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Spin observables in the $pn \rightarrow p\Lambda$ reaction

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The T matrix of the $pn \rightarrow p\Lambda$ reaction, which is a strangeness changing weak process, is derived. The explicit formulas of the spin observables are given for s-wave $p\Lambda$ final states which kinematically corresponds to inverse reaction of the weak nonmesonic decay of Λ hypernuclei. One can study interferences between amplitudes of the parity-conserving and -violating, spin-singlet and -triplet, and isospin-singlet and -triplet. Most of them are not available in the study of the nonmesonic decay and will be measured in the coming experiment. They clarify the structure of the reaction and constrain strongly theoretical models for the weak hyperon nucleon interaction. [S0556-2813(99)04607-5]

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The nonmesonic decay (NM decay) of Λ hypernuclei ($N\Lambda \rightarrow NN$) is the only process through which one has studied the strangeness-changing weak baryon-baryon (BB) interaction so far. Since the weak interaction does not conserve parity, a complete understanding of the process needs study of both parity-conserving and -violating amplitudes. For the weak nucleon-nucleon (NN) interaction, which is a nonstrange part of the weak BB interaction, one can study only its parity-violating part, because the parity-conserving part is completely masked by the strong interaction. Both amplitudes can be studied with the weak NM decay since no strong interaction can change flavor. The weak NN and hyperon nucleon (YN) interaction can be understood in an unified way based on the $SU_F(3)$ symmetry. The study of the NM decay is thus interesting and informative. One can study kinematically a limited region of the weak YN interaction using NM decay. In the present Brief Report we show that many spin observables measurable in the inverse $pn \rightarrow p\Lambda$ reaction will open a new opportunity to study the weak YN interaction generally.

Until recently experimental data were available on total- and partial-decay rates of the NM decay. Proton stimulated decay ($p\Lambda \rightarrow pn$) gives $I=0,1$ final two-nucleon state though neutron stimulated decay ($n\Lambda \rightarrow nn$) gives only the $I=1$ one. The branching ratio of $\Gamma(n\Lambda \rightarrow nn)/\Gamma(p\Lambda \rightarrow pn)$ has been studied for several hypernuclei. Isospin structure studied by the ratio suggests dominance of $I=1$ amplitudes over the $I=0$ ones, which contradicts calculations of the meson exchange model where dominant tensor-type interaction prefers the $I=0$ final state. Generally the NM decay is assumed to be a two-body process due to a momentum transfer (~ 0.4 GeV/c) much larger than the Fermi momentum. However, experimental data are affected by the final state interaction and multinucleon mechanism due to the existence of other nucleons. This situation obscures the assumption of the two-body process and makes comparison of measured branching ratios with theoretical models conceptually indirect.

Protons from the proton stimulated decay are emitted asymmetrically with respect to the polarization of Λ hypernuclei. Recently the asymmetry parameter has been studied by producing polarized Λ hypernuclei [1,2]. The asymmetry parameter is due to interference of parity-conserving and -violating amplitudes. The relative phase of two amplitudes gives additional constraint on theoretical models for the process. However, the precision of the experiment is limited by the final state interaction and magnitude of the polarization [3,4].

Recent sophisticated meson-exchange models of the weak BB interaction [5,6] have not completely solved an inherent problem for the NM decay which is a difficulty to reproduce the transition rate and branching ratio simultaneously [7]. The meson exchange model is unable to account for the short range mechanism which is important in the NM decay due to the large momentum transfer. A quark exchange model is a natural one to incorporate the short range dynamics [8–10], although in order to make realistic comparison with experiments the interplay between meson-exchange and quark-exchange mechanism has yet to be clarified. The NM decay is the only tool to investigate the weak BB interaction beyond the NN interaction at present. However, the initial ΛN state is constrained by the Λ hypernuclear structure and the final two nucleon state is affected by final state interaction [11,6]. One wishes to derive a two-body process of the NM decay to understand the weak BB interaction though above facts make the derivation difficult.

Recently it has been proposed that study of the NM decay can be extended by the study of the inverse reaction ($pn \rightarrow p\Lambda$) [12–14,9]. The Q value of the reaction is the mass difference between neutron and Λ (176 MeV) which requires 369 MeV proton kinetic energy for a free neutron target. At this energy the strong interaction cannot produce strange particle; thus detection of Λ is the evidence of generation of strangeness by weak interaction. The feasibility of the experiment is largely dependent on the cross section, for which several calculations have been carried out. The observed NM-decay rate gives cross section of $\sim 10^{-39}$ cm^2 [12] at the corresponding kinematical region which is ~ 10 MeV above the threshold ($E_p \sim 400$ MeV). The theoretically calculated cross sections vary almost an order of magnitude 10^{-39}–10^{-40} cm^2, depending on models used, reflecting our insufficient knowledge of the NM decay [13,14,9]. The cross section is very small but the experiment is feasible with a sophisticated detector system under preparation [15,16].

There are essential differences in the study of the $pn \to p\Lambda$ reaction although the reaction is the just inverse reaction of the NM decay. In the inverse reaction one can employ a spin polarized proton beam and the polarization of Λ produced by the reaction can be measured by using the large asymmetry parameter $\alpha_- = 0.642 \pm 0.013$ [17] of the $\Lambda \to p\pi^-$ decay. The polarization of the proton beam can be either longitudinal or transverse with magnitude approaching unity. This situation makes various spin observables measurable in the experiment. Such spin observables give interferences between amplitudes of parity-conserving and -violating, spin-singlet and -triplet, and isospin-singlet and -triplet. They will open a new opportunity to study the weak YN interaction. Here we derived the formulas of the spin observables and clarify the relation to the amplitudes commonly used in the study of the NM decay.

The general T matrix of $pn \to p\Lambda$ can be expressed as follows assuming rotational invariance in the center-of-mass system:

$$\begin{aligned}\langle s_{p'} s_\Lambda ; \boldsymbol{p}' | \hat{T} | s_p s_n ; \boldsymbol{p} \rangle = & \sum_{S,S',L,L',J,L_z,L_z'} (1/2 s_p' 1/2 s_\Lambda | S' S_z') \\ & \times (L' L_z' S' S_z' | JM) Y_{L',L_z'}(\hat{p}') \\ & \times (1/2 s_p 1/2 s_n | S S_z) \\ & \times (L L_z S S_z | JM) Y^*_{L,L_z}(\hat{p}) \\ & \times 4\pi \langle (L'S') JM; p' | \hat{T} | (LS) JM; p \rangle . \end{aligned} \tag{1}$$

Here s_p', s_Λ, s_p, and s_n are baryon spins. $\boldsymbol{p}, \boldsymbol{p}'$ are the momenta of initial and final proton. In order to calculate the polarization observables, we introduce the following density matrix ρ:

$$\rho_i = \frac{1 + \boldsymbol{\sigma}_i \cdot \boldsymbol{P}_i}{2}, \tag{2}$$

where i stands for proton (p) or Λ (Λ) and $\boldsymbol{P}_i$ is the polarization vector of particle i. The differential cross section can be simply calculated by taking the following trace of the baryon spins:

$$\frac{d\sigma}{d\Omega} \sim \mathrm{Tr}[\rho_\Lambda \hat{T} \rho_p \hat{T}^\dagger]. \tag{3}$$

We restrict our treatment to s-wave production for the $p\Lambda$ states to focus our discussion on the relation to the NM decay. Accordingly the maximum angular momentum is $J = 1$. By this truncation one can have a transparent representation of the observables by the following well-known six amplitudes:

$$\begin{aligned} a &= \langle {}^1S_0 | \hat{T} | {}^1S_0, I=1, P=+ \rangle, \\ b &= \langle {}^1S_0 | \hat{T} | {}^3P_0, I=1, P=- \rangle, \\ c &= \langle {}^3S_1 | \hat{T} | {}^3S_1, I=0, P=+ \rangle, \\ d &= \langle {}^3S_1 | \hat{T} | {}^3D_1, I=0, P=+ \rangle, \\ e &= \langle {}^3S_1 | \hat{T} | {}^1P_1, I=0, P=- \rangle, \\ f &= \langle {}^3S_1 | \hat{T} | {}^3P_1, I=1, P=- \rangle, \end{aligned} \tag{4}$$

where isospin (I) and parity (P) of the initial pn system are explicitly written. Using the above amplitudes, the spin structure of the T matrix is given as follows similar to the one for the NM decay by Block and Dalitz [18] as

$$\begin{aligned} \hat{T} = & a \frac{1 - \boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma}_\Lambda}{4} - b \frac{1 - \boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma}_\Lambda}{8} (\boldsymbol{\sigma}_p - \boldsymbol{\sigma}_\Lambda) \cdot \hat{\boldsymbol{p}} + c \frac{3 + \boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma}_\Lambda}{4} \\ & + d \frac{1}{2\sqrt{2}} (3 \boldsymbol{\sigma}_p \cdot \hat{\boldsymbol{p}} \boldsymbol{\sigma}_\Lambda \cdot \hat{\boldsymbol{p}} - \boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma}_\Lambda) + e \frac{\sqrt{3}(3 + \boldsymbol{\sigma}_p \cdot \boldsymbol{\sigma}_\Lambda)}{8} \\ & \times (\boldsymbol{\sigma}_p - \boldsymbol{\sigma}_\Lambda) \cdot \hat{\boldsymbol{p}} - f \frac{\sqrt{6}}{4} (\boldsymbol{\sigma}_p + \boldsymbol{\sigma}_\Lambda) \cdot \hat{\boldsymbol{p}}, \end{aligned} \tag{5}$$

where $\hat{\boldsymbol{p}} = \boldsymbol{p} / |\boldsymbol{p}|$.

The differential cross section is written as follows:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = \left. \frac{d\sigma}{d\Omega} \right|_{\text{unpol.}} & [1 + \boldsymbol{P}_p \cdot \hat{\boldsymbol{p}} A_p + \boldsymbol{P}_\Lambda \cdot \hat{\boldsymbol{p}} A_\Lambda + \boldsymbol{P}_p \cdot \hat{\boldsymbol{p}} \boldsymbol{P}_\Lambda \cdot \hat{\boldsymbol{p}} A^L_{p\Lambda} \\ & + \boldsymbol{P}_p \times \hat{\boldsymbol{p}} \cdot \boldsymbol{P}_\Lambda \times \hat{\boldsymbol{p}} A^T_{p\Lambda} + \boldsymbol{P}_p \times \boldsymbol{P}_\Lambda \cdot \hat{\boldsymbol{p}} A^{T'}_{p\Lambda}]. \end{aligned} \tag{6}$$

Coefficients of each term are represented as follows:

$$A = |a|^2 + |b|^2 + 3[|c|^2 + |d|^2 + |e|^2 + |f|^2], \tag{7}$$

$$A_p = 2\sqrt{3}\,\mathrm{Re}[-ab^*/\sqrt{3} + e(c - \sqrt{2}d)^* - f(\sqrt{2}c + d)^*]/A, \tag{8}$$

$$A_\Lambda = 2\sqrt{3}\,\mathrm{Re}[-ae^* + b(c - \sqrt{2}d)^*/\sqrt{3} - f(\sqrt{2}c + d)^*]/A, \tag{9}$$

$$\begin{aligned} A^T_{p\Lambda} = & \mathrm{Re}[-\sqrt{2}a(\sqrt{2}c + d)^* + 2|c|^2 - \sqrt{2}cd^* - 2|d|^2 \\ & + \sqrt{6} f(b + \sqrt{3}e)^*]/A, \end{aligned} \tag{10}$$

$$\begin{aligned} A^L_{p\Lambda} = & \mathrm{Re}[-2a(c - \sqrt{2}d)^* + 2|c|^2 + 2\sqrt{2}cd^* + |d|^2 \\ & + 2\sqrt{3}be^* + 3|f|^2]/A, \end{aligned} \tag{11}$$

$$\begin{aligned} A^{T'}_{p\Lambda} = & \sqrt{6}\,\mathrm{Im}[af^* - (b/\sqrt{3} + e)(\sqrt{2}c + d)^* \\ & + f(c - \sqrt{2}d)^*]/A. \end{aligned} \tag{12}$$

In the present reaction we have six observables including cross section (A). It has to be stressed that all six observables are measurable in the experiment.

A_p and A_Λ are correlations that violate parity. Experimentally A_p is obtained by measuring differences of the cross section for longitudinally polarized beams

$$A_p = \frac{\sigma(h_p=1)-\sigma(h_p=-1)}{\sigma(h_p=1)+\sigma(h_p=-1)}, \tag{13}$$

where helicity is defined as $h_p = \boldsymbol{\sigma}_p \cdot \hat{\boldsymbol{p}}$ and $h_p \sim 1$ is experimentally achievable. Similarly, the polarization of Λ in the beam direction gives A_Λ.

There are nine interference terms $[3(P=+)\times 3(P=-)]$ that violate parity. A_p has no interference term between $J=0$ and $J=1$ states because spin average is taken in the final $p\Lambda$ system. One can thus see five terms $[1(J=0)+2\times 2(J=1)]$ in the equation.

A_Λ gives the polarization of Λ in the proton beam direction that violates parity. It cannot be described by the definite isospin of the two nucleons in the initial state because an exchange of proton and neutron is equivalent to the parity when we average spin of the initial pn system. Thus A_Λ gives the interference between $I=0$ and $I=1$ matrix elements and four interference terms $[2(I=0)+2(I=1)]$ between the same isospin disappear.

The asymmetry parameter in the NM decay (α_p) is the only interference term that has been experimentally measured so far [19,1,2]. Spin polarized hypernuclei has asymmetric emission of protons from the proton stimulated NM decay represented as

$$W(\theta) = 1 + \alpha_p \cos\theta. \tag{14}$$

α_p has been given as $2\sqrt{3}f(\sqrt{2}c+d)/A$ assuming the initial ΛN system is in a relative s wave [20]. It is essentially equivalent to A_Λ except for a difference in the initial- and final-state interactions. Here we skip a subtle issue related to the convention of phase which is irrelevant to the present argument. It is noticed that A_Λ includes the contribution of the singlet initial state, which is missing in the formula of α_p. It is obvious that singlet state alone gives no asymmetry. However, the ΛN system buried in a hypernucleus can be singlet and triplet states whose interference terms make the formula of α_p equivalent to that of A_Λ.

There are three double polarization observables. Spin polarization is classified into transverse and longitudinal types. $A^T_{p\Lambda}$ is the correlation of transverse polarization. The $|c|^2$ term ($^3S_1 \rightarrow {}^3S_1$) keeps initial polarization although the $|d|^2$ term ($^3D_1 \rightarrow {}^3S_1$) flips it. No parity violation appears in this correlation thus interference terms are restricted to the same parity.

$A^{T'}_{p\Lambda}$ is a parity and T (time reversal) violating observable. It corresponds to generation of the Λ polarization in the direction defined by transverse proton polarization and proton momentum. The T violating correlation being searched for in the $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$ decay is $\boldsymbol{p}_\pi \times \boldsymbol{p}_\mu \cdot \boldsymbol{P}_\mu$ (P even and T odd) [21]. No search has been carried out for flavor changing baryon-baryon interaction. So far it is known that theories that violate T invariance also violate parity [22], making $A^{T'}_{p\Lambda}$ (P odd and T odd) correlation interesting. These consideration makes the search valuable even though expected precision is inferior to the kaon decay [12,16]. It is known that spurious T violation is seen in the $\Lambda \rightarrow p\pi^-$ decay due to final state interaction. The final state interaction has to be evaluated for the T violation experiment. This is left for the future study.

$A^L_{p\Lambda}$ is the correlation for the longitudinal polarization. It corresponds to the spin-flip probability in the beam direction and is a parity-conserving correlation. However, the correlation would not give a deep insight to the $pn \rightarrow p\Lambda$ reaction that has the large parity violation. Experimental data can be transparently related to the relevant amplitudes in the helicity representation. We have six independent amplitudes $T(h_{p'}, h_\Lambda; h_p, h_n)$, which are given in terms of multipole amplitudes as

$$T(1,1;1,1) = \frac{c_+ - \sqrt{3}f}{\sqrt{2}}, \tag{15}$$

$$T(-1,-1;-1,-1) = \frac{c_+ + \sqrt{3}f}{\sqrt{2}}, \tag{16}$$

$$T(-1,1;1,-1) = \frac{-a + c_- + b_+}{2}, \tag{17}$$

$$T(1,-1;-1,1) = \frac{-a + c_- - b_+}{2}, \tag{18}$$

$$T(1,-1;1,-1) = \frac{a + c_- - b_-}{2}, \tag{19}$$

$$T(-1,1;-1,1) = \frac{a + c_- + b_-}{2}, \tag{20}$$

where

$$c_+ = \sqrt{2}c + d, \tag{21}$$

$$c_- = c - \sqrt{2}d, \tag{22}$$

$$b_+ = b + \sqrt{3}e, \tag{23}$$

$$b_- = b - \sqrt{3}e. \tag{24}$$

Here all h_i represent spins of baryons in the direction of incoming proton momentum. Using longitudinal polarization of proton and Λ, we can determine four independent combinations of the absolute magnitude of amplitudes, which can also be represented by combinations of A, A_p, A_Λ, and $A^L_{p\Lambda}$. One can conveniently obtain expressions of observables using longitudinal polarization by interference terms. For example polarization of p and Λ, which are antiparallel gives

$$\frac{\sigma(h_p=1,h_\Lambda=-1)-\sigma(h_p=-1,h_\Lambda=1)}{\sigma(h_p=1,h_\Lambda=-1)+\sigma(h_p=-1,h_\Lambda=1)}$$
$$=\frac{|T(1,-1;1,-1)|^2-|T(-1,1;-1,1)|^2}{|T(1,-1;1,-1)|^2+|T(-1,1;-1,1)|^2}$$
$$\sim \mathrm{Re}[(a+c_-)b_-^*]. \tag{25}$$

It is interesting that we can remove f in Eq. (25), which was suggested to be dominant from the phenomenological analysis [18], though it may not be so large in the meson-exchange models. Here we have not discussed terms relevant to polarization of target neutron since feasibility of the experiment is currently questionable.

Here we restricted our discussion to the relative s wave which corresponds to a proton kinetic energy of ~ 400 MeV, although it can be extended to include higher partial waves. The present kinematic regime is selected because the NM decay rate can give an order of magnitude estimation of the cross section and the obtained result should be useful to understand the NM decay in detail. However, one can study energy dependence of the $pn\to p\Lambda$ reaction safely up to proton energy around 680 MeV where Λ and kaon pair production becomes possible only for the limit of infinitely heavy hypernuclei. The study of energy dependence will give information on the general structure of the weak YN interaction. The study of the p-wave component of the reaction is particularly interesting. If the meson exchange models is insufficient to describe the NM decay only in the short range region, the models should well describe the long range part which is naturally associated with the p-wave part of the interaction.

In summary, we derived formulas of spin observables in the $pn\to p\Lambda$ reaction. Those observables are useful not only to study the NM decay of Λ hypernuclei but also to study the weak BB interaction generally. The spin polarization of the incident proton beam can be large and precisely given. The polarization of Λ is also well determined experimentally. The spin observables are affected little by nuclear effects which, however, limit study of the NM decay. The spin and isospin of the ΛN system is determined by the hypernuclear wave functions for the NM decay though the $pn\to p\Lambda$ reaction has no such limitation. The reaction is shown to be useful for the study of the weak BB interaction.

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