Polarization of Λ Hyperons Produced by the Quasifree (π^+,K^+) Reaction on ^{12}C

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The polarization of quasifree Λ hyperons produced by the (π^+,K^+) reaction on ^{12}C and on the deuteron was measured for the first time. The asymmetry of pions from weak decay of the Λ hyperon was used to determine the polarization. The polarization for the deuterium target was found to be consistent with that for the elementary $n(\pi^+,K^+)\Lambda$ reaction. The polarization of the Λ produced by the quasifree process from ^{12}C is consistent with that for the elementary reaction, which demonstrates that the spin characteristics of the elementary reaction are not modified by the nuclear medium.

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The (π^+,K^+) reaction has been suggested to be useful for the production of hypernuclei [1,2], especially in exciting states in which the Λ shell-model orbitals couple to high-spin valence neutron-hole states. Experiments have demonstrated clearly the Λ single-particle orbitals thus describing the shell structure of the Λ in heavy hypernuclei [3–5]. Another important characteristic of the reaction is its potential to produce polarized hypernuclei. Polarization of many hypernuclear states has been theoretically predicted recently [6,7]. Once a polarized hypernucleus is produced the asymmetries in the angular distribution of mesonic decay [8] and nonmesonic decay [9,10] products will provide a new and useful tool for the spectroscopic study of hypernuclei [11]. A recent experiment on the production of polarized hypernuclei and their asymmetric nonmesonic decay will be reported elsewhere [12]. The dominant part of the cross section, however, is in the high excitation region, which is characterized by the so-called quasifree formation of a Λ hyperon from a nucleus since the large momentum transfer of the reaction makes the sticking probability of this Λ to the nucleus small. The quasifree reaction, by which one sees incoherent production of Λ's from a nucleus, is characterized by the elementary $n(\pi^+,K^+)\Lambda$ reaction. The kaon momentum spectrum of the (π^+,K^+) reaction then reflects the momentum distribution of a nucleon in a nucleus. Nuclear effects are usually summarized in the effective nucleon number which represents the distortion of incoming and outgoing meson waves and gives simply a reduction of the cross section. Since it is known that Λ single-particle spin-orbit and spin-spin interactions are quite small, the polarization of Λ's produced by the quasifree reaction is expected to reflect that of the elementary process.

We studied the asymmetry of pions from the decay of polarized Λ hypernuclei produced by the (π^+,K^+) reaction on CD_2 and plastic scintillator (CH) targets. The polarization was introduced by the reaction through detection of the kaons at $\pm 14°$. Pions from the weak decay of a Λ have an asymmetric angular distribution with respect to the polarization (P) given by

$$1+P\alpha\cos\theta\,, \quad (1)$$

where θ stands for polar angle with respect to the polarization and $\alpha=-0.642\pm0.013$ for the $\Lambda\to p\pi^-$ decay [13]. The asymmetry hence provides a measure of the polarization of the decaying Λ.

The pion beam was provided by the K2 beam line of the 12-GeV proton synchrotron at KEK (KEK PS) at a momentum of 1.05 GeV/c where the cross section of the elementary charge conjugate $p(\pi^-,K^0)\Lambda$ reaction is near its maximum. The pion flux was around $(3\text{–}4)\times10^6$/spill for $(2\text{–}3)\times10^{12}$ primary protons/spill, where a spill consisted of 2.0 sec of continuous beam every 4.0 sec. Beam contamination electrons were rejected by a gas Čerenkov counter while muons were estimated to be less than 5%. Since we measure up-down asymmetry by using symmetric counters, no beam intensity is relevant. The momenta of incident pions and outgoing kaons were measured by the PIK spectrometer system, details of which have been presented elsewhere [14]. Scattered kaons were clearly identified with negligible background, by the mass spectrum obtained by combining time of flight (TOF) and momenta.

Decay particles were detected by the counter system ROYAL which was designed to be sensitive to 10- to 50-MeV pions and 30- to 200-MeV protons emitted from the target. A schematic view of ROYAL is shown in Fig. 1. ROYAL consisted of two symmetric counter systems above and below the target which could be rotated to exchange the positions of these counters in order to cancel spurious asymmetries. Each counter system consisted of sixteen NaI detectors each of which was $81\times81\times76$ mm^3 and four slabs of scintillator 5 mm thick placed in front

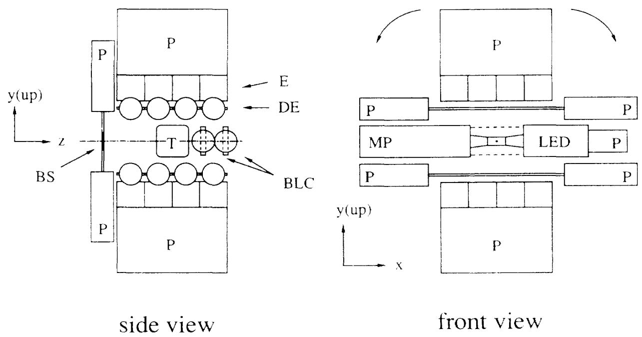

FIG. 1. Schematic view of the ROYAL decay counter system. Beam direction is defined as z direction. It is rotatable in the x-y plane. T represents segmented target which is viewed by a multianode (64 channel) phototube (MP) and LED supplies light for the normalization of pulse height. Two Lucite Čerenkov counters are placed right after the target to reject pions. E stands for NaI E counter. DE is ΔE counter of 5-mm-thick plastic scintillator. P's represent photomultipliers.

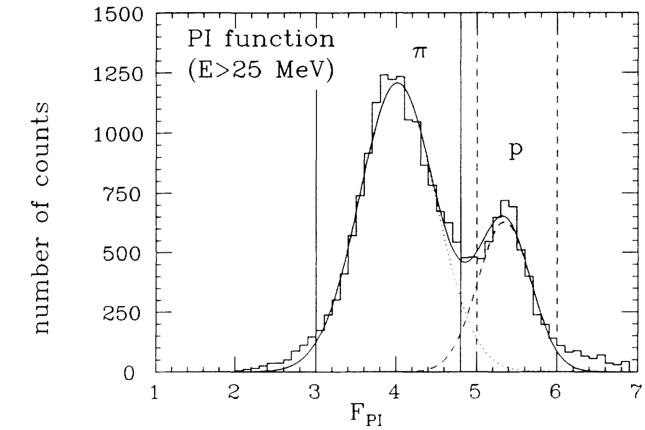

FIG. 2. Typical particle identification (PI) function for decay particles whose energy is higher than 25 MeV. Vertical solid lines show the gate for pions.

of the NaI detector to give dE/dx information for particle identification. A particle identification spectrum typically obtained is shown in Fig. 2. The pion gate includes around 2% protons and this was corrected for to obtain the asymmetry. The scintillator target covered an area of 60(wide)$\times$20(high) mm^2 with a thickness of 64 mm and was divided into two halves (an "upper" and a "lower" half), each consisting of 32 segments of plastic scintillator, to obtain better spatial resolution of the interaction vertex. The CD_2 target has a circular shape but almost the same dimension as that of the scintillator target in area and thickness. Details of the decay counters and the segmented target will be presented in future publications.

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

$$\left(\frac{N_1^{\uparrow}(14)N_2^{\downarrow}(14)N_1^{\downarrow}(-14)N_2^{\uparrow}(-14)}{N_2^{\uparrow}(14)N_1^{\downarrow}(14)N_2^{\downarrow}(-14)N_1^{\uparrow}(-14)}\right)^{1/4}=\frac{1+A}{1-A}, \tag{2}$$

where $N_1^{\uparrow}(\theta)$ stands for number of counts in the ROYAL counter system 1 when it was in the up position and the kaon spectrometer was set at θ degrees. Here up is the direction defined by $\mathbf{k}_{\pi^+}\times\mathbf{k}_{K^+}$. First-order systematic errors related to normalization of beam intensity, fluctuation of beam intensity, asymmetry of solid angle, and misalignment of beam center all cancel in this ratio. In order to determine any spurious instrumental asymmetry we measured the (π^+,π^+X) and (π^+,pX) reactions simultaneously with the (π^+,K^+) reaction since no up-down asymmetry is expected in the former reactions because no parity violating weak interaction is involved. These measurements indicated that the instrumental asymmetry was less than 2%.

Figure 3(a) shows an excitation energy spectrum for $^{12}C(\pi^+,K^+)$ at $P_{\pi^+}=1050$ MeV/c where no correction for the spectrometer acceptance has been made, since it has been shown already that the quasifree Λ production process reproduces the spectrum shape fairly well [5]. Figure 3(b) shows the excitation energy spectrum gated by decay pions detected in the ROYAL counters where the energy of the pions was larger than 25 MeV. The peak in the $^{12}_{\Lambda}C$ ground-state region disappears, being consistent with the small branching ratio for mesonic decay of this Λ hypernucleus [15].

In order to derive the polarization from the measured

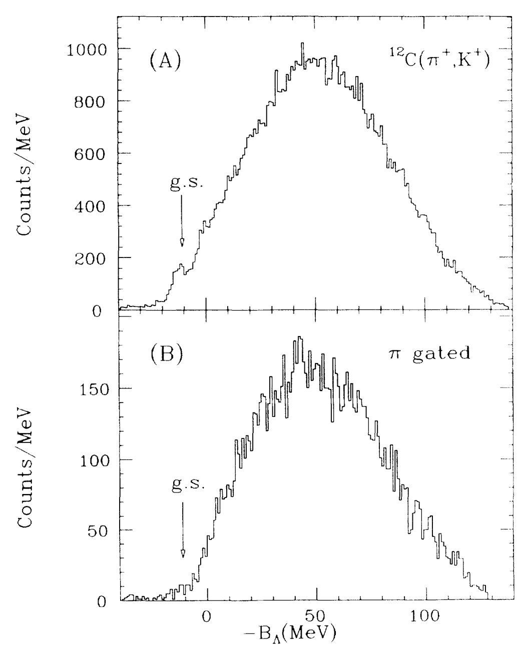

FIG. 3. (a) Kaon spectrum obtained from bombardment of the scintillator target by 1050-MeV/c pions. Horizontal axis represents binding energy of Λ. The broad bump in the spectrum corresponds to the quasifree production of hyperon from ^{12}C. (b) Spectrum gated by decay pions.

TABLE I. Measured Λ spin polarizations are listed for comparison. $\theta_{\rm c.m.}$ stands for the c.m. scattering angle. Polarization (P) is derived from the measured asymmetry (A) using Eq. (3), where $\varepsilon(E)$ is obtained by Monte Carlo simulation (see text).

Reaction		P_π (MeV/c)	$\cos\theta_{\rm c.m.}$	Asymmetry	Polarization
$d(\pi^+,K^+)$	Our experiment	1056	0.94–0.7	0.32 ± 0.05	0.64 ± 0.10
	Calculation [16]	1056	0.94–0.7		0.74
$p(\pi^-,K^0)$	Ref. [18]	1040	0.9–0.8		0.37 ± 0.10
			0.8–0.6		0.91 ± 0.08

asymmetry, one has to estimate the effect of the finite solid angle of the counters, the effect of the beam profile on the target, the effect of various cuts on the decay particle, and the shift of the angular distribution of pions due to the recoil momentum of the Λ. The measured asymmetry is thus represented as

$$A=P\alpha\varepsilon(E)\,, \tag{3}$$

where $\varepsilon(E)$ summarizes those effects. Since the evaluation of $\varepsilon(E)$ is rather complex, we used a Monte Carlo simulation. We assumed that a Λ is knocked out by the quasifree process by which the excitation energy dependence of $\varepsilon(E)$ is given through the recoil momentum distribution. $\varepsilon(E)$ is around 0.75 which is dominantly determined by the solid angle of ROYAL and found to have a less than 5% excitation energy dependence.

The asymmetry for Λ's produced from deuterium was obtained by subtracting the carbon contribution determined with the scintillator target from the data of the CD_2 target. Since a neutron in deuterium has small Fermi momentum, no excitation energy dependence was extracted and one expects the same polarization as that of the elementary $n(\pi^+,K^+)\Lambda$ reaction. The polarization can be estimated by using the elementary amplitude given by the phase-shift analysis [16] which is based on available data [17,18]. Table I shows the measured asymmetry and polarization together with calculated values. The measured polarization is consistent within an error with the calculated one, which indicates that the quasifree reaction on the deuteron is essentially the free reaction. Since the previous measurements, on which the phase-shift analysis is based, scatter rather largely as shown in Table I, we can also state that our measurement supports the analysis.

The polarization obtained for the (π^+,K^+) reaction on the scintillator (CH) target is shown in Fig. 4. Here a target neutron is bound in a carbon nucleus and moving with the Fermi momentum. The elementary amplitude has been given as a function of kinematical variables for a free neutron target. Since a neutron bound in a nucleus is off the mass shell, proper assumptions are necessary to give the amplitude. The four-momentum of the neutron is given as

$$p_n=(M_{^{12}{\rm C}}-E_{^{11}{\rm C}},\mathbf{p})\,. \tag{4}$$

Here the energy $M_{^{12}{\rm C}}-E_{^{11}{\rm C}}$ is almost equal to $m_n-{\rm BE}$, where BE is the binding energy of the neutron. We assumed that the πN $(K\Lambda)$ invariant mass $(\sqrt{s})$ and c.m. scattering angle of the two-body reaction (θ) characterize the amplitude, where s is given by $(p_{\pi^+}+p_n)^2$. Thus we used the on-shell elementary amplitude for the corresponding s and θ. This procedure has previously been shown to reproduce the cross section of the quasifree reaction [19].

The three-momentum ($\mathbf{p}$) in Eq. (4) is determined by the momentum density distribution, for which we used a harmonic oscillator wave function with oscillator parameter 1.75 fm. It is assumed that ^{12}C has four neutrons in the p shell and two neutrons in the s shell, respectively, the s shell being bound 16.4 MeV deeper than the p shell.

The calculated polarization is shown in Fig. 4. The calculation reproduces the polarization for the ^{12}C target at the peak of the quasifree process well. We are therefore led to the conclusion that the polarization in the quasifree peak is the same as that expected for the elementary process. This shows that the reaction mechanism is really characterized by the quasifree process in this region as far as the spin observable is concerned, the first demonstration of this fact for hyperon formation from nuclei. The use of Λ is essential for the present argument since polarization can easily be derived experimentally and depolarization due to final-state interaction is expected to be small. Depolarization in the nuclear reaction is usually caused by the spin-orbit and/or the spin-spin interaction. It is, however, known that these in-

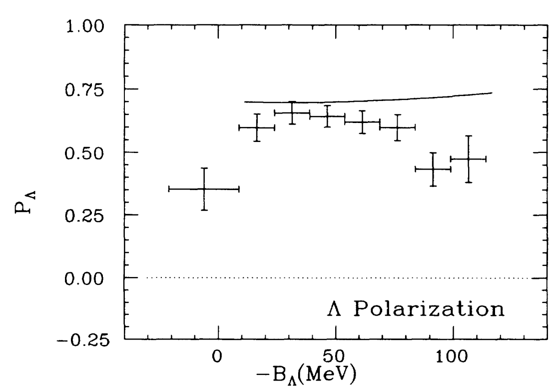

FIG. 4. Polarization obtained from the measured asymmetry assuming free Λ production. The calculated polarization is shown by a solid line (see text).

teractions are quite small for Λ hypernuclei [20,21] giving only a negligible contribution to the depolarization.

One observes a reduction of the polarization in the bound and high excitation regions. Since no free Λ exists in the bound region, pions are from mesonic decay of Λ hypernuclei. According to predictions of the asymmetry parameters for mesonic decays of Λ hypernuclei [8] and of the polarization of Λ hypernuclei [22], one expects almost no asymmetry for pions from the bound region, corresponding to null polarization. The reduction of the polarization observed in the bound region is consistent with this argument. The reduction thus gives the ratio of free Λ production to formation of hypernuclei. For Λ hypernuclei produced in the low excitation region through Λ-nucleus interaction even a Λ can escape a nucleus energetically. One thus expects a gradual decrease of the polarization toward the low excitation energy region as seen in the experiment. Λ hypernuclei can be produced even in the peak of the quasifree process which results in a reduction of the polarization. The observed polarization might indicate the reduction, although a quantitative discussion needs further investigation.

In the highly excited region above 80 MeV, one thinks that Σ production would give the observed reduction of the polarization. However, its cross section is too small for the observed reduction. A possible explanation is depolarization due to the ΛN interaction since there the Λ has enough energy to knock another nucleon out of the nucleus. The probability of spin flip through a triplet component in the scattering increases at high energy [23], although quantitative comparison with the experiment will be discussed in the future, where one also has to investigate the procedure we used to obtain the off-shell two-body amplitude for which no established procedure exists.

We found that the Λ polarization for the quasifree (π^+,K^+) reaction on ^{12}C is almost consistent with what is expected from the elementary process. This demonstrates for the first time that the reaction mechanism is characterized by the quasifree process in terms of polarization. There is depolarization in the bound region and in the highly excited region. The mechanism for this depolarization appears to be due, in the bound region, to a contribution of pionic decay of the Λ hypernuclei and, in the high excitation region, possibly to the ΛN interaction.

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