}_{\Lambda}$C is calculated to be 0.56 MeV [10] which is ~0.1–0.2 that of the nucleon (~3–5 MeV). Quark models, which naturally account for the short range interaction, predict much smaller ℓs splitting [11,12], although quark models have yet to give an extensive description of the *YN* interaction.

The smallness of the ℓs splitting of single-Λ states was first suggested by the (K^-,π^-) reaction on ^{16}O [4]. The difference of energy between the $[(p_{1/2})_n^{-1},(p_{1/2})_\Lambda]0^+$ and $[(p_{3/2})_n^{-1},(p_{3/2})_\Lambda]0^+$ states in ${}^{16}_{\Lambda}$O is almost the same as that of the $(p_{1/2})_n^{-1}$ and $(p_{3/2})_n^{-1}$ states in ^{15}O, setting an upper limit of 0.3 MeV for the ℓs splitting of single-p_Λ states. A later theoretical calculation gave weaker constraint [13]. A small splitting was also indicated by the ^{13}C$(K^-,\pi^-){}^{13}_{\Lambda}$C reaction and 0.36 ± 0.3 MeV was obtained [5,14]. Hypernuclear γ rays observed in ${}^{9}_{\Lambda}$Be indicated that the $3/2^+$ and $5/2^+$ states, which have $[(s_{1/2})_\Lambda, 2^+({}^8\text{Be})]$ configuration, are too close to be separated by NaI detectors suggesting small ℓs splitting [6]. However, the possibility that the $5/2^+$ state was not populated in the (K^-,π^-) reaction was not completely ruled out.

On the other hand, data suggesting larger ℓs splitting appeared recently. Single-Λ states in ${}^{89}_{\Lambda}$Y studied by the (π^+,K^+) reactions at KEK are broader than instrumental energy resolution, especially for large ℓ_Λ orbits. The apparent ℓs splitting increases almost linearly with the orbital angular momentum. This could be interpreted, using the Woods-Saxon prescription [15], as an unresolved ℓs doublet with $V_{LS} \sim 6$ MeV. Another suggestion was recently obtained by the analysis of old emulsion data on ${}^{16}_{\Lambda}$O [16]. The level spacing of 0^+ and 2^+ states, which are dominantly given by $[(p_{1/2})_n^{-1}, (p_{1/2})_\Lambda]0^+$ and $[(p_{1/2})_n^{-1}, (p_{3/2})_\Lambda]2^+$, respectively, indicates the larger ℓs splitting. However, when the intershell coupling is taken into account, about half of the 0^+-2^+ spacing in ${}^{16}_{\Lambda}$O should be attributed to the intrinsic ℓs splitting [17]. The effective ΛN interactions used in these analyses led to a predicted ℓs splitting of p_Λ in ${}^{13}_{\Lambda}$C of 0.7–1.0 MeV [18]. We note that these values are all substantially larger than the previous measurements. The situation calls for definitive measurement of the ℓs splitting.

${}^{13}_{\Lambda}$C is an ideal hypernucleus with which to extract the ℓs splitting. The $1/2^-$ and $3/2^-$ states at around 11 MeV are dominantly represented as $(p_{1/2})_\Lambda$ and $(p_{3/2})_\Lambda$ coupled to the 0^+ (^{12}C) core, respectively. Therefore the energy difference between the $1/2^-$ and $3/2^-$ states directly gives the ℓs splitting of single-p_Λ states [14]. So far, the ℓs splitting has been measured mostly by magnetic spectrometers. The best energy resolution of magnetic spectrometers achieved for the study of hypernuclei is around 2 MeV. Since the ℓs splitting is predicted to be $\sim$0–1 MeV, one wishes to measure it with precision better than 0.1 MeV. Since the p_Λ states in ${}^{13}_{\Lambda}$C are just below the particle emission threshold, γ rays can be observed by which the energy resolution is greatly improved.

The (K^-, π^-) reaction at forward angles is a unique way to excite $(p_{1/2})_\Lambda$ states in ${}^{13}_{\Lambda}$C strongly. The so-called substitutional transition $[(p_{1/2})_n \rightarrow (p_{1/2})_\Lambda]$ is dominant for momentum transfers much smaller than the Fermi momentum. Recently γ rays from the transition from the $(p_{1/2})_\Lambda$ state to the ground state (GS) in ${}^{13}_{\Lambda}$C were observed [19]. This was the first precise measurement of the $1\hbar\omega$ energy of a single-Λ state. In order to extract the ℓs splitting, γ rays from transitions from both the $(p_{1/2})_\Lambda$ and $(p_{3/2})_\Lambda$ states to the GS have to be measured. Excitation of the $(p_{3/2})_\Lambda$ state requires transfer of two units of angular momentum ($\Delta\ell = 2$), which is expected to dominate for π^-'s are scattered at angles of 10° to 20°. Based on these considerations we designed an experiment to measure γ rays from the $1/2^-$ and $3/2^-$ states which were excited by the ^{13}C$(K^-, \pi^-){}^{13}_{\Lambda}$C reaction [20].

The experiment (AGS-E929) was carried out at the D6 beam line of the alternating-gradient synchrotron (AGS) of BNL. The ^{13}C(K^-, π^-) reaction at $P_K = 0.93$ GeV/c was used to produce ${}^{13}_{\Lambda}$C. The incident K^- momentum was chosen so as to maximize the production rate of the states. The K^- beam intensity was typically $\sim 8 \times 10^4$/spill for 5×10^{12} proton/spill. A spill consisted of 1.4 sec of continuous beam every 4 sec. The beam-line spectrometer measured the incident K^- momentum. The momentum of the outgoing π^- was measured by the 48D48 spectrometer, which has a momentum resolution of 15 MeV/c (FWHM). Its large angular acceptance ($\sim$0°–16°) [21] made simultaneous measurement of forward ($\sim$4°) and large ($\sim$13°) scattering angles possible. This is vital for the small ℓs splitting.

Figure 1 shows the detectors around the target region. BS is a plastic scintillator which defines the incident beam.

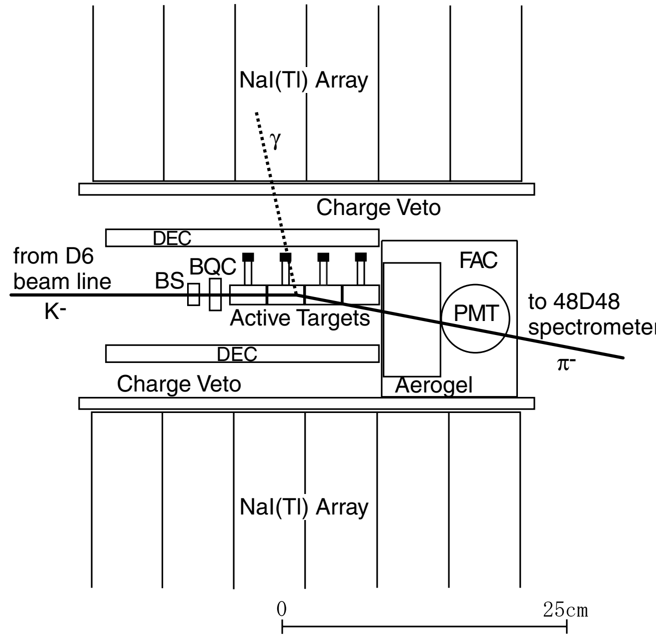

FIG. 1. Detector system at the target region is shown schematically. See text for the description of each detector element.

K^-'s were tagged by time of flight with a counter farther upstream in the beam line. BQC is the differential-type quartz Čerenkov counter which vetoes π^-'s in the beam. FAC is the aerogel Čerenkov counter which tags π^-'s right after the target. The (K^-, π^-) trigger was very clean with these conditions. The biggest background is the K^- decay in flight mostly from $K^- \rightarrow \pi^-\pi^0$ and $K^- \rightarrow \mu^-\nu$. These events gave (K^-, π^-) trigger signals identical to hypernuclear production. We used an active target to suppress them.

The active target was a benzene liquid scintillator whose carbon was 99% enriched ^{13}C. The target was contained in four quartz containers of 30(thickness) $\times$ 15(height) $\times$ 60(width) mm^3, giving a total thickness of 120 mm. Charged particles from the weak decay of Λ hypernuclei deposit energy in the target. Every (K^-, π^-) event deposits energy in the active target due to energy loss of the K^- and π^-. Optimization of container shape to increase the weak decay signal and to reduce the energy-loss signal gave good separation of the weak decay signal [22,23] which was much better than that of a previous measurement [19]. Plastic scintillators above and below the active target (DEC) gave supplementary signals to tag the weak decay. The excitation energy ($E_{\rm ex}$) spectrum of the ^{13}C$(K^-, \pi^-){}^{13}_{\Lambda}$C reaction was obtained from the measured K^- and π^- momenta. The p_Λ states appear at around $E_{\rm ex} = 11$ MeV. The overwhelming K^- decay and limited momentum resolution obscure the $E_{\rm ex}$ spectrum. However, tagging by the active target and DEC made it almost background free [22,23]. A relatively wide cut ($0 < E_{\rm ex} < 25$ MeV) for the p_Λ state was chosen to maximize 11 MeV γ rays where clean γ ray spectra were obtained as shown later.

γ rays from the ${}^{13}_{\Lambda}$C were measured by two detectors located below and above the target as shown in Fig. 1. Each detector consisted primarily of an array of 36 NaI crystals, each of which had a dimension of $6.5 \times 6.5 \times 30$ cm^3. Four plastic scintillators were placed in front of each NaI array to veto charged particles. High beam intensity can be tolerated by this segmented NaI detector. It is rare that an 11 MeV γ ray is fully contained in one NaI crystal. Signals from up to three adjacent crystals were added to obtain the full energy peak. The energy resolution is primarily determined by that of the crystal which had a dominant amount of energy deposited. Therefore NaI crystals with good energy resolution were selected and placed at the center of the NaI array.

The energy calibration of the NaI's was carried out using several γ rays, up to 9 MeV from the ^{58}Ni(n, γ) reaction. During the run, energy calibration of the whole system was monitored by ^{22}Na sources for stability over several days and light from light-emitting diodes was fed into all NaI's for stability over much shorter times. The energy calibration was stable within a percent for the worst crystal. This was quite adequate for the present measurement.

Energy spectra of γ rays in coincidence with π^-'s scattered at $0° < \theta_\pi < 7°$, $7° < \theta_\pi < 10°$, and $10° < \theta_\pi < 16°$ are shown in Fig. 2 (upper panel). We can clearly see a peak corresponding to p_Λ-to-GS transitions, although the two transitions of interest are not resolved. Doppler shift due to recoil of ${}^{13}_{\Lambda}$C was corrected on an event-by-event basis. The recoil momentum and γ ray direction were obtained from the reaction vertex, given by the drift chamber information, and the position of the NaI crystal which had maximum energy deposited. The correction is typically less than 100 keV. The width of a prominent 4.9 MeV peak, due to the $3/2^+ \rightarrow$ GS transition in ${}^{13}_{\Lambda}$C, becomes appreciably narrower and consistent with expected energy resolution. This observation verifies that the Doppler shift was properly corrected and variation of the energy calibration among each detector was well controlled.

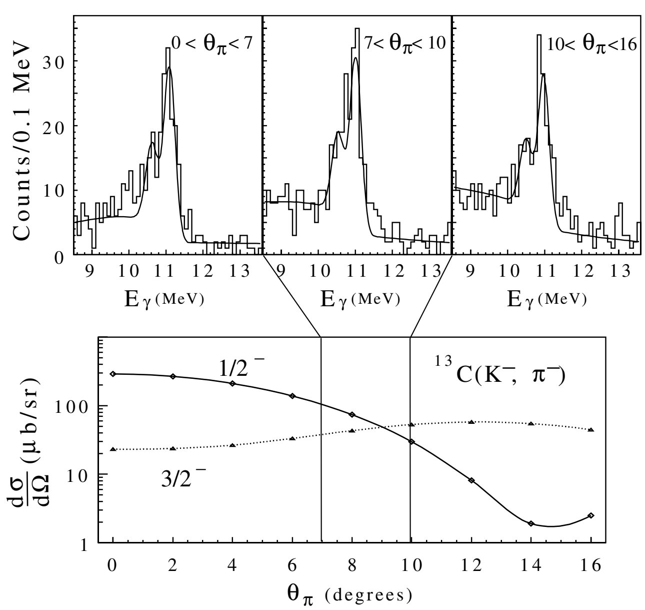

FIG. 2. γ ray spectra taken in coincidence with scattered π^-'s (upper panel) and differential cross section of $1/2^-$ and $3/2^-$ states calculated by Motoba [18] (lower panel) are shown.

The response function of the NaI detector for 11 MeV γ rays was obtained by a GEANT simulation which included the detector geometry and the procedure to sum energy of NaI crystals. The response function was folded with the energy resolution of the NaI detector [350 keV (FWHM) at 11 MeV] which was extrapolated from 9 MeV with a $\sqrt{E_\gamma}$ dependence. The background underneath the peak was assumed to be an exponential in energy plus a constant background. A fitting function with these conditions reproduces well a peak in each spectrum as shown in Fig. 2 (upper panel). A shoulder approximately 0.5 MeV lower than the 11 MeV peak of interest is due mainly to single escape and a tail extends to the low energy region. Since the peak width is well fit as a single transition, we conclude that the ℓs splitting is small compared to our resolution. We derived peak positions by fitting a single γ ray peak for each of the three spectra.

Angular distributions of π^- for the $(p_{1/2})_\Lambda$ and $(p_{3/2})_\Lambda$ states, calculated by the distorted wave impulse approximation, are shown in Fig. 2 (lower panel). The $(p_{1/2})_\Lambda$ state is dominant at $0° < \theta_\pi < 7°$, on the other hand the $(p_{3/2})_\Lambda$ state is dominant at $10° < \theta_\pi < 16°$. Both states are almost equally excited at $7° < \theta_\pi < 10°$. In order to obtain the ℓs splitting, the relative yields of $(p_{1/2})_\Lambda$ and $(p_{3/2})_\Lambda$ states must be estimated for each spectrum. Since two states cannot be separated experimentally, relative yield in each spectrum is calculated by using the theoretical differential cross section [Fig. 2 (lower panel)] and the acceptance of the 48D48 spectrometer for scattered π^-'s. The acceptance was estimated by a GEANT simulation which included the magnetic field distribution and relevant information of all counters. The simulation reproduces the spatial and angular profiles of incident K^-'s and outgoing π^-'s at the target and thus reproduces the acceptance.

Peak positions are plotted as a function of predicted yield ratio (R) in Fig. 3 where $R = [N(1/2^-) - N(3/2^-)]/[N(1/2^-) + N(3/2^-)]$. Here $N(1/2^-)$ and $N(3/2^-)$ stand for γ ray yield from the $1/2^-$ and $3/2^-$ states, respectively. The error bars on the peak positions include only statistical errors in the fitting. Systematic error in the energy calibration (less than 1%) can be ignored for the measurement of splitting. The ℓs splitting is obtained by linear fitting of the three points. It is 152 ± 54(stat) $\pm$ 36(syst) keV. This splitting will broaden the energy resolution of the NaI detectors by less than 5%, which justifies fitting a single γ ray in each spectrum.

We now describe how systematic errors were estimated. The observed γ ray yield at each scattering angle is not completely consistent with the calculation. We take the difference as a systematic error in the estimation of R, where

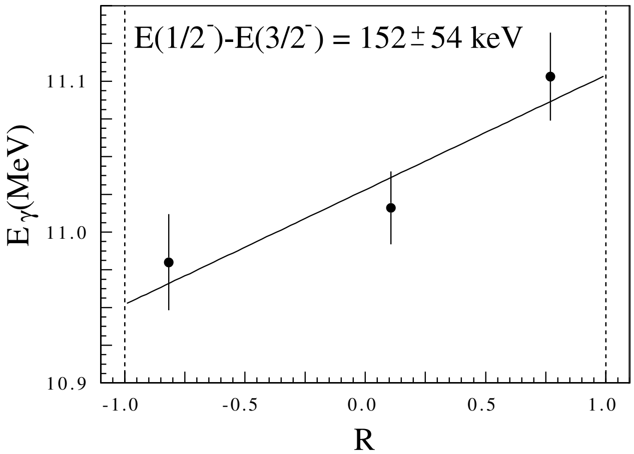

FIG. 3. Peak positions obtained by fitting the γ ray spectra are shown as a function of R.

we change the absolute cross section keeping the angular distribution which is theoretically robust [18] to reproduce the yield. We then obtained 30 keV as the maximum deviation from the central value for the ℓs splitting. The fit with the response function in Fig. 2 gave $\chi^2 = 0.87$–1.27. Repeating the analysis with different fitting functions gives, at most, a 19 keV change in the result for the ℓs splitting, as long as the same function is used for all three spectra. Correction of Doppler shift is found to be of negligible importance.

The observed ℓs splitting is quite small. The ℓs splitting for the single-nucleon p states around this mass region is ~3–5 MeV, thus the ℓs splitting for the single-p_Λ state is about 20–30 times smaller than that for the nucleon. Furthermore the $p_{1/2}(\Lambda)$ state appears higher than the $p_{3/2}(\Lambda)$ state, as is the case for nucleon.

Recently *YN* interactions have been refined in both an OBE model [24] and a quark model [25]. Hypernuclear structure calculation with a cluster model shows that the ℓs splitting in ${}^{13}_{\Lambda}C$ is 0.39–0.96 MeV for *YN* interactions based on an OBE model and it is ~0.2 MeV for a *YN* interaction based on a quark model [26]. Systematic study of light Λ hypernuclei shows that the *YN* interactions based on an OBE model need to be modified so that a smaller ℓs splitting, as indicated by the present experiment, can be accommodated [27]. A new mechanism will be required for the unified understanding of the baryon-baryon (*NN*, *YN*, and *YY*) interaction. In summary the ℓs splitting of single-Λ states has been directly observed. It is much smaller than that for the nucleon. The state-of-the-art calculation of the *YN* interaction based on OBE models is unable to reproduce the present result.

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