Behaviour of the Potentials due to Strangeness degree of freedom in ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$H* Hypernuclei

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Introduction

Strangeness degree of freedom can be experimentally implanted into a bound nucleus forming a composite system of nucleons and hyperons. Strangeness degree of freedom when injected to a bound nucleus may induce several dynamical changes in the nuclear structure such as shape, size, density profile, nuclear core polarization etc. The hypernuclei containing one or more quanta of hyperons plays an important role in our understanding of the hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions which is otherwise very difficult. The hypernuclear systems as a finite nucleus and also infinite body systems as hyperon stars provide a unique opportunity to enhance our knowledge about the role of strangeness in a nuclear medium of different densities. Since YN scattering data are scarce, therefore, it is imperative to perform hypernuclear structure calculations to extract useful information about YN and YY interactions. Few-body calculations of light hypernuclei are essentially important not only to explore their binding energies but also to know more about the -nuclear interactions, particularly on their spin dependence. In continuation with earlier studies of ${}^{5}_{\Lambda}$He and ${}^{6}_{\Lambda\Lambda}$He hypernuclei [1, 2], we investigate the effect of the strange-sector potential strengths on the energy breakdown and present a clear understanding of their interplay for both 0^+ and 1^+ states of the ${}^{4}_{\Lambda}$H hypernucleus.

Hamiltonian and Wave Function

The Hamiltonian H of a hypernucleus with $A-1$ baryon and a Λ baryon can be written as

$$H = H_{NC} + H_{\Lambda}, \quad (1)$$

where, H_{NC} is the non-strange nuclear core Hamiltonian,

$$H_{NC} = T_{NC} + \sum_{i<j}^{A-1} v_{ij} + \sum_{i<j<k}^{A-1} v_{ijk}, \quad (2)$$

and H_{Λ} is the Hamiltonian due to the presence of Λ-baryon,

$$H_{\Lambda} = T_{\Lambda} + \sum_{i=1}^{A-1} v_{\Lambda i} + \sum_{i<j}^{A-1} v_{\Lambda ij} \quad (3)$$

The basic ingredients in these Hamiltonians are two- and three-body NN and YN forces. For non-strange sector, we use well-established Argonne v18 potential [3] and Urbana IX (UIX) three-body potential [4] which successfully explain the nuclear energy spectra. For strange sector, we use a ΛN two-pion exchange potential [5] with spin and space-exchange component along with a three-body two-pion exchange interaction [6] with strongly dispersive ΛNN interactions [7].

The charge symmetric potential ΛN including spin-spin component is written in the form

$$v_0(r)(1-\varepsilon+\varepsilon P_x) + \frac{v_\sigma}{4} T_\pi^2(r)\boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N \quad (4)$$

The first term is a sum of direct potential ($v_0(r) = v_c(r) - v_{2\pi}(r)$) and space-exchange potential ($\varepsilon v_0(r)(P_x - 1)$), where, ε determines the odd-state potential, which is the strength of the space-exchange potential relative to the direct potential and $v_{2\pi} = \overline{v} T_\pi^2(m_\pi r)$ is the two-pion attractive potential. The terms $\bar{v} = (v_s + 3v_t)/4$ and $v_\sigma = v_s - v_t$ are, respectively, the spin-average and spin-dependent strengths, with $v_{s(t)}$ the singlet(triplet) state depths.

The ΛNN potential arises due to projecting out Σ, Δ, etc., degrees of freedom from a coupled channel formalism and written as a sum of two terms, $V_{\Lambda ij} = V^D_{\Lambda ij} + V^{2\pi}_{\Lambda ij}$, as shown in Fig. 1. The dispersive potential $V^D_{\Lambda ij}$, arising from the suppression mechanism owing to $\Lambda N - \Sigma N$ coupling [8], is written as

$$V^D_{\Lambda ij} = W^D T_\pi^2(m_\pi r_{\Lambda i}) T_\pi^2(m_\pi r_{\Lambda j})[1 + \boldsymbol{\sigma}_\Lambda \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)/6]. \quad (5)$$

where, W^D is the repulsive potential strength. The $V^{2\pi}_{\Lambda ij}$ is a two-pion exchange attractive potential and is written as a sum of two terms representing p- and s-wave $\pi - N$ scattering, $V^{2\pi}_{\Lambda ij} = V^P_{\Lambda ij} + V^S_{\Lambda ij}$ as in Ref. [6]. The explicit form of these potentials are

$$V^P_{\Lambda ij} = -\left(C^P/6\right)(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)\{X_{i\Lambda}, X_{\Lambda j}\}, \quad (6)$$

and

$$V^S_{\Lambda ij} = C^S Z(m_\pi r_{i\Lambda}) Z(m_\pi r_{j\Lambda}) \boldsymbol{\sigma}_i \cdot \hat{\mathbf{r}}_{i\Lambda} \boldsymbol{\sigma}_j \cdot \hat{\mathbf{r}}_{j\Lambda} \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \equiv C^S O^S_{\Lambda ij} \quad (7)$$

where, C^P and the C^S are the attractive potential strengths of $V^P_{\Lambda ij}$ and $V^S_{\Lambda ij}$, respectively.

The Wave Function WF of a single-Λ hypernucleus with all dynamical correlations that have any significant

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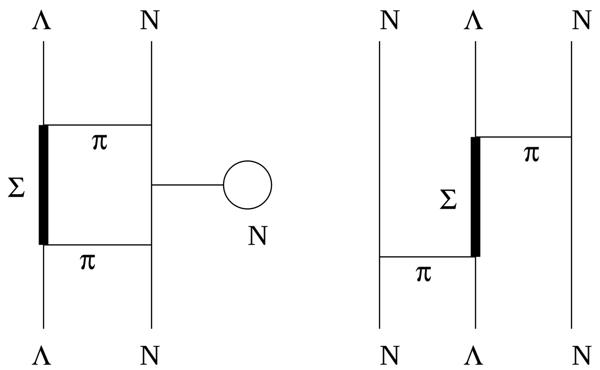

FIG. 1: Diagram representing $V^D_{\Lambda NN}$ and $V^{2\pi}_{\Lambda NN}$.

contribution to total energy may be written as

$$
\begin{aligned}
|\Psi\rangle &= \left[1+U^3+\sum_{i<j}^{A-1} U^{LS}_{ij}\right]\left[\prod_{j=1}^{A-1}(1+u^{\sigma}_{\Lambda j})\right]\left[\prod_{i<j}^{A-1}(1+U_{ij})\right]\Psi_J \\
&+ \eta\sum_{n=1}^{A-1}[1+U^3]\left[S\prod_{i<j}^{A-1}(1+U_{ij})\right]u^x_{\Lambda n}P_x\Psi_J \qquad (8)
\end{aligned}
$$

The detailed discussion about the WF can be found in Ref [1].

Results and Discussions.

In order to know the role of strange sector potential strengths and the various sensitivities among them, we perform variational Monte Carlo study to obtain the ground-state energy of the ${}^4_\Lambda$H hypernucleus. We begin our study by choosing the values of $\bar{v}$=6.15 and ε=0.1. The strength of C^P and C^S is fixed at 1.00 MeV and 1.5 MeV respectively, and then W^D is adjusted to a suitable value to reproduce experimental binding energy: 2.22(MeV), which is the average of ${}^4_\Lambda$H and ${}^4_\Lambda$He mirror hypernuclei. We use three different sets of v_s and v_t with a constant value of v_σ as given in Table I. For each value of $\bar{v}$, we use three values of ε: 0.1, 0.2 and 0.3. Due to strong suppression of S-wave ΛNN potential similar to its counterpart S-wave NNN potential and weak spin part of the ΛN potential for the spin-zero core nuclei, the effect of the variations in C^S and v_σ is negligible. Thus, the strengths which matter for this study are $\bar{v}$, ε, C^P and W^D. To investigate the effect of the these strength of the strange-sector potentials on energy breakdown and their interplay, we change the value of attractive potential strength C^P from 0.5 MeV to 2.0 MeV for all three sets of $\bar{v}$ and ε. As these potential strengths are directly related to the expectation values of operators in the Hamiltonian and also to the correlation functions in the WF. Hence, a change in any of the strengths of these potential strengths may lead to appreciable change in the energy breakdown and also in the ground state energy, therefore we adjust W^D to a suitable value that reproduces B_Λ. The strengths of the C^P and W^D that reproduce the experimental B_Λ along with the various sets of $\bar{v}$ and ε is presented in Fig 2. Similar are the results for the 1^+ state or for ${}^4_\Lambda$H* hypernucleus. The study has established the value of parameters appearing in the two- and three-body potentials in the strange sector. We can understand the role of the strange-sector potentials and their interplay for ${}^4_\Lambda$H and ${}^4_\Lambda$H* hypernuclear systems from Fig 2. Furthermore, the range of the parameters of strange sector potential is now, at least roughly, known.

TABLE I: The ΛN strengths in units of MeV.

v_s	v_t	$\bar{v} = (v_s + 3v_t)/4$	$v_\sigma = v_s - v_t$
6.33	6.09	6.15	0.24
6.28	6.04	6.10	0.24
6.23	5.99	6.05	0.24

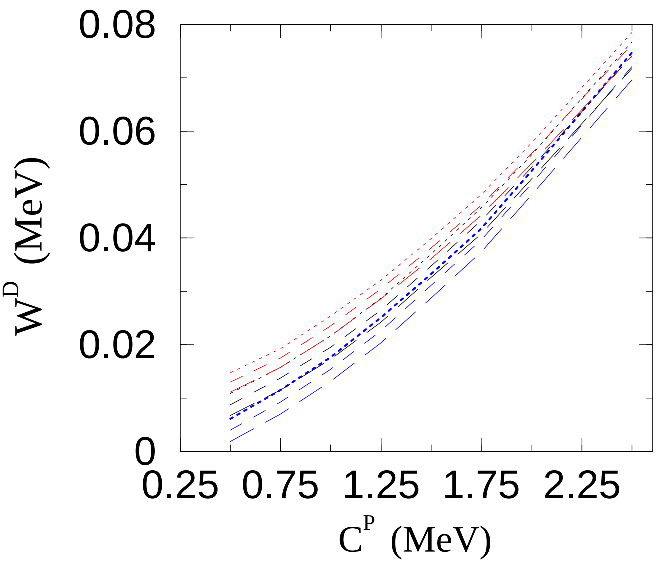

FIG. 2: Curves show the set of strengths giving B^{exp}_Λ. The dotted, dashed and long dashed lines represent ε=0.1, 0.2 and 0.3, and the red, black and blue colors represent $\overline{v}1$, $\overline{v}2$ and $\overline{v}3$, respectively.

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