Proton asymmetry in the weak decay of polarized hypernuclei

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Abstract

Polarization observables are evaluated for the nonmesonic weak decay of hypernuclei in a relativistic nuclear model. The asymmetries in the decay of ${}^{\Lambda}{}^3\text{B}$ and ${}^{\Lambda}{}^3\text{C}$ are in good agreement with preliminary experimental data from KEK. The hypernuclear dependence of the intrinsic Λ asymmetry parameter a_{Λ} is discussed. The resulting spin polarization of the outgoing proton is also calculated. In contrast to the nonmesonic decay rate, the polarization observables are not very sensitive to short-range correlations, whereas the effect of interactions in the final state is substantial.

1. INTRODUCTION

The weak decay of the Λ and other hyperons has been of interest for many years as an example of a weak interaction not involving leptons. The nucleon produced in the mesonic decay of a Λ ($\Lambda \rightarrow \pi N$) has a very low momentum ($< 100 \text{ MeV}/c$) and it is therefore Pauli blocked in the nuclear medium. Thus, the two-body, nonmesonic mode $\Lambda N \rightarrow NN$ is the dominant process in all but the lightest hypernuclei. In the absence of strong interactions the lowest-order Hamiltonian for weak quark-quark interactions is assumed to be given by the combination of $V-A$ theory with the Cabibbo hypothesis[1]; however, the modification of the weak force due to strong interaction corrections is not yet well understood. The nonmesonic reaction may help to shed some light on these corrections, as well as provide valuable information on the reaction mechanism of the decay and the modifications of the baryon properties in the nuclear medium.

Motivated by recent experiments at Brookhaven[2] and KEK[3] we have developed a formalism[4] for relativistic calculations of the nonmesonic hypernuclear decay in a shell model approach which includes the effects of short-range correlations and final state distortions. Most previous theoretical studies have analyzed the nonmesonic decay mode in a non-relativistic nuclear matter model keeping only the relative ΛN S -wave contributions. We have treated the details of the nuclear structure input as well as possible. In this spirit, the transformation into the relative ΛN two-body frame is

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avoided and, therefore, nucleon orbitals with arbitrary n, ℓ and j can be easily incorporated. The relativistic approach might turn out to be more appropriate in the study of polarization observables, in view of its success to predict spin observables in elastic proton-nucleus scattering. As already discussed in Ref. [4] the obtained nonmesonic rates Γ_{nm} for ${}^{\Lambda}{}^3\text{He}$, ${}^{\Lambda}{}^3\text{B}$ and ${}^{\Lambda}{}^3\text{C}$ in the pion exchange model are a factor 2-4 smaller than the Brookhaven data[2]. It is well known that the pion mechanism cannot reproduce either the experimental neutron- to proton-induced ratios Γ_n/Γ_p , even with their large error bars. Including kaon exchange further reduces the total rate Γ_{nm} by 15-20% while the ratio Γ_n/Γ_p is enhanced by almost a factor of two. The need to incorporate heavier meson exchanges such as ρ, ω and K^* is evident.

A recent KEK experiment[3] has measured the angular asymmetry of the exiting protons in the weak decay of polarized ${}^{\Lambda}{}^3\text{B}$ and ${}^{\Lambda}{}^3\text{C}$. This is an interesting quantity since it depends linearly on parity violating (PV) amplitudes and, therefore, complements the information extracted from the total and partial rates which are dominated by the parity conserving (PC) amplitudes. In this work we use our relativistic, finite nucleus model to calculate polarization observables in the weak decay of hypernuclei. Results for the asymmetry are discussed in Sect. 2, while Sect. 3 is devoted to the spin polarization of the outgoing proton. The conclusions are given in Sect. 4.

2. ASYMMETRY

The (π^+, K^+) reaction has been shown to produce hypernuclear states with large spin polarization aligned preferentially along the axis normal to the reaction plane. The intensity of protons from the decay of polarized hypernuclei is given by

$$I(\chi) = \text{Tr}(\mathcal{M}\hat{\rho}\mathcal{M}^\dagger), \quad (1)$$

where χ is the angle formed by the direction of the proton and the polarization axis, $\mathcal{M}$ describes the transition from the initial hypernucleus to the final state and $\hat{\rho}$ is the density matrix for the polarized spin- J hypernucleus. The trace is carried out over all hypernuclear spin projections, as well as all the possible final states for which a proton emerges at an angle χ . For pure vector polarization P_y perpendicular to the plane of the (π^+, K^+) reaction

$$\hat{\rho}_i(J) = \frac{1}{2J+1} \left(1 + \frac{3}{J+1} P_y \hat{S}_y \right), \quad (2)$$

and Eq. (1) can then be written as

$$I(\chi) = I_0 \left(1 + \frac{3}{J+1} P_y \frac{\text{Tr}(\mathcal{M}\hat{S}_y\mathcal{M}^\dagger)}{\text{Tr}(\mathcal{M}\mathcal{M}^\dagger)} \right) = I_0 (1 + \mathcal{A}), \quad (3)$$

where $I_0 = \text{Tr}(\mathcal{M}\mathcal{M}^\dagger)/(2J+1)$ is the isotropic intensity for the unpolarized hypernucleus, $\mathcal{A}$ denotes the asymmetry, and A_y is the hypernuclear asymmetry parameter which has a trivial $\cos \chi$ dependence[4]. In order to remove dependencies on the hypernuclear spin, we redefine the asymmetry as $\mathcal{A} = p_{\Lambda} a_{\Lambda}$ where the Λ -spin polarization p_{Λ} and the intrinsic Λ asymmetry parameter a_{Λ} are given by

$$p_{\Lambda} = \begin{cases} -\frac{J}{J+1} P_y & \text{if } J = J_c - \frac{1}{2} \\ P_y & \text{if } J = J_c + \frac{1}{2} \end{cases} \quad a_{\Lambda} = \begin{cases} -\frac{J+1}{J} A_y & \text{if } J = J_c - \frac{1}{2} \\ A_y & \text{if } J = J_c + \frac{1}{2} \end{cases}, \quad (4)$$

where J_c is the nuclear-core spin.

Our results for a_Λ are shown in Table 1 at $\chi = 0^\circ$ for the experimental cut-off of 40 MeV on the minimum proton kinetic energy. Including short-range correlations (SRC) and form-factors (FF) does not change a_Λ appreciably, even though their influence is substantial on the decay rate[4]. We note that the reduction caused by SRC and FF in the decay rate, however large in magnitude it may be, is uniform for different proton kinematics and, therefore, cancels in the ratio of rates that defines the asymmetry. On the other hand, final state interactions (FSI) redistribute the strength in the differential rate producing an important effect in the asymmetry parameter. Including kaon exchange increases a_Λ by 15-20%. We obtain similar a_Λ values for ^{12}C and ^{11}B , while preliminary studies for ^4He [4] give a larger result ($a_\Lambda = -0.60$) when all the ingredients of the calculation are considered. This indicates a dependence of a_Λ on the hypernucleus, which is also observed even when distortion effects are removed. This observation should be corroborated by a systematic study of heavier hypernuclei. We point out that the sign of a_Λ is fixed in our calculation, as opposed to previous theoretical estimates of the asymmetry parameter[5] which used the squares of the amplitudes of a nuclear matter calculation and, therefore, their relative sign was not known.

Table 1

Intrinsic Λ asymmetry parameter a_Λ

^{12}C	^{11}B
free	-0.684
SRC,FF	-0.668
SRC,FF,FSI	-0.397
π, K	-0.457

Table 2

Asymmetry $A = P_y A_y = P_\Lambda a_\Lambda$

^{12}C	^{11}B
free	-0.103
SRC,FF	-0.103
SRC,FF,FSI	-0.057
π, K	-0.142
SRC,FF,FSI	-0.457
Exp.	-0.01 $\pm$ 0.10

For the (π^+, K^+) process at the kinematics of the KEK experiment[3] ($p_+ = 1.05$ GeV/c and $\theta_{K^+} = 14^\circ$) the hypernuclear polarization has been predicted to be $P_y(^{12}\text{C}) = -0.45[6]$ and $P_y(^{11}\text{B}) = -0.30[7]$. As shown in Table 2, the resulting asymmetries A are not in very good agreement with the central values of the measurements, even though the error bars are very large. However, due to the poor energy resolution of the experiment (5-7 MeV), the ^{12}C hypernucleus is created in three possible 1^- states. The states 1_2^- and 1_3^- will decay electromagnetically to the lower $1_{g.s.}^-$ ground state, which eventually experiences the nonmesonic weak decay. Therefore, we can no longer

assign a polarization of -0.45 to the ground state $1_{g.s.}^-$, since it has been partly populated through electromagnetic transitions from excited states having a different polarization. To correct the polarization, we neglect the contribution of the 1_3^- state since it has the smallest spectroscopic factor[8] and, furthermore, it loses more of its polarization since it may experience electromagnetic transitions through several excited states to reach the $1_{g.s.}^-$ state. In the weak coupling limit, the 1_2^- state at ~ 2 MeV can be constructed as a $p_{1/2}$ neutron hole and a Λ in the $1s_{1/2}$ state. According to Ref. [6], the transition to $[p_{1/2}, \Lambda s_{1/2}]^-$ at $\theta_{K^+} = 15^\circ$ has a large positive polarization, $P_y = 0.75$. Employing the spin depolarization formalism of Ref. [7] for the electromagnetic decay $1_2^-(M1) \rightarrow 1_{g.s.}^-$, we find a polarization loss of 50%. After weighing the 1_2^- and 1_3^- polarization with the appropriate spectroscopic factors we arrive at an upper limit of $P_y(^{12}\text{C}) = -0.25$. Improved calculations that include the 1_3^- state as well as multiple electromagnetic transitions such as $1_2^-(M1) \rightarrow 2_1^-(M1) \rightarrow 1_{g.s.}^-$, can reduce the polarization slightly further[9]. As shown in Table 2, with this corrected value of $P_y(^{12}\text{C})$ the experimental asymmetry can be reasonably well reproduced.

The hypernucleus ^{11}B is created by particle emission from excited states of ^{12}C in which a Λ in a $p_{1/2}$ or $p_{3/2}$ orbit is coupled to a ^{11}C core in its ground state. In the range of excitation energy between the $(p + ^{11}\text{B})$ and the $(\Lambda + ^{11}\text{C})$ particle decay threshold there are two 2^+ states and a narrow 0^+ state. A polarization of $P_y(^{11}\text{B}) = -0.30$ was obtained[7] by averaging the polarization of the two 2^+ states and neglecting the 0^+ because of its small formation cross section. However, hypernuclear nuclear structure calculations by Auerbach *et al.*[10] predict strong configuration mixing which reduces the cross section of the lower 2^+ state by a factor of three relative to the second 2^+ state. This prediction has been roughly verified by a reanalysis of older emission data[11]. Taking these relative weights into account we find a corrected value of $P_y(^{11}\text{B}) = -0.42$, which again leads to a better agreement with the measured asymmetry.

3. PROTON POLARIZATION

The outgoing proton spin polarization along an axis perpendicular to the (π^+, K^+) reaction plane is given by

$$P_y = \frac{\text{Tr}(\hat{\rho}_f \sigma_y)}{\text{Tr}(\hat{\rho}_f)}, \quad (5)$$

where $\hat{\rho}_f = M \hat{\rho}_i M^\dagger$ is the density matrix describing the final state. Results for the proton polarization in the weak decay of ^{12}C are shown in Fig. 1 as a function of the angle χ between the proton direction and the hypernuclear polarization axis. The net polarization of the hypernucleus, which we have taken to be $P_y = -0.45$, destroys the usual $\cos \chi$ dependence characteristic of a spin- $\frac{1}{2}$ particle. Although not explicitly shown in the figure, SRC and FF increase the magnitude of P_y by about 12%. FSI reduce $|P_y|$ by 17%, while including kaon exchange increases it by another 5%. Since the various model ingredients of the calculation produce similar and relatively small effects on the proton polarization, this observable does not appear to be adequate to learn more about the nonmesonic decay mechanism. Moreover, the measurement of the proton polarization is impracticable with the particle fluxes and energy resolution of the present experimental facilities.

Figure 1. Proton polarization from the decay of $^{12}\bar{C}$.

4. CONCLUSIONS

We have presented results for polarization observables in the nonmesonic decay of hypernuclei using a relativistic nuclear model. Even though the decay rates cannot be reproduced, the calculated asymmetries are in reasonable agreement with the measurements, once the hypernuclear polarization obtained via the (π^+, K^+) reaction has been corrected for hypernuclear structure. The proton polarization is not an adequate observable to obtain additional information on the weak decay process due to the small effects produced by the various ingredients of the model.

Given the present energy resolution, more sophisticated hypernuclear structure calculations for the hypernuclear polarization P_p , used as an input in the present work, are necessary. This is a difficult task since these models should provide reliable estimates of formation cross sections and polarizations of excited states in order to obtain, after applying a spin depolarization formalism, accurate values of P_p . Ideally, an energy resolution of 200 keV would allow to discriminate single states and, therefore, the corresponding polarization could be determined with reduced uncertainty. It is unfortunate that, due to the present statistical errors, the asymmetry does not provide a sufficient test of the theoretical models. This prevents gaining new insight on the nonmesonic decay. Higher intensity pion fluxes are necessary. These two experimental requirements could be achieved with the high energy resolution and coincidence capabilities of PILAC.

On the theoretical side there are a number of improvements that should be pursued as the field of weak hypernuclear decay develops. On the level of the elementary $\Lambda N \rightarrow NN$ amplitude it is important to construct a transition potential that includes heavier mesons such as the ρ , ω and K^* . Regarding our finite nucleus calculation, we have assumed the weak coupling limit for the hypernuclear ground state wave function.

Hypernuclear structure calculations indicate that this is a very good approximation; nevertheless, our formalism could easily incorporate more complicated wave functions that include configuration mixing.

Once the nonmesonic decay rates, partial rates and asymmetries are available for a number of different hypernuclei it should become possible to disentangle the various ingredients in the $\Lambda N \rightarrow NN$ process and place severe constraints on the QCD corrections present in the weak interaction.

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