Two-pion-exchange in the non-mesonic weak decay of $\Lambda$-hypernuclei

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Abstract

The non-mesonic weak decay of $\Lambda$-hypernuclei is studied within a one-meson-exchange potential supplemented by a chirally motivated two-pion-exchange mechanism. The effects of final state interactions on the outgoing nucleons are also taken into account. Particular attention is paid to the asymmetry of the protons emitted by polarized hypernuclei. The one-meson-exchange model describes the non-mesonic rates and the neutron-to-proton ratio satisfactorily but predicts a too large and negative asymmetry parameter. The two-pion exchange mechanism modifies the strength and sign of some decay amplitudes. As a consequence, while the rates change moderately, the asymmetry parameter is strongly affected, acquiring values that lie well within the experimental observations.

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1. Introduction

Hypernuclei may be considered as a powerful “laboratory” for unique investigations of the baryon–baryon strangeness-changing weak interactions. The field of non-mesonic weak decay has indeed experienced a phase of renewed interest in the last few years. On the one hand, different theoretical [1–7] and experimental [8–11] indications have recently appeared in favour of a solution of the well-known and long-standing puzzle on the ratio $\Gamma_n/\Gamma_p$ [12,13] between the rates for the $\Lambda n \rightarrow nn$ and $\Lambda p \rightarrow np$ non-mesonic weak decay processes. Nowadays, values of this neutron-to-proton ratio around 0.3–0.4 for $s$- and $p$-shell hypernuclei are common to both theoretical and experimental analyses. An important role in this achievement has been played by a non-trivial interpretation of data, which required analyses of two-nucleon induced decays, $\Lambda NN \rightarrow nNN$, and accurate studies of nuclear medium effects on the weak decay nucleons. On the other hand, considerable concern is rooted in the persistence of another open problem, of more recent origin, which regards an asymmetry in the non-mesonic weak decay of polarized hypernuclei and whose solution is expected to provide new constraints for a deeper understanding of the dynamics of hypernuclear decay.

While inexplicable inconsistencies appeared between the first asymmetry experiments of Refs. [14,15], as discussed in Ref. [13], very recent and more accurate data [9,16,17] favour small observable asymmetries, compatible with a vanishing value, for both $s$- and $p$-shell hypernuclei. On the contrary, theoretical models based on one-meson-exchange potentials [1,4,18,19] (generally including the pseudoscalar and vector mesons $\pi$, $\rho$, $K$, $K^*$, $\omega$ and $\eta$) and/or direct quark mechanisms [2] predicted rather large and negative intrinsic asymmetry values (from $-0.7$ to $-0.5$ in the above quoted studies). It must be noted that, on the contrary, the mentioned models have been able to account fairly well for the total non-mesonic decay rates and for the ratios $\Gamma_n/\Gamma_p$ measured for $s$- and $p$-shell hypernuclei.

Recently, an effective field theory approach based on tree-level pion- and kaon-exchange and leading-order contact interactions has been applied to hypernuclear decay [20]. The
coefficients of the considered four-fermion point interaction Lagrangian have been fitted to reproduce the total and partial decay widths for $^3\Lambda$He, $^{12}_Λ$B and $^{12}_C$, and the asymmetry parameter for $^5\Lambda$He. In this way, a dominating central, spin- and isospin-independent contact term has been predicted.

Prompted by this work, in Ref. [21] a model based on $(\pi + K)$-exchange and the direct quark mechanism has been supplemented with the exchange of the scalar–isoscalar $\sigma$-meson, where the corresponding weak couplings are obtained by fitting decay data for s-shell hypernuclei. The $\pi + K + \sigma +$ direct quark model turned out to reproduce all decay observables for $^3\Lambda$He reasonably, while the $\pi + K + \sigma$ model was unable to account for the experimental value of the asymmetry. Similarly, a one-meson-exchange potential containing $\pi$, $\rho$, $K$, $K^*$, $\omega$, $\eta$ and $\sigma$ has been applied more recently [22] to the evaluation of $\Gamma_{NM}$, $\Gamma_\sigma/\Gamma_p$ and the intrinsic asymmetry $a_A$ for $^3\Lambda$He and $^5\Lambda$C. The unknown $\sigma$ couplings have been fixed to reproduce data for the $^3\Lambda$He total and partial decay widths. The authors found that, despite the inclusion of the $\sigma$ meson improved the overall agreement with experiment, the asymmetry data for $^3\Lambda$He could not be reproduced.

The contributions of uncorrelated and correlated two-pion-exchange to the non-mesonic weak decay has also been studied in Refs. [3,5,23,24]. Some preliminary papers [23] paved the way for a model that considered, in addition to $\pi$ and $\omega$, the exchange of two-pions correlated in the scalar–isoscalar $(2\pi/\sigma)$ and vector–isovector $(2\pi/\rho)$ channels [5], with a phenomenological treatment which is quite similar to the scheme used in the pioneering work of Ref. [25]. The results of Ref. [5] demonstrate how the correlated two-pion-exchange improves the calculation of $\Gamma_\sigma/\Gamma_p$ over the one-pion-exchange model. After adding the exchange of the kaon it was found [24] that the correlated two-pion-exchange also entails some improvement in the evaluation of the asymmetry parameter. In Ref. [3], a meson-exchange potential including pion, kaon, omega and uncorrelated plus correlated two-pions $(\pi + K + \omega + 2\pi + 2\pi/\sigma)$ has been considered. The correlated two-pion-exchange in the scalar–isoscalar channel has been treated in terms of a chiral unitary approach which has revealed to reproduce $\pi\pi$ scattering data in the scalar sector and in which the $\sigma$-meson appears as a dynamically generated resonance. A sizable cancellation between $2\pi/\sigma$ and $2\pi/\sigma$-exchange was found for the relevant momenta ($\approx 410$ MeV) in the non-mesonic decay. Consequently, the total two-pion-exchange contribution to the decay rates turned out to be moderate but its effect on the asymmetry parameter was not evaluated.

The present Letter investigates the effects of the two-pion-exchange mechanism on the non-mesonic decay observables for s- and p-shell hypernuclei. We employ a finite nucleus approach and pay special attention to the proton asymmetry. The weak transition potentials for two-pion-exchange are adopted from Ref. [3] and are added to the exchange of the pseudoscalar and vector mesons $\pi$, $\rho$, $K$, $K^*$, $\omega$ and $\eta$, with potentials taken from Ref. [1]. Correlated two-pion-exchange in the vector–isovector channel is not considered here, since the one-meson-exchange potential we use already includes the $\rho$-meson. We do not take into account the two-nucleon induced decay mode, $\Gamma_2 : \Lambda NN \to nNN$ [12,13,26], which can be safely neglected when evaluating the decay asymmetries [18] even if its contribution to the total non-mesonic decay rate is significant. We will see that the implementation of two-pion-exchange contributions modifies the decay widths moderately but has a tremendous influence on the decay asymmetries, bringing them to values that are in perfect agreement with the recent experimental data.

The Letter is organized as follows. The formalism employed for the calculation of decay rates and asymmetries is outlined in Section 2. Numerical results for these observables are presented and compared with data in Section 3. Finally, in Section 4 we draw our conclusions.

2. Formalism

The rate associated to a neutron (proton) stimulated decay can be evaluated by the following average:

$$\Gamma_{n(p)} = \frac{1}{2 J} \sum_{M_J} \sigma_{n(p)}(J, M_J),$$

in terms of the intensities $\sigma_{n(p)}(J, M_J)$ of neutrons (protons) emitted along the quantization axis in the non-mesonic decay of a hypernucleus with third component $M_J$ of the total spin $J$. Following the standard nuclear structure techniques described in Ref. [1], the nucleon intensities are written in terms of twobody amplitudes describing the transition from an initial $\Lambda N$ state to a final $NN$ state. This transition is mediated by a weak transition potential, $V_{\sigma,\tau}(R)$, which depends on the relative coordinate between the interacting $\Lambda$ and nucleon, $r$, and their spin, $\sigma$, and isospin, $\tau$, variables.

The wave function describing the relative motion of the two nucleons under the influence of a suitable $NN$ interaction is obtained from the Lippmann–Schwinger equation. For the initial $\Lambda N$ system we start from single particle harmonic oscillator wave functions, with oscillator parameters that have been adjusted to reproduce the $\Lambda$ separation energy in the hypernucleus under consideration and the charge form factor for the corresponding nuclear core. The corresponding correlated $\Lambda N$ wave function is obtained by multiplying a correlation function that as been adjusted to microscopic G-matrix calculations in nuclear matter. For the baryon–baryon strong interactions we take the Nijmegen soft-core model, version NSC97f [27], which has been used with success in hypernuclear structure calculations as well as in the decay of hypernuclei.

The weak transition potential is built from the exchange of virtual mesons belonging to the ground state pseudoscalar and vector octets, $\pi$, $\eta$, $K$, $\rho$, $\omega$, $K^*$. [1]. In the present work we complement this one-meson-exchange (OME) potential with the contributions of uncorrelated $(2\pi/\sigma)$ and correlated $(2\pi/\sigma)$ two-pion-exchange taken from Ref. [3]. The scheme was built originally for the nucleon–nucleon interaction, leading to a $2\pi/\sigma$-exchange potential with a moderate attraction at $r \gtrsim 0.9$ fm and a repulsion at shorter distances [28], in contrast with the attraction at all distances of the standard phenomenological $\sigma$-meson exchange. Once the uncorrelated and correlated
two-pion-exchange are added together, an attractive nucleon–nucleon potential is obtained for all distances. Applying an appropriate conversion factor that replaces a strong $\pi NN$ vertex with the weak $\pi \Lambda N$ one, the potential was implemented in the study of the weak decay of hypernuclei \[3\]. The relevant diagrams for uncorrelated and correlated two-pion-exchange with intermediate $N$ and $\Delta$ states built in Ref. \[3\] are depicted in Fig. 1. Two-nucleon intermediate states are not considered in the uncorrelated (direct and crossed) diagrams in order to avoid double counting, while diagrams containing intermediate $\Sigma$ and $\Sigma^*$ baryons are not included since their individual contributions were found to approximately cancel each other. In addition, in the range of momenta relevant for the non-mesonic weak decay, it was found that the results from the uncorrelated two-pion diagrams with intermediate $\Delta N$ and $\Delta\Delta$ states are largely dominated by the isoscalar piece, which is the only one retained in their final results. As for the $2\pi/\sigma$ correlated contribution, the box in Fig. 1 contains the pion–pion scattering $t$-matrix summed up to all orders in the unitary approach. We also note that the complete scalar–isoscalar two-pion-exchange potential given in Ref. \[3\] is of pure parity-conserving nature. The reason is that the parity-violating contribution is strongly reduced by the lack of direct coupling of the $\Lambda$ to $\Delta$ intermediate states.

We have also neglected the possible contributions coming from $KK$ and $\pi K$ exchange, following the work of Ref. \[29\] that finds small contributions of these mechanisms to the strong scalar–isoscalar $\Lambda N$ and $\Lambda\Lambda$ strong interactions.

The study of polarized hypernuclei provides us with new and complementary phenomenological insights on the weak hyperon–nucleon interaction. The asymmetric angular emission of protons originates from the interference among parity-conserving (PC) and parity-violating (PV) $\Lambda p \to np$ transition amplitudes, whereas the decay widths $\Gamma_p$ and $\Gamma_p$ are the result of the incoherent sum of PC and PV amplitudes squared. While investigations of the decay rates basically serve to clarify the isospin structure of the non-mesonic transitions, asymmetry studies allow us to extract significant information on the strength and the relative phases of the different decay amplitudes.

Neglecting for the moment nucleon final state interactions, the intensity of protons from $\Lambda p \to np$ decays emitted along a direction forming an angle $\theta$ with respect to the hypernuclear spin-polarization axis is \[30\]:

$$ I(\theta, J) = I_0(J)[1 + A(\theta, J)] $$

where $J$ is the hypernuclear total spin, $I_0$ the isotropic intensity for an unpolarized hypernucleus, $I_0 \equiv \Gamma_p$, $P_\gamma$ the hypernuclear polarization, which depends on the kinematics and dynamics of the hypernuclear production reaction, and $A(\theta)$ the hypernuclear asymmetry parameter:

$$ A(\theta) = \frac{3}{J + 1} \sum_{M_J} M_J \sigma_p(J, M_J) $$

The shell model weak-coupling scheme, in which the $1s_{1/2}$ $\Lambda$ is assumed to be coupled to the nuclear core ground state with total spin $J_c$, allows rewriting the asymmetry $A$ in terms of the polarization of the hyperon spin, $p_\Lambda$, and the corresponding intrinsic $A$ asymmetry parameter, $a_\Lambda$, such that:

$$ A(\theta, J) = p_\Lambda(J) a_\Lambda \cos \theta $$

In this way, $a_\Lambda$ can be interpreted as being an intrinsic attribute of the elementary $\Lambda p \to np$ process, in which case it should be practically independent of the decaying hypernucleus. Several calculations \[1,4,12,13,18–20,22,30\] have indeed demonstrated that this asymmetry shows only a moderate dependence on the hypernuclear structure.

Nucleon final state interactions strongly modify the weak decay intensity and the experimentally accessible quantity is an observable proton intensity of the form \[18\]:

$$ I^M(\theta, J) = I_0^M(J)[1 + p_\Lambda(J) a_\Lambda^M(J) \cos \theta] $$

The corresponding observable asymmetry is thus obtained from the measured or calculated intensity as:

$$ a_\Lambda^M(J) = \frac{1}{p_\Lambda(J)} \frac{I^M(0^\circ, J) - I^M(180^\circ, J)}{I^M(0^\circ, J) + I^M(180^\circ, J)} $$

and in general depends on the considered hypernucleus and on experimental conditions such as the adopted proton detection threshold. From Eqs. \(2\), \(4\) and \(6\) it is evident that to determine experimentally $a_\Lambda^M$, a measurement of the hypernuclear polarization $P_\gamma$ is required. Such a measurement has been possible for $^4$He \[15\], but only theoretical evaluations of $P_\gamma$ are available for $p$-shell hypernuclei \[14,16,17\].

The relation between intrinsic and observable asymmetries has been investigated for the first time in Ref. \[18\], where the Monte Carlo intranuclear cascade model of Ref. \[31\] has been used to account for nucleon final state interactions.
The non-mesonic weak decay rates (in units of the free $A$ decay width) and intrinsic asymmetry parameters predicted for $^{5}_A$He and $^{12}_A$C are compared with recent data. See text for details.

<table>
<thead>
<tr>
<th>$^{5}_A$He</th>
<th>$^{12}_A$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>$\Gamma_n$</td>
</tr>
<tr>
<td>OME</td>
<td>0.122</td>
</tr>
<tr>
<td>$\pi$</td>
<td>0.040</td>
</tr>
<tr>
<td>$\pi + K$</td>
<td>0.097</td>
</tr>
<tr>
<td>$\pi + K + 2\pi$</td>
<td>0.121</td>
</tr>
<tr>
<td>$\pi + K + 2\pi + 2\pi/\sigma$</td>
<td>0.111</td>
</tr>
<tr>
<td>OME + $2\pi + 2\pi/\sigma$</td>
<td>0.114</td>
</tr>
<tr>
<td>KEK-E508 [9,10,16]</td>
<td>0.424 ± 0.024</td>
</tr>
<tr>
<td>KEK-E462 [17]</td>
<td></td>
</tr>
<tr>
<td>KEK-E462 [10] (analysis of [6])</td>
<td></td>
</tr>
<tr>
<td>KEK-E508 [9,11,16]</td>
<td>0.26 ± 0.11 (1N + 2N)</td>
</tr>
<tr>
<td>OME</td>
<td>0.175</td>
</tr>
<tr>
<td>$\pi$</td>
<td>0.066</td>
</tr>
<tr>
<td>$\pi + K$</td>
<td>0.134</td>
</tr>
<tr>
<td>$\pi + K + 2\pi$</td>
<td>0.195</td>
</tr>
<tr>
<td>$\pi + K + 2\pi + 2\pi/\sigma$</td>
<td>0.182</td>
</tr>
<tr>
<td>OME + $2\pi + 2\pi/\sigma$</td>
<td>0.194</td>
</tr>
<tr>
<td>KEK-E508 [9,11,16]</td>
<td>0.940 ± 0.035</td>
</tr>
<tr>
<td>KEK-E508 [17]</td>
<td></td>
</tr>
<tr>
<td>KEK-E508 [11] (analysis of [6])</td>
<td>0.38 ± 0.14 (1N)</td>
</tr>
<tr>
<td>KEK-E307 [33]</td>
<td>0.828 ± 0.056 ± 0.066</td>
</tr>
</tbody>
</table>

### 3. Results

The weak decay observables predicted for $^{5}_A$He and $^{12}_A$C are compared with recent data obtained at KEK in Table 1. Concerning the ratio $\Gamma_n/\Gamma_p$, only experimental results from nucleon–nucleon coincidence experiments [9–11] are quoted. These data should be preferred over the ones obtained from single-nucleon studies; the former are less affected by nucleon induced decays—neglected [10] or accounted for in experimental analyses—even when extracting the ratio from nucleon–nucleon coincidence observables. They have been obtained in Ref. [6] by fitting data on nucleon–nucleon spectra from Refs. [9–11]. Note that the determinations of $\Gamma_n/\Gamma_p$ by Ref. [6] are sometimes significantly smaller than the corresponding experimental results quoted in Table 1. This signals the importance of final state interactions and two-nucleon induced decays—neglected [10] or accounted for in an approximate way [11] in experimental analyses—even when extracting the ratio from nucleon–nucleon coincidence observables.

We start recalling the results of the OME model, including the exchange of the mesons belonging to the ground state pseudoscalar and vector octets. These results slightly differ from those of Ref. [4] due to the use here of numerically improved correlated $NN$ wave functions. Both the neutron-to-proton ratio and the total non-mesonic width are reasonably reproduced within the OME model, especially if one considers that non-negligible two-nucleon induced decay rates, namely $\Gamma_2/(\Gamma_n + \Gamma_p) \simeq 0.20$ for $^{5}_A$He and $\Gamma_2/(\Gamma_n + \Gamma_p) \simeq 0.25$ for $^{12}_A$C [6,32], should be taken into account as well. The values predicted for the intrinsic asymmetries are large and negative, in contrast to the small values, compatible with zero, reported by experiments.

The effects of uncorrelated ($2\pi$) and correlated ($2\pi/\sigma$) two-pion contributions are better visualized by including them, sequentially, to those of the lighter mesons ($\pi$ and $K$). As it is well known, the dominant tensor component in the one-pion-exchange mechanism disfavors neutron-stimulated decays and produces very small $\Gamma_n/\Gamma_p$ values. The addition of kaon-exchange reduces $\Gamma_{NM}$ by about 40% while increasing $\Gamma_n/\Gamma_p$ to values compatible with data. This result is also well known, being mainly due to (i) the enhancement of the parity-violating $AN(3S_1) \rightarrow nN(3P_1)$ transition contributing especially to neutron-induced decays and (ii) the reduction of the tensor component, which for kaon-exchange has opposite sign of the one for pion-exchange. The size of the asymmetry is doubled and practically reaches the large value of the OME model. In fact, for all observables, the pion-plus kaon-exchange contributions already constitute a large fraction of the OME result.

As expected from the size of their respective potentials, see Fig. 14 of Ref. [3], the uncorrelated two-pion-exchange mechanism has a much larger influence than the correlated one. We observe that the $2\pi$ contribution increases $\Gamma_p$ substantially and $\Gamma_n$ more moderately, hence giving rise to a decrease of
Table 2

Hypernuclear amplitudes and interference terms in the proton-induced decay of $^3\Lambda$He

<table>
<thead>
<tr>
<th>Transition</th>
<th>OME</th>
<th>OME + $2\pi + 2\pi/\sigma$</th>
<th>OME</th>
<th>OME + $2\pi + 2\pi/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A: ^1S_0 \rightarrow ^1S_0$</td>
<td>$-0.1044$</td>
<td>$+0.0835$</td>
<td>$A_E$</td>
<td>$-0.2854$</td>
</tr>
<tr>
<td>$B: ^3S_1 \rightarrow ^3P_0$</td>
<td>$+0.0057$</td>
<td>$+0.0057$</td>
<td>$B_C$</td>
<td>$+0.0027$</td>
</tr>
<tr>
<td>$C: ^3S_1 \rightarrow ^3S_1$</td>
<td>$-0.1399$</td>
<td>$+0.1480$</td>
<td>$B_D$</td>
<td>$-0.0029$</td>
</tr>
<tr>
<td>$D: ^3S_1 \rightarrow ^3D_1$</td>
<td>$-0.1814$</td>
<td>$-0.1814$</td>
<td>$C_F$</td>
<td>$-0.0856$</td>
</tr>
<tr>
<td>$E: ^3S_1 \rightarrow ^3P_1$</td>
<td>$+0.3833$</td>
<td>$+0.3833$</td>
<td>$D_F$</td>
<td>$-0.2186$</td>
</tr>
<tr>
<td>$F: ^3S_1 \rightarrow ^3P_1$</td>
<td>$+0.2234$</td>
<td>$+0.2234$</td>
<td>$a_A$</td>
<td>$-0.590$</td>
</tr>
</tbody>
</table>

$\Gamma_p = \sum_{\alpha=a,F} |a|^2$

0.257 0.275

the $\Gamma_p/\Gamma_p$ ratio with respect to the $\pi + K$ result, while the correlated $2\pi/\sigma$ contribution affects the partial rates mildly.

The most spectacular change induced by the uncorrelated two-pion mechanism is seen in the asymmetry parameter, which turns from being large and negative to being small and positive. Incorporating the $2\pi/\sigma$ mechanism brings some additional changes, basically tempering out the above mentioned effects.

The remaining heavier mesons produce very moderate changes in the decay widths, while the asymmetry parameter, being built from interferences, shows a much stronger sensitivity. In short, the incorporation of the scalar–isoscalar two-pion exchange terms to the OME model leaves the rates basically unaltered, while reducing substantially the absolute value of the intrinsic asymmetry in such a way that the predictions for all weak decay observables are in excellent agreement with the measured values. We note, however, that a proper comparison with the observed asymmetries requires to account for the final state interactions of the weak decay nucleons as they go out of the residual nucleus [18], as we will do later.

Let us first analyze the effect of the isoscalar–scalar mechanism on the various transition amplitudes and the corresponding influence on the final value of the asymmetry. By applying appropriate projection operators to the elementary $AN \rightarrow nN$ potential, it is possible to select, from the hypernuclear transition amplitude, the contributions coming from specific spin-space transitions, $2S+1L_J \rightarrow 2S+1L_J'$. For $\Lambda$He, the resulting amplitudes are denoted by the capital letters $A, B, C, D, E, F$ in complete analogy with the notation $a, b, c, d, e, f$ used for the same amplitudes in the two-body case. In order to disentangle the contributions to the asymmetry coming from the various interferences, we also perform calculations for specific pairs of transitions, which will be denoted as $A_E, B_C, B_D, C_F$ and $D_F$. Table 2 shows the size of each proton-induced decay amplitude, including its sign, for the OME and OME + $2\pi + 2\pi/\sigma$ models. The sum of the modulus squared of these amplitudes builds up the corresponding value of $\Gamma_p$. The contribution to the asymmetry of all possible interferences between pairs of amplitudes is also shown. The sum of all these interferences produces the final result for the intrinsic asymmetry.

Except for the negligible $B(1S_0 \rightarrow 3P_0)$ amplitude, the other ones turn out to be of relevance in the determination of the proton decay asymmetry. In the case of the OME model, the parity-conserving amplitudes ($A, C$ and $D$) are negative, and the parity-violating ones ($B, E$ and $F$) positive. The larger contributions to the asymmetry turn out to be negative and correspond to the interferences $AE, DF$ and $CF$. The two-pion scalar–isoscalar mechanism affects the parity conserving amplitudes which are diagonal in $S$ and $L$, namely $A$ and $C$. As we see, they even change their sign which, in turn, transform the negative interferences $AE$ and $CF$ into positive contributions that largely cancel the negative $DF$ one. The small reduction in magnitude of the $BD$ and $DF$ contributions to the asymmetry is just a reflection of the slight increase of the $\Gamma_p$ rate. With the above mentioned sign changes, the asymmetry of $\Lambda$He turns from being large and negative in the OME model to being slightly positive in the OME plus chiral $2\pi + 2\pi/\sigma$ model, in perfect agreement with the experimental observations.

In contrast to previous phenomenological models which include the exchange of correlated pions [5,23,24] or $\sigma$-meson exchange [21,22], the two-pion scalar–isoscalar contributions considered in the present work are theoretically well grounded in the sense that all the coupling constants are determined from chiral meson–meson and meson–baryon Lagrangians and by imposing SU(3) symmetry. Having such different origin, it becomes difficult to perform a comparative analysis with those phenomenological models and we just mention the relevant differences. The authors of Ref. [24] found that to reproduce the small and positive experimental value of $a_A(\Lambda)$, their $2\pi/\sigma$ potential [23] is too strong and must be decreased to half of its calculated value, hence producing an important reduction of the amplitude $A$. This in turn reduces the negative $AE$ term and the asymmetry gets dominated by their positive $F(C + D)$ term. It becomes then clear that the positive asymmetry in Ref. [24] is obtained with a completely different behavior of amplitudes than what is found in the present work. The one-pion plus one-kaon exchange model of Ref. [21] is modified by a $\sigma$-exchange contribution. It is found that the measured values of $\Gamma_{NM}$ and $\Gamma_p/\Gamma_p$ in $^3\Lambda$He would be reproduced with a small value for the parity-violating coupling constant ($B_\sigma \sim 1$) and a large value of the parity-conserving one ($A_\sigma \sim 4$), but the asymmetry would turn positive and large, of the order of 0.6. Another reasonable fit to the rates is found with $A_\sigma \sim -1.5$, but then the asymmetry is very large and negative, close to $-1$. This work concludes that the additional inclusion of the direct quark mechanism permits finding a solution that reproduces both the partial rates and the asymmetry, in which case the values $A_\sigma \sim 4$ and $B_\sigma \sim 6.6$ are found. Qualitatively similar results are obtained in Ref. [22] in the sense that their $\sigma$-exchange potential added to the full OME exchange model can fit $\Gamma_{NM}$ and $\Gamma_p/\Gamma_p$ but not the asymmetry. However, their solutions are
intrinsicly very different, since the PV strength of the $\sigma$ meson is dominant in Ref. [22] ($B_\sigma/A_\sigma \sim 10$–20) while the PC and PV $\sigma$ amplitudes are of comparable strength in Ref. [21]. It is again clear that the phenomenological $\sigma$-exchange potential is radically different from the two-pion mechanism considered in the present work, which has a purely PC nature. We have analyzed how the incorporation of a PV term would affect the value of the asymmetry parameter. Our numerical simulations reveal that the effect of including a PV term that changes the $\sigma$-exchange rate by less that 10% (an upper bound to the negligible contribution quoted Ref. [3]) may affect the asymmetry more pronouncedly, from $-0.1$ to $0.2$ in $^4$He and from $-0.05$ to $-0.35$ in $^{12}$C. Nevertheless, these values are still compatible with experimental data.

Finally, we present in Table 3 our results for the asymmetry after incorporating the effects of final state interactions (FSI) for different cuts on the kinetic energy of the emitted nucleons. These results are then directly comparable with the observed asymmetries. We show predictions for three hypernuclei and for the OME and OME $+ 2\pi + 2\pi/\sigma$ models. We observe that, as in our OME study of Ref. [18], the incorporation of FSI reduces the magnitude of the observable asymmetry with respect to the intrinsic asymmetry and that, as the kinetic energy cut is increased, $a_A^{th}$ tends to recover the value of $a_A$. The results of Table 3 show that the OME model cannot reproduce the measured values of the asymmetries, while the additional incorporation of the $2\pi + 2\pi/\sigma$ mechanism provides asymmetry results in complete agreement with the data for all hypernuclei, which correspond to $T_p \sim 30$ MeV.

4. Conclusions

We have studied the non-mesonic weak decay of hypernuclei within a one-meson-exchange model supplemented with the contributions of the uncorrelated $(2\pi)$ and correlated $(2\pi/\sigma)$ two-pion-exchange mechanisms. These last mechanisms are based on a chiral unitary model which describes $\pi\pi$ scattering data up to around 1 GeV and are taken from Ref. [3]. Our finite nucleus approach includes realistic strong correlations both in the initial and final states and considers the final state collisions of the nucleons in their way out of the residual nucleus.

We have found that the two-pion-exchange mechanisms modify moderately the partial decay rates but have a tremendous influence on the asymmetry parameter, due to the change of sign of some relevant amplitudes. The one-meson-exchange plus two-pion-exchange model turns out to be able to reproduce satisfactory, not only the total and partial hypernuclear weak decay rates, but also the asymmetries observed in the angular distribution of protons emitted by polarized hypernuclei.

Recent studies on the validity of the $\Delta I = 1/2$ isospin rule in the non-mesonic decay [21,34–36] have been of large interest, especially due to their connections with the determination of $T_\sigma$ and the asymmetry parameter. Although this kind of studies should be warmly supported, our results, based on pure $\Delta I = 1/2 \Lambda N \rightarrow nN$ transitions, would leave little room for $\Delta I = 3/2$ contributions. Certainly, a clearer answer to this question will come from accurate measurements of four-body hypernuclear decays.

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