Asymmetry Parameter for the Nonmesonic Decay of ${}^5_\Lambda$He

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We report the preliminary result of an exact calculation of the asymmetry parameter, a_Λ, in the nonmesonic hypernuclear decay, based on a one-meson-exchange (OME) model. For the case of ${}^5_\Lambda$He and including one-pion-exchange only, the result is shown not to differ considerably from the one obtained with the approximate formula widely used in the literature. In particular, the sign of a_Λ remains negative, in disagreement with its most recent experimental determination. Whether these facts remain true for heavier hypernuclei and in a more complete OME model is still under investigation.

1 Introduction

The free decay of a Λ hyperon occurs almost exclusively through the mesonic mode, $\Lambda \rightarrow \pi N$, with the nucleon emerging with a momentum of about 100 MeV/c. Inside nuclear matter ($p_F \approx 270$ MeV/c) this mode is Pauli blocked, and already for Λ hypernuclei with $A \gtrsim 5$ the weak decay is dominated by the nonmesonic channel, $\Lambda N \rightarrow NN$. The simplest model for this process is the exchange of a virtual pion, and in fact this can reproduce reasonably well the total decay rate, $\Gamma_{nm} = \Gamma_n + \Gamma_p$, but fails badly for other observables like the n/p branching ratio, Γ_n/Γ_p. In an attempt for improvement, most of the theoretical work has opted for the inclusion of other mesons in the exchange process. None of these models gives fully satisfactory results [1].

Another important observable of the weak nonmesonic decay is the asymmetry parameter [2], a_Λ, which depends on the interference between the amplitudes for parity-conserving (PC) and parity-violating (PV) proton-induced transitions to final states where the two emitted nucleons have different total isospins. It is experimentally extracted from measurements of the angular distribution of the emitted protons in the nonmesonic decay of polarized hypernuclei. There are large discrepancies, both experimentally and theoretically, in the determination of a_Λ [1], specially after the newest experimental results for the decay of ${}^5_\Lambda$He [3] giving a positive value for this observable, differently from previous measurements based on the decay of ${}^{12}_\Lambda$C [4], which would be expected to yield approximately the same result (see below). In strong disagreement with the new measurement, all calculations so far find a negative value for a_Λ, which makes the investigation of this observable particularly relevant.

We have recently derived [5] an expression for an exact finite-nucleus shell-model calculation of a_Λ in terms of the appropriate matrix elements of the transition potential, V, which is constructed in a one-meson-exchange (OME) model based on the ground pseudoscalar and vector meson octets (π, η, K, ρ, ω, K^*) [6] and including two effects that have been systematically neglected in the literature, namely, the kinematical effects due to the difference between the lambda and nucleon masses and the first-order nonlocality corrections [7]. We have also shown [5] that, if one constrains the two emitted nucleons to fly apart with opposite momenta, this expression reduces to the approximate formula usually adopted in the literature (Eq. 8, below). However, in general, other contributions come into play when this constraint is relaxed. Here we report the first results of such an exact calculation of the asymmetry parameter, done for ${}^5_\Lambda$He within a simple one-pion-exchange (OPE) model but including the two corrections mentioned above.

2 Hypernuclear asymmetry

Hypernuclei produced from a (π^+, K^+) reaction end up with considerable vector polarization, P_V, along the direction normal to the reaction plane, $\hat{\mathbf{n}} = (\mathbf{k}_{\pi^+} \times \mathbf{k}_{K^+})/|\mathbf{k}_{\pi^+} \times \mathbf{k}_{K^+}|$. Therefore the polarized *mixed* initial hypernuclear state can be described by the density matrix [2]

$$\rho(J_I) = \frac{1}{2J_I+1}\left[1 + \frac{3}{J_I+1} P_V \mathbf{J}_I \cdot \hat{\mathbf{n}}\right], \qquad (1)$$

where J_I is the hypernuclear spin.

The angular distribution of the emitted protons (particle #2 = proton) coming from the proton-induced decay,

$\Lambda\, p \to n\, p$, of the *pure* initial hypernuclear state $|\nu_I J_I M_I\rangle$, where ν_I specifies the remaining quantum numbers besides those related to the hypernuclear spin, is given by

$$\frac{d\Gamma(\nu_I J_I M_I \to \hat{\mathbf{p}}_2)}{d\Omega_{p_2}} = \int d\Omega_{p_1} \int dF \sum_{s_1 s_2 M_R} \left| \langle \mathbf{p}_1 s_1 \mathbf{p}_2 s_2\, \nu_R J_R M_R | \hat{V} | \nu_I J_I M_I \rangle \right|^2 , \tag{2}$$

where we have introduced the compact notation ($\hbar = c = 1$)

$$\int dF \ldots \; = \; 2\pi \sum_{\nu_R J_R} \int \frac{p_2^2\, dp_2}{(2\pi)^3} \int \frac{p_1^2\, dp_1}{(2\pi)^3}\, \delta\left(\frac{p_1^2}{2\mathrm{M}} + \frac{p_2^2}{2\mathrm{M}} + \frac{P^2}{2\mathrm{M_R}} - \Delta_{\nu_R J_R} \right) \ldots , \tag{3}$$

M being the nucleon mass; $\mathrm{M_R}$, that of of the residual nucleus, which is left in state $|\nu_R J_R M_R\rangle$; $\Delta_{\nu_R J_R}$, the liberated energy; and $\mathbf{P} \equiv \mathbf{p}_1 + \mathbf{p}_2$, the total momentum of the emitted nucleons. (To avoid confusion, we will be using roman font (M,m) for masses and italic font (M,m) for azimuthal quantum numbers.)

It is then possible to show [5] that the angular distribution of protons from the decay of the polarized mixed state described by Eq. 1 has the form

$$\frac{d\Gamma(\nu_I J_I \to \hat{\mathbf{p}}_2)}{d\Omega_{p_2}} = \frac{\Gamma_p}{4\pi}\, (1 + P_V A_V\, \hat{\mathbf{p}}_2 \cdot \hat{\mathbf{n}}) , \tag{4}$$

where Γ_p is the full proton-induced decay rate, and the *vector hypernuclear asymmetry*, A_V, is given by

$$A_V = \frac{3}{J_I + 1}\, \frac{\sum_{M_I} M_I \sigma(\nu_I J_I M_I)}{\sum_{M_I} \sigma(\nu_I J_I M_I)} . \tag{5}$$

We have introduced the *decay strengths*

$$\sigma(\nu_I J_I M_I) \; = \; \int d\Omega_{p_1} \int dF \sum_{s_1 s_2 M_R} \left| \langle \mathbf{p}_1 s_1 \; \tilde{\mathbf{p}}_2\, s_2\, \nu_R J_R M_R | \hat{V} | \nu_I J_I M_I \rangle \right|^2 , \tag{6}$$

where $\tilde{\mathbf{p}}_2 \equiv p_2 \mathbf{e}_z$ and $\mathbf{e}_z$ is the unit vector for the z-axis.

It is clear that, with the help of Eq. 4, one can extract the value of the product $P_V A_V$ from the counting rates parallel and opposite to the polarization direction. Since P_V can also be independently measured, this experimentally determines the vector hypernuclear asymmetry, A_V. This quantity should depend on the details of (hyper)nuclear structure. In an attempt to subdue this dependence, and adopting a weak-coupling model of the Λ to the core nucleus, one defines the *intrinsic asymmetry parameter*, a_Λ, as follows [2]

$$a_\Lambda = \left\{ \begin{array}{rl} A_V & \text{if} \quad J_I = J_C + \frac{1}{2} , \\ -\dfrac{J_I + 1}{J_I} A_V & \text{if} \quad J_I = J_C - \frac{1}{2} , \end{array} \right. \tag{7}$$

where J_C is the spin of the core. With this definition, it is usually believed that one gets an observable which is characteristic of nonmesonic decay in general, since it should be only mildly dependent of the particular hypernucleus considered. This hypothesis, however, seems to be contradicted by the present state of affairs, namely, the large discrepancy between the values for a_Λ when determined from measurements of the decay of ${}^{12}_{\Lambda}$C and of ${}^{5}_{\Lambda}$He.

We have shown [5] that, if one makes the approximation of treating the final state of the emitted nucleons as though the transition $\Lambda\, p \to n\, p$ ocurred in vacuum, thus constraining the two nucleons to fly apart with opposite momenta ($\mathbf{P} \equiv \mathbf{p}_1 + \mathbf{p}_2 = 0$) in the CM frame, then our exact expression for the vector asymmetry, Eq. 5, will reduce, in the case of ${}^{5}_{\Lambda}$He, to the approximate formula usually adopted in the literature [1], namely,

$$A_V = \frac{2\,\Re \left[\sqrt{3}\, a e^* - b\, (c^* - \sqrt{2}\, d^*) + \sqrt{3}\, f\, (\sqrt{2}\, c^* + d^*) \right]}{|a|^2 + |b|^2 + 3\,(|c|^2 + |d|^2 + |e|^2 + |f|^2)} , \tag{8}$$

where

$$\begin{aligned} a &= \langle np,{}^1\mathrm{S}_0 | \hat{\mathrm{V}} | \Lambda\mathrm{p},{}^1\mathrm{S}_0 \rangle , \\ b &= i \langle np,{}^3\mathrm{P}_0 | \hat{\mathrm{V}} | \Lambda\mathrm{p},{}^1\mathrm{S}_0 \rangle , \\ c &= \langle np,{}^3\mathrm{S}_1 | \hat{\mathrm{V}} | \Lambda\mathrm{p},{}^3\mathrm{S}_1 \rangle , \\ d &= -\langle np,{}^3\mathrm{D}_1 | \hat{\mathrm{V}} | \Lambda\mathrm{p},{}^3\mathrm{S}_1 \rangle , \\ e &= i \langle np,{}^1\mathrm{P}_1 | \hat{\mathrm{V}} | \Lambda\mathrm{p},{}^3\mathrm{S}_1 \rangle , \\ f &= -i \langle np,{}^3\mathrm{P}_1 | \hat{\mathrm{V}} | \Lambda\mathrm{p},{}^3\mathrm{S}_1 \rangle . \end{aligned} \tag{9}$$

This is so because Eq. 8 is adapted form the corresponding expression derived for the two-body reaction $pn \rightarrow p\Lambda$ in free space [8]. In actual fact, however, the final state of the hypernuclear decay is a three-body one, and the ensuing kinematical complications should be properly dealt with, which requires a direct integration over the available phase space in order to compute A_V from the exact expressions in Eqs. 5 and 6. Such a calculation, for several hypernuclei and in several OME models, is presently under way [5]. The extra factors in the transition amplitudes in Eqs. 9 are due to differences in phase conventions, as explained in [7].

3 Numerical results and conclusions

TABLE I. Results for the asymmetry parameter a_Λ. See text for detailed explanation.

Theoretical results for ${}^{5}_{\Lambda}$He (OPE only)	
Approximate calculation: Eq. 8. [7]	-0.4456
Exact calculation: Eqs. 5 and 6.	-0.4487
Experimental results [1, Table 23]	
$a_\Lambda = -2A_V({}^{12}_{\Lambda}\mathrm{C})$ [4]	-0.9 ± 0.3
$a_\Lambda = A_V({}^{5}_{\Lambda}\mathrm{He})$ [3]	0.24 ± 0.22

In Table I, we compare the results obtained for the asymmetry parameter, a_Λ, in the decay of ${}^{5}_{\Lambda}$He, within the one-pion-exchange (OPE) model including the kinematical effects of the lambda-nucleon mass difference and nonlocal terms [7], with the existing experimental determinations for this observable as cited in Ref. [1]. We give the theoretical results calculated, both through the approximate formula in Eq. 8, and by means of the exact expressions in Eqs. 5 and 6.

One can draw the following conclusions:

1. The comparison of our result for the exact calculation of A_V, based on Eqs. 5 and 6, with the approximate one, based on Eq. 8, suggests that the effects of the three-body kinematics in the final states of nonmesonic decays are not very important. Consequently, the approximate formula in Eq. 8, which is widely used in the literature, seems to be vindicated by our exact calculation, at least for the s-shell hypernucleus ${}^{5}_{\Lambda}$He.

2. However, it remains to be seen whether the same conclusion applies to p-shell (${}^{12}_{\Lambda}$C) and other hypernuclei, where, not to mention other effects related to nuclear structure, additional transitions occur besides those listed in Eqs. 9. This will be the subject of a forthcoming paper [5].

3. The large discrepancies found in the different experimental determinations of a_Λ, as well as between those and the theoretical calculations of this observable, remain unexplained and need further investigation.

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