Polarization of ${}^{5}_{\Lambda}$He Produced by the (π^+, K^+) Reaction

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We have measured the polarization of ${}^{5}_{\Lambda}$He produced by the (π^+, K^+) reaction for the first time by observing the asymmetric emission of its weak decay pions. The large asymmetry parameter of the mesonic decay, which is unique to ${}^{5}_{\Lambda}$He, made the measurement possible. The measurement is consistent with the theoretical prediction by which the mechanism of the hypernuclear polarization was clarified. This technique will open a new field to the spectroscopic study of hypernuclei. [S0031-9007(98)05852-9]

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Nuclear-spin orientation has been useful for studies of many nuclear properties. The angular distributions of particles emitted by the strong interaction, photons by the electromagnetic interaction and weak decay particles, show specific patterns, depending on spins relevant to the transitions. Processes caused by the weak interaction could have parity-violating asymmetry with respect to the spin polarization. The asymmetry has been used not only to study nuclear structure but also to study the parity-violating component of the force between nucleons.

The study of hypernuclei has yet to reach such an advanced stage. Recently, the (π^+, K^+) reaction has demonstrated remarkable progress for the study of hypernuclei. Deeply bound single-particle levels were clearly seen in that reaction [1,2]. Since these earlier studies were done for obtaining energies and cross sections of the levels, theoretical predictions were frequently used to assign their spins and parities.

The weak decay of hypernuclei gives information about the strangeness-changing weak hadronic interaction in nuclei in which the partial and total decay rates have been intensively studied. In a next-generation accelerator that can provide intense meson beams, one hopes to further study the properties of hypernuclei for which the production and detection of the spin orientation will be vital. For instance, the production of polarized Λ and its asymmetric weak decay has been used to study its magnetic moment. In the present Letter we show that polarized ${}^{5}_{\Lambda}$He can be produced with a polarization consistent with the calculation, which in fact demonstrates that we understand the mechanism of hypernuclear polarization.

Λ hypernuclei have two types of hadronic decay modes. One is mesonic decay (M decay) and the other is nonmesonic decay (NM decay). M decay is a process in which the hypernucleus weakly decays by the emission of a pion, similar to the Λ weak decay outside the nuclear medium. The Λ has an asymmetry parameter ($\alpha_\Lambda = 0.642 \pm 0.013$) [3] for $p\pi^-$ decay due to the interference of the s- and p-wave amplitudes. The hypernucleus also has an asymmetry parameter for M decay which can be reliably calculated [4]. Hypernuclei that have a large asymmetry parameter and large branching ratio for M decay are useful, though one can find only a few of them [4]. ${}^{5}_{\Lambda}$He is one such rare case.

NM decay is a process by which a Λ and a nucleon in a nucleus undergo a weak interaction, making two nucleons in the final state. Its parity-violating asymmetry parameter [5] is poorly predicted, since NM decay is not yet well understood. An experimental study of the asymmetry parameter will clarify the mechanism of NM decay. If it turns out to be large, there will be many practical uses, since NM decay becomes dominant for hypernuclei heavier than $A \sim 7$.

Recently, polarized ${}^{12}_{\Lambda}$C hypernuclei were produced by the ^{12}C(π^+, K^+) reaction, and their asymmetric NM decay was observed [6]. The asymmetry parameter was found to be quite large (-1.0 ± 0.4), although the statistics were limited and its polarization had to be calculated, since the M decay of ${}^{12}_{\Lambda}$C has a small branching ratio and a small asymmetry parameter [4]. The polarization of Λ produced by the quasifree process [7] was measured and found to be consistent with that calculated for the $n(\pi, K^+)\Lambda$ reaction with a minor correction due to the binding effect of a neutron [8]. One can accept that the hypernuclear polarization is calculable, though one desires experimental evidence.

A study of ${}^{5}_{\Lambda}$He by the (π^+, K^+) reaction was carried out to make up for the shortcomings of the ${}^{12}_{\Lambda}$C study. The purpose of the experiment is to obtain (1) the polarization of ${}^{5}_{\Lambda}$He by observing the M decay, (2) the branching ratio in order to clarify the isospin structure of the M and NM decays, and (3) the asymmetry parameter of NM decay. In this Letter we present the results of (1), the polarization of ${}^{5}_{\Lambda}$He. The results of subjects (2) and (3) will appear in future publications. It must be noted that the M decay of ${}^{5}_{\Lambda}$He has a large asymmetry parameter (almost equal to that of free Λ) with little theoretical ambiguity [9] and a large branching ratio [10]. These facts made the polarization measurement possible in the present experiment.

The experiment (PS-E278) was carried out at the K6 beam line of KEK-PS. The ${}^{6}\mathrm{Li}(\pi^+, K^+ p){}^{5}_{\Lambda}\mathrm{He}$ reaction at $P_\pi = 1.05$ GeV$/c$ was used to produce polarized ${}^{5}_{\Lambda}$He. The π^+ beam intensity was typically $\sim 3 \times 10^6$/spill, where a spill consisted of 1.7 sec of continuous beam every 4.0 sec. The beam-line spectrometer measured the incident pion momentum. The momentum of outgoing kaons was measured by the superconducting kaon spectrometer (SKS), which has a good energy resolution (2 MeV FWHM) and a large acceptance ($\sim$100 msr) [11]. The large solid angle makes the simultaneous measurement of positive and negative scattering angles possible, which is essential for removing any spurious error in the asymmetry measurement. The target was 95% enriched metal ^{6}Li with a size of $2 \times 5 \times 6$ cm^3. A differential-type Lucite Čerenkov counter located just behind the target was sensitive only to pions, and was effective in reducing the trigger rate. Target thickness was $\sim 2-3$ times thicker than usual, though the data-taking rate was kept tolerably low. Scattered kaons were clearly identified with negligible background from the mass spectrum obtained by time of flight.

Decay particles from the ${}^{5}_{\Lambda}$He were measured by the decay-counter system shown in Fig. 1. Two sets of detector systems were placed below and above the target. Each detector system consisted of a Si microstrip detector (SSD), a multiwire proportional chamber (MWPC), a plastic scintillator hodoscope (DH), a range shower counter (RSC), and 36 NaI detectors. Each NaI detector had a dimension of $6.5 \times 6.5 \times 30$ cm^3. The SSD with a thickness of 0.5 mm covers a 62×62 mm^2 area with 1 mm pitch. The MWPC has three layers that cover a 192×192 mm^2 area with a 2 mm pitch. The tracks of the charged particles were identified by the SSD, MWPC, and DH. A range shower counter, consisting of 32 layers of thin (0.2 mm) lead and 1 mm plastic sheets [12], worked as a range counter for protons below 100 MeV and charged pions below 40 MeV, and as a gamma-ray shower counter. Charged particles that punched through the RSC were tagged by a plastic counter (CTC). The whole system covered 32.1% of the total solid angle for charged particles.

Pions and protons from the ${}^{5}_{\Lambda}$He decay were identified by dE/dx information given by SSD and by their total energy. The detector was sensitive to 10–50 MeV pions, which was appropriate to the present study, since the decay pion peaked at about 32 MeV. The particle identification (PI) spectrum is shown in Fig. 2 for the decay particles from ${}^{5}_{\Lambda}$He. The broad peak on the left is due to pions, and the sharp peak on the right is due to protons. The left side of the dashed line in the spectrum is taken to be the pion window. In order to derive the pion asymmetry, contamination of protons in the pion region was evaluated. The Landau tail in the dE/dx spectrum tends to pions leaking into the proton region, although

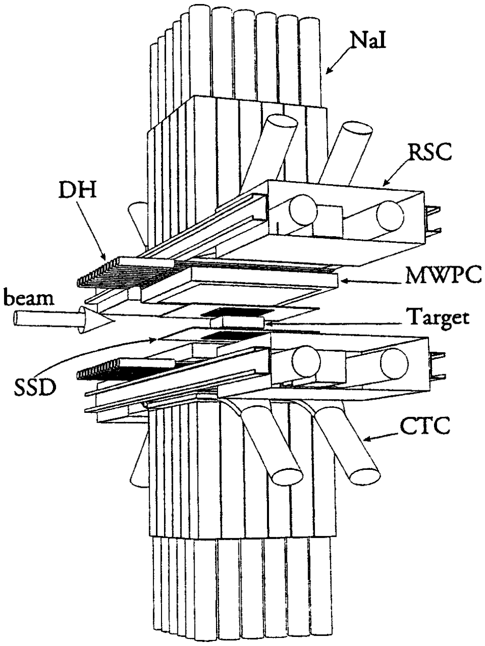

FIG. 1. Perspective view of the decay-counter system.

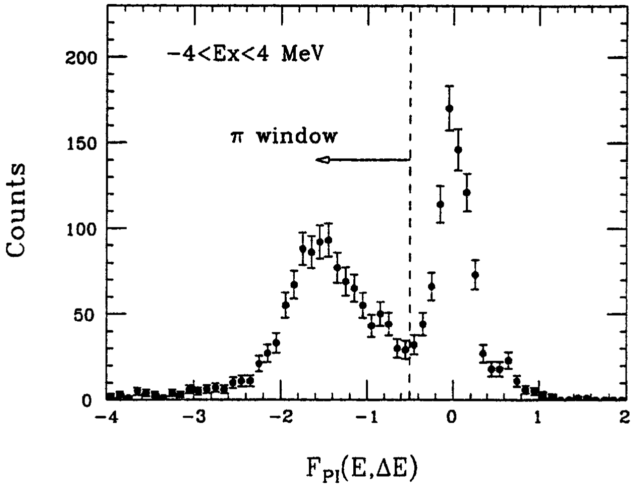

FIG. 2. PI spectrum of decay particles gated by the ground-state region of ${}^{6}_{\Lambda}$Li.

little contamination of protons is expected in the pion region. The contamination was found to be negligible.

The excitation-energy (Ex) spectra of the ^{6}Li(π^+, K^+) reaction are shown in Fig. 3. The ground state is clearly seen in both the inclusive and pion-gated spectra. The peak was hardly seen in the previous experiment, where the ${}^{6}_{\Lambda}$Li was studied based on the (K^-, π^-) reaction. The ground state is 4 MeV below the Λ emission threshold, above which the production of the Λ by the quasifree process is expected. Experimentally, we define the ground state as the region $-4 < \mathrm{Ex} < 4$ MeV.

The asymmetry (A) was obtained from the experimental coincidence yields as

$$\sqrt{\left(\frac{N^{\uparrow}(+\theta)N^{\downarrow}(-\theta)s}{N^{\downarrow}(+\theta)N^{\uparrow}(-\theta)}\right)} = \frac{1 + A}{1 - A}. \qquad (1)$$

Here, $N^{\uparrow}(+\theta)$ represents the number of counts in the up decay counter system when kaons are detected by the SKS spectrometer at $\theta = dx/dz$, where x is positive. Here, the z and y directions are the beam direction and the upward direction, respectively, and the x direction is given by a right-handed coordinate system. First-order systematic errors, related to the normalization of the beam intensity, the fluctuation of the beam intensity, the asymmetry of the solid angle, and the misalignment of the beam center all cancel in this ratio. In order to determine any spurious instrumental asymmetry, the $(\pi^+, \pi^+ X)$ reaction was measured simultaneously with the (π^+, K^+) reaction, since no up-down asymmetry is expected in the former reaction, where no parity-violating weak interaction is involved.

The observed asymmetry (A^{π}) is related to the polarization (P) by

$$A^{\pi} = P\alpha^{\pi}\varepsilon. \qquad (2)$$

Here, α^{π} represents the asymmetry parameter of the ${}^{5}_{\Lambda}$He M decay, and ε is the reduction factor of the asymmetry due to the finite solid angle of the detector, which was estimated by a Monte Carlo simulation (GEANT). The α^{π} was taken to be equal to that of free Λ decay. The value is sufficiently accurate for the present study [9]. The observed polarization is given in Table I. The instrumental asymmetry was less than 3%. The errors are dominantly from statistics.

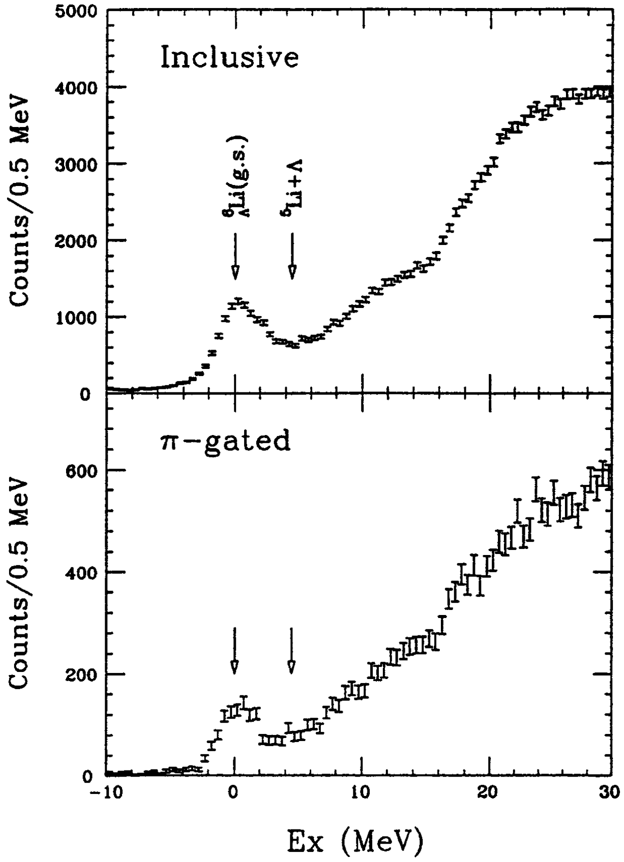

FIG. 3. Excitation-energy (Ex) spectra of the ^{6}Li(π^+, K^+) reaction. The upper plot is the inclusive spectrum, and lower plot is the pion-gated spectrum.

The ${}^{6}_{\Lambda}$Li ground state produced by the (π^+, K^+) reaction lies 0.9 MeV above the proton emission threshold and is 4 MeV bound for the Λ [10]. The states around the ${}^{6}_{\Lambda}$Li ground-state region exclusively produce ${}^{5}_{\Lambda}$He by emitting a proton. In order to calculate the polarization of ${}^{5}_{\Lambda}$He, first the polarization of the ${}^{6}_{\Lambda}$Li states was calculated, and then depolarization due to the proton emission to make ${}^{5}_{\Lambda}$He was estimated.

The cross section and polarization have been calculated for the ^{6}Li(π^+, K^+) reaction at 1.05 GeV/c [13]. The distorted-wave impulse approximation (DWIA) calculation employed the polarization of the elementary (π^+, K^+) reaction, the initial nuclear and final hypernuclear wave functions, and the distortion of meson waves due to the meson nucleus interaction. The ${}^{6}_{\Lambda}$Li ground state is a doublet of 1^- and 2^- with a configuration of $(p_{3/2})_n^{-1}(s_{1/2})_{\Lambda}$. The calculated polarization is shown in Table II for three typical scattering angles [13]. The 2^- state has the largest cross section among the states in the ground-state region. The state emits a proton with a pure

TABLE I. Observed asymmetry and polarization obtained by Eq. (2). See the text for the predicted values.

Reaction		$\theta = 2 \sim 7°$	$\theta = 7 \sim 15°$
$(\pi^+, \pi^+ X)$	A^π	-0.001 ± 0.014	-0.014 ± 0.013
	P	<0.03	<0.03
(π^+, K^+)	A^π	-0.128 ± 0.042	-0.203 ± 0.048
$-4 < \mathrm{Ex} < 4$	P	0.247 ± 0.082	0.393 ± 0.094
	$P_{\mathrm{cal}}(2)$	0.181	0.368
	$P_{\mathrm{cal}}(4)$	0.123	0.250
$4 < \mathrm{Ex} < 12$	A^π	-0.064 ± 0.030	-0.224 ± 0.035
	P	0.124 ± 0.058	0.433 ± 0.068

$p_{3/2}$ partial wave. No depolarization takes place for such a stretched transition [14]. The polarization of the 1^- state is opposite to that of the 2^- state though the spin polarization of Λ is in the same direction for both states. The proton emission from the 1^- state is $p_{3/2}$ which flips the ${}^5_\Lambda$He polarization.

The excited states in the ground-state region are the ${1_2}^-$ and ${0_1}^-$ with the configuration of $(p_{1/2})_n^{-1}(s_{1/2})_\Lambda$. Both states produce ${}^5_\Lambda$He by the proton emission. The null polarization of the 0^- state and the small polarization of the ${1_2}^-$ state reduce the ${}^5_\Lambda$He polarization. Theoretical polarization and cross section were used to obtain expected polarization in the experiment. $P_{\mathrm{cal}}(2)$ in Table I is the calculated polarization for only the ground-state doublet, and $P_{\mathrm{cal}}(4)$ is that for four states. The ${1_2}^-$ and ${0_1}^-$ states are predicted to be $\sim$6 MeV. The observed polarization is closer to $P_{\mathrm{cal}}(2)$ which is reasonable since the ground-state region ($-4 < \mathrm{Ex} < 4$ MeV) has little contribution from the ${1_2}^-$ and ${0_1}^-$ states.

TABLE II. Predicted cross section and polarization of low-lying ${}^6_\Lambda$Li hypernuclear states shown for three typical scattering angles. The ${1_{gs}}^-$ and ${2_1}^-$ states have mostly the $(p_{3/2})_p(s_{1/2})_\Lambda$ configuration. The ${1_2}^-$ and ${0_1}^-$ states are mostly the $(p_{1/2})_p(s_{1/2})_\Lambda$ configuration.

State (${}^6_\Lambda$Li)		$\theta = 6°$	$\theta = 12°$	$\theta = 18°$
${1_{gs}}^-$	$\frac{d\sigma}{d\Omega}$ [μb/sr]	0.78	0.64	0.34
	$P({}^6_\Lambda\mathrm{Li})$	-0.443	-0.586	-0.570
	$P({}^5_\Lambda\mathrm{He})$	0.222	0.293	0.285
${2_1}^-$	$\frac{d\sigma}{d\Omega}$ [μb/sr]	6.90	4.19	1.64
(0.42 MeV)	$P({}^6_\Lambda\mathrm{Li})$	0.249	0.441	0.568
	$P({}^5_\Lambda\mathrm{He})$	0.249	0.441	0.568
${1_2}^-$	$\frac{d\sigma}{d\Omega}$ [μb/sr]	0.97	0.81	0.44
(6.12 MeV)	$P({}^6_\Lambda\mathrm{Li})$	0.127	0.163	0.154
	$P({}^5_\Lambda\mathrm{He})$	0.127	0.163	0.154
${0_1}^-$	$\frac{d\sigma}{d\Omega}$ [μb/sr]	3.43	1.92	0.68
(6.18 MeV)	$P({}^6_\Lambda\mathrm{Li})$	0.0	0.0	0.0
	$P({}^5_\Lambda\mathrm{He})$	0.0	0.0	0.0

Above Ex = 4 MeV, pions are dominantly from the Λ produced by the quasifree process. The asymmetry of the region ($4 < \mathrm{Ex} < 12$ MeV) is quite similar to that of the ground state. The leakage of pions from the region does not affect the observed polarization of ${}^5_\Lambda$He. The large asymmetry of ${}^5_\Lambda$He that is similar to the quasifree process reflects the fact that the dominant state (${2_1}^-$) keeps the maximum polarization of Λ produced by the elementary process in proton emission.

In summary, we have demonstrated that the polarized ${}^5_\Lambda$He hypernucleus is produced by the (π^+, K^+) reaction. The large asymmetry parameter and the large branching ratio of the ${}^5_\Lambda$He M decay were essential for the polarization measurement. The observed polarization is consistent with the DWIA calculation, which includes the polarization in the elementary reaction and the depolarization due to proton emission. The present study demonstrates that the theoretical model well describes the polarization mechanism. Thus, the calculated polarization can be used even when a direct measurement is practically impossible due to the small branching ratio and small asymmetry parameter of the M decay. This is usually the case for most hypernuclei beyond the S shell.

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