Asymmetry in the Nonmesonic Weak Decay of Polarized ${}^{5}_{\Lambda}$He Hypernuclei

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We have measured the asymmetric emission of protons from the nonmesonic decay of polarized ${}^{5}_{\Lambda}$He produced by the (π^+, K^+) reaction. ${}^{5}_{\Lambda}$He is an s-shell hypernucleus and its polarization is due to the Λ. One expects to obtain direct information on the elementary weak $\vec{\Lambda} p \to np$ process. The asymmetry parameter has been determined to be 0.24 ± 0.22. The implication of the result is discussed.

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A Λ hyperon bound in a Λ hypernucleus decays either by a mesonic decay process ($\Lambda \to N\pi$) or a nonmesonic decay process ($\Lambda N \to NN$). The nonmesonic decay (NM decay) gives information on the weak hyperon-nucleon interaction. In such a flavor-changing weak process, no strong interaction contributes, thus one can study both the parity-violating (PV) and parity-conserving (PC) parts of the interaction. In contrast, in nonstrange nuclei only the PV part of the weak nucleon-nucleon interaction can be accessed, because the PC part is masked by the strong interaction [1]. The weak nucleon-nucleon and hyperon-nucleon interaction can be investigated in a unified way under the $SU(3)_F$ symmetry, where NM decay thus plays an important role.

Since the momentum transfer of the NM decay ($\sim$400 MeV$/c$) is much larger than the Fermi momentum, the NM decay can be taken as a two-body process, although the decay takes place inside a nucleus. In addition, with such a large momentum transfer, one can investigate the interaction at short range, where quark degrees of freedom may have to be taken into account in order to understand the NM decay mechanism.

There are two observables used to investigate the NM decay mechanism. One is partial decay rates, especially the ratio of proton-stimulated decay ($\Lambda p \to np$) to neutron-stimulated decay ($\Lambda n \to nn$). The other is the asymmetric emission of protons from the proton-stimulated decay with respect to the spin polarization of Λ. The branching ratio is sensitive to the isospin structure of the ΛN weak interaction, because only the final isospin, $I_f = 1$, is present in the neutron-stimulated decay, while both $I_f = 0$ and 1 are present in the proton-stimulated decay. On the other hand, the decay asymmetry is due to interference between the PC and PV amplitudes. The asymmetry parameter provides information about the spin-parity structure of the interaction. Note that the PC and PV amplitudes have different final spins and isospins due to the antisymmetrization on the final two-nucleon system.

Recently, the experiment (E160) at the KEK 12-GeV proton synchrotron (KEK-PS) measured the NM decay of ${}^{12}_{\Lambda}$C and ${}^{11}_{\Lambda}$B, and demonstrated a large asymmetry parameter of $\alpha^{\mathrm{NM}} = -1.0 \pm 0.4$ [2]. In that experiment, the following conditions prevailed: (1) The polarization of hypernuclei was theoretically calculated; the depolarization due to the particle and γ decays had to be taken into account along with an assumption concerning the hypernuclear structure [3]. (2) The p-wave contribution in the initial ΛN state of the NM decay made a comparison with theoretical calculations difficult. (3) The observed asymmetry is not free from final-state interactions and multinucleon mechanisms [4] due to the existence of other nucleons. A study of the weak decay of ${}^{5}_{\Lambda}$He can overcome the above-mentioned difficulties [5].

The polarized ${}^{5}_{\Lambda}$He was produced by the (π^+, K^+) reaction on ^{6}Li. The ground state of ${}^{6}_{\Lambda}$Li is above the ${}^{5}_{\Lambda}$He $+$ p threshold and below the ^{5}Li $+$ Λ threshold [6,7]. ${}^{5}_{\Lambda}$He is exclusively produced from the ground state of ${}^{6}_{\Lambda}$Li by

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emitting a proton. The polarization of ${}^{5}_{\Lambda}$He was measured experimentally by observing the asymmetry of the mesonic decay [8,9]. Since the core nucleus, ^{4}He, is a 0^+ state, there is no ambiguity in extracting the spin polarization of the Λ from the hypernuclear polarization. The final-state interaction between the decay products and the nucleons in the nucleus is much smaller than in the ${}^{12}_{\Lambda}$C case. In addition, since all of the nucleons and Λ are in the s shell, the relative s wave in the initial ΛN system contributes almost exclusively in the NM decay process.

In a previous paper [9], we show that the polarization of ${}^{5}_{\Lambda}$He measured by its mesonic decay was large and its magnitude was found to be consistent with a theoretical prediction [8]. In this Letter we present a measurement of the asymmetric proton emission from the NM decay, and derive the asymmetry parameter of the NM decay using the measured polarization.

The experiment was carried out at the K6 beam line of KEK-PS with the superconducting kaon spectrometer [10]. Decay particles were measured with two identical counters symmetrically placed above and below the target. Since the details of the experimental condition and layout of our apparatus have been presented elsewhere [9], we briefly describe only what is relevant to the present discussion.

Decay protons and pions were identified by dE/dx information measured with a silicon microstrip detector, combining the total energy deposit (E_{RSC}) and the range (R) in the range shower counter (RSC). Figure 1 shows the particle identification (PI) spectra for the decay particles from ${}^{5}_{\Lambda}$He (a) using dE/dx and E_{RSC} and (b) using dE/dx and R. The peak on the right-hand side is due to protons, and the other is due to pions. For energetic particles, the separation of pions and protons is worse due to π^- absorption which increases measured energy. Since the π^- absorption changes the range of the π^- only slightly, the dE/dx and R were used for higher E_{RSC} particles ($E_{\mathrm{RSC}} > 50$ MeV). The right-hand side of the dashed line in each spectrum is taken to be the proton window. The leakage of pions into the proton window was evaluated to be 2.6% for PI using E_{RSC} and dE/dx and 5.1% for PI using R and dE/dx. These values were used to correct the obtained proton asymmetry.

The inclusive ${}^{6}\mathrm{Li}(\pi^+, K^+)$ spectrum is shown in Fig. 2(a) as a function of the ${}^{6}_{\Lambda}$Li excitation energy E_X. Figure 2(b) is the spectrum in coincidence with the decay protons. The present decay counter system has large acceptance for energetic protons from the NM decay, although it has little acceptance for the protons from quasifree-Λ decay, because they are boosted strongly forward. Therefore the ground state of ${}^{6}_{\Lambda}$Li is enhanced in the proton-coincidence spectrum and is clearly separated from the huge quasifree-Λ region. Experimentally, we defined the ground-state region to be E_X between -4 and 4 MeV.

The asymmetry A_p was obtained from the number of counts in the upper and lower counters as

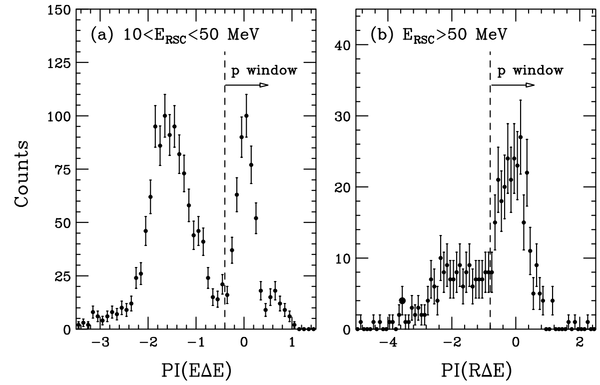

FIG. 1. PI spectra for decay particles from the ground-state region of ${}^{6}_{\Lambda}$Li by (a) using dE/dx and the total energy deposit on RSC, and (b) using dE/dx and the range in RSC. The energy of the decay particles is in the region $10 < E_{\mathrm{RSC}} < 50$ and $E_{\mathrm{RSC}} > 50$ MeV, respectively.

$$\sqrt{\frac{N^{\uparrow}(+\theta)N^{\downarrow}(-\theta)}{N^{\downarrow}(+\theta)N^{\uparrow}(-\theta)}} = \frac{1 + A_p}{1 - A_p}\,. \tag{1}$$

Here, $N^{\uparrow}(+\theta)$ represents the number of counts in the upper counter at the scattering angle θ of the (π^+, K^+) reaction positive, where the direction of polarization is upward. This ratio cancels out any first-order systematic errors related to the acceptance of the decay counter system and the SKS spectrometer and the alignment of the beam center.

The observed proton asymmetry A_p is related to the polarization P by

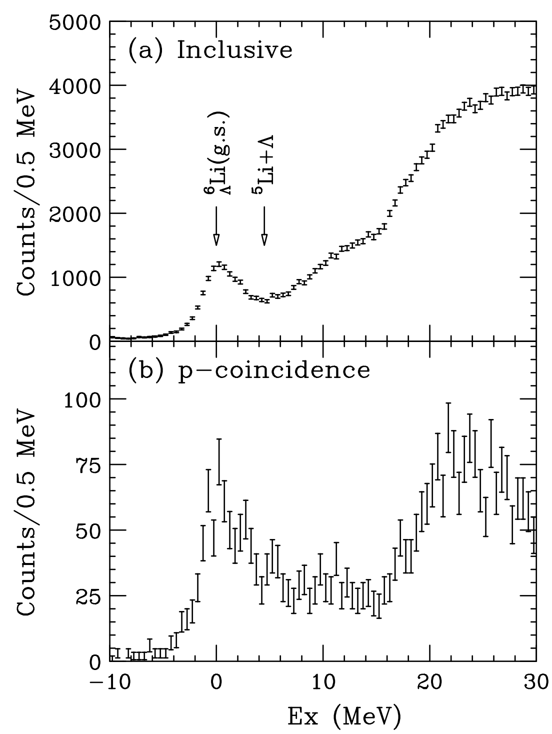

FIG. 2. Excitation energy spectra of the ${}^{6}\mathrm{Li}(\pi^+, K^+)$ reaction: (a) inclusive; (b) in coincidence with decay protons.

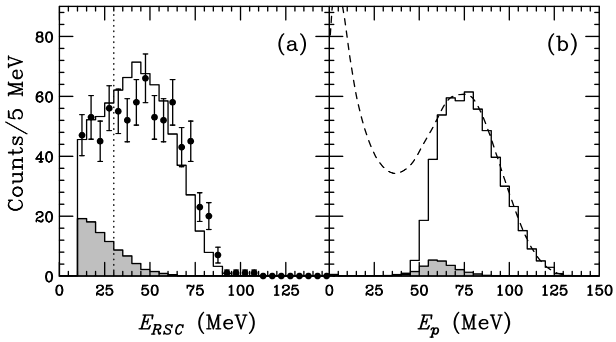

FIG. 3. A proton-energy spectrum observed with RSC (a), where histograms are obtained by the simulation. The proton-energy spectrum at the nucleus is shown in (b) by a dashed line. It becomes a solid line by selecting events above 30 MeV [dotted line in (a)] due mostly to energy loss in the target. The shaded regions in the histograms represent the contribution of protons scattered by the nuclear cascade process.

$$A_p = P\alpha^{\mathrm{NM}}\varepsilon k\,. \tag{2}$$

Here, α^{NM} represents the asymmetry parameter of NM decay, and $\varepsilon = 0.804$ is the reduction factor of the asymmetry due to the finite solid angle of the decay counter system, which was estimated by a Monte Carlo simulation. The observed asymmetry is reduced from that for a two-body ΛN interaction due to nuclear effects which are represented by k in Eq. (2). The nuclear effects are due to the Fermi momentum of Λ and the rescattering of emitted nucleons through a nuclear cascade process, which tend to reduce the asymmetry.

The attenuation factor k depends on both the nuclear effects and the experimental condition. A Monte Carlo simulation was employed to evaluate k within the same framework in the appendix of Ref. [11] for the nuclear effects. The simulation well reproduces the observed proton-energy spectrum with RSC (E_{RSC}), as shown in Fig. 3(a). We choose the protons above 30 MeV, where the nuclear cascade process gives negligible contribution to the asymmetry. The proton-energy spectrum at the nucleus (E_p) is modified due primarily to energy loss in the target. Figure 3(b) shows the E_p spectrum corresponding to protons whose E_{RSC} is above 30 MeV. By this procedure, we select the two-body nature of NM decay, where the Q value ($\sim$170 MeV) is shared by the final proton and neutron. For the present condition k was found to be 0.935.

The observed proton asymmetries A_p are given in Table I. The instrumental asymmetry was estimated to be less than 0.03 by measuring the $(\pi^+, \pi^{+\prime}X)$ reaction. No up/down asymmetry is expected in the reaction, because no parity-violating weak interaction is involved. The asymmetry parameter α^{NM} has been derived by Eq. (2) with the proton asymmetry A_p^{corr} which is corrected for the π^- leakage into the proton window. Although the asymmetry parameters derived in the two scattering-angle regions seem to be much different from each other, they agree within the experimental errors. We also know of no particular reason to cause such a difference. Therefore we derived the final value for the asymmetry parameter as $\alpha^{\mathrm{NM}} = 0.24 \pm 0.22$ by taking a weighted average.

TABLE I. Observed proton asymmetry A_p and asymmetry parameter α^{NM}, derived by Eq. (2), are shown. The polarization P obtained from the observed asymmetry of mesonic decay [9] is also shown.

Reaction		$2 < \theta < 7°$	$7 < \theta < 15°$
$(\pi^+, \pi^{+\prime}X)$	A_p	0.004 ± 0.024	0.004 ± 0.023
(π^+, K^+)	P	0.247 ± 0.082	0.393 ± 0.094
$-4 < E_X < 4$	A_p	0.076 ± 0.058	0.027 ± 0.077
	A_p^{corr}	0.082 ± 0.060	0.035 ± 0.080
	α^{NM}	0.441 ± 0.356	0.120 ± 0.271
		0.24 ± 0.22	

Table II shows the six amplitudes for the NM decay process whose initial ΛN system is in the S state [12]. Three amplitudes (c, d, e) have the final isospin, $I_f = 0$ and the others (a, b, f) have $I_f = 1$. The asymmetry parameter comes from interference between the PC and PV amplitudes that have different final isospins, since the exchange of a proton and a neutron is related to both the parity and isospin. Recently, explicit formulas of the asymmetry parameter have been given for the s-wave Λp initial state [13]. Here are the following terms: ae, $b(c - \sqrt{2}\,d)$, and $(\sqrt{2}\,c + d)f$. The experimental values of Γ_n/Γ_p [7,11,12,14,15] suggest the dominance of the amplitude f, although the meson-exchange model predicts dominance of the amplitude d. The term $(\sqrt{2}\,c + d)f$ thus gives the largest contribution to the asymmetry parameter.

The present result suggests that the asymmetry parameter of the NM decay has a positive sign, which is opposite to theoretical calculations based on the meson-exchange model [16]. On the other hand, the asymmetry parameter for p-shell hypernuclei derived in the E160 experiment is consistent with the calculations. One expects a contribution from the relative P state in the initial ΛN system for the p-shell hypernuclei, although most of the decay rate comes from the initial S state, according to Ref. [17]. It is not completely excluded that statistical fluctuations cause such a difference between the experiments. However the experiments suggest a difference of the asymmetry parameter between s-shell hypernuclei and p-shell hypernuclei.

TABLE II. Six amplitudes in the NM decay process whose initial ΛN system is the relative S state.

Initial	Final	Rate	I_f	Parity change
$^1S_0$	$^1S_0$	a^2	1	no
	$^3P_0$	b^2	1	yes
$^3S_1$	$^3S_1$	c^2	0	no
	$^3D_1$	d^2	0	no
	$^1P_1$	e^2	0	yes
	$^3P_1$	f^2	1	yes

A possible explanation of the difference is that the meson-exchange model describes well the long-range part of the interaction that is associated with the P-state component. On the other hand, the short-range part includes effects that have not been taken into account in the meson-exchange model. The effects may also be an origin of the inconsistency between the theory and the experiment in Γ_n/Γ_p data. The ΛN system in the s-shell hypernuclei may have minor D-state contributions. It is probably smaller than that of the two-nucleon system since no pion-exchange interaction is relevant in the ΛN system, although the theoretical estimation has yet to be done.

An effort to describe the short-range part of the interaction has been made by including a direct quark-exchange mechanism [18,19]. The model suggests a large $I_f = 1$ amplitude [19], which lessens the discrepancy, at least in the branching ratio. However, a consistent understanding of both the meson-exchange and quark-exchange mechanisms including their relative phase is necessary to obtain any conclusions concerning the asymmetry parameter.

In summary, we have measured the asymmetry parameter for NM decay of an s-shell hypernucleus, ${}^{5}_{\Lambda}$He, where its polarization has been measured experimentally. The present result shows that the asymmetry parameter for the s-shell hypernuclei is quite different from the theoretical calculations, which is consistent with the asymmetry parameter for the p-shell hypernuclei. The inconsistency may have the same origin as the long-standing problem on the branching ratio. The present result suggests the need for further studies in both theoretical calculations and experiments. Recently, the study of the weak production of the $pn \rightarrow p\Lambda$, which is the inverse reaction of NM decay, has been proposed [20]. The longitudinal analyzing power of the reaction gives a quantity similar to the asymmetry parameter of NM decay [13]. The experiment is now under preparation at RCNP [21], and is expected to clarify the NM decay mechanism.

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