Properties of deformed Λ hypernuclei*

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Abstract The properties of Be and B isotopes and the corresponding Λ hypernuclei are studied by using a deformed Skyrme Hartree-Fock approach with realistic nucleonic Skyrme forces, pairing correlations, and a microscopically determined lambda-nucleon interaction based on Brueckner-Hartree-Fock calculations of hypernuclear matter. The results suggest that the core nuclei and the corresponding hypernuclei have similar deformations with the same sign.

Key words deformed Λ hypernuclei, Skyrme Hartree-Fock

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1 Introduction

The study of hypernuclei is crucial to provide the information about hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions. Currently there are many experimental data for various single-Λ hypernuclei over almost the whole mass table[1] and a few double-Λ hypernuclei. Many theoretical calculations of hypernuclei were based on spherical symmetry, except some attempts of deformed Hartree-Fock (HF) calculations with nonrealistic interactions[2] and the Nilsson model study of *p*-shell nuclei in Ref. [3]. However, it is well known that many *p*-shell and *d*-shell nuclei are deformed in the ground state. For example, according to experiment, ^{10}B and ^{11}C have large quadrupole moments[4]. So far there is no study of a self-consistent model treating the core and the hypernuclei with realistic effective interactions for both nucleon-nucleon and ΛN channels.

The aim of this paper is to investigate how much the observables of hypernuclei depend on the deformation in a self-consistent deformed SHF (DSHF) model including the hyperon degree of freedom (hereafter we call this model the extended DSHF model). As an example, we study first the well-deformed Be and B isotopes and the corresponding Λ hypernuclei. The DSHF method has been used to describe the properties of light and medium-heavy normal nuclei in Ref. [5] and is extended in this paper to the study of hypernuclei. For this purpose we generalize the microscopic ΛN force developed in Refs. [6, 7] for nearly symmetric nuclei to isospin asymmetric nuclei. This effective ΛN interaction is derived from Brueckner-Hartree-Fock (BHF) calculations of isospin-asymmetric hypernuclear matter[8] with the Nijmegen soft-core hyperon-nucleon potential NSC89 and the Argonne V_{18} nucleon-nucleon interaction, including explicitly the coupling of the lambda-nucleon to the sigma-nucleon states.

This paper is organized as follows. In Section 2 we briefly introduce the extended DSHF model including an effective hyperon-nucleon interaction derived from microscopic BHF calculations of asymmetric nuclear matter. The calculated results of DSHF for core nuclei and extended DSHF for hypernuclei with one or two Λ are given in Section 3. Finally, a summary is given in Section 4.

2 Extended deformed Skyrme Hartree-Fock

We extend the self-consistent DSHF method solved in coordinate space with axially symmetric shape[9], including the ΛN interaction. Namely, we

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solve the SHF Schrödinger equation

$$\left[-\nabla\cdot\frac{1}{2m_{\mathrm{q}}^{*}(\boldsymbol{r})}\nabla+V_{\mathrm{q}}(\boldsymbol{r})-\mathrm{i}\nabla W_{\mathrm{q}}(\boldsymbol{r})\cdot(\nabla\times\boldsymbol{\sigma})\right]\times \phi_{\mathrm{q}}^{\mathrm{i}}(\boldsymbol{r})=e_{\mathrm{q}}^{\mathrm{i}}\phi_{\mathrm{q}}^{\mathrm{i}}(\boldsymbol{r}), \tag{1}$$

where V_{q} is the Skyrme mean field of nucleons or hyperon(s) and W_{q} the nucleonic spin-orbit mean field. In Eq. (1), the extended SHF mean fields are given by

$$\begin{aligned} V_{\mathrm{q}} &= V_{\mathrm{q}}^{\mathrm{SHF}}+\frac{\partial\epsilon_{\mathrm{N}\Lambda}}{\partial\rho_{\mathrm{q}}}+\frac{\partial}{\partial\rho_{\mathrm{q}}}\left(\frac{m_\Lambda}{m_\Lambda^*}\right)\frac{\tau_\Lambda-C\rho_\Lambda^{5/3}}{2m_\Lambda}\,,\\ V_\Lambda &= \frac{\partial\epsilon_{\mathrm{N}\Lambda}}{\partial\rho_\Lambda}+\frac{\partial}{\partial\rho_\Lambda}\left(\frac{m_\Lambda}{m_\Lambda^*}\right)\frac{\tau_\Lambda-C\rho_\Lambda^{5/3}}{2m_\Lambda}-\\ &\quad\left(\frac{m_\Lambda}{m_\Lambda^*}-1\right)\frac{5}{3}\frac{C\rho_\Lambda^{2/3}}{2m_\Lambda}\,, \end{aligned} \tag{2}$$

where $V_{\mathrm{q}}^{\mathrm{SHF}}$ $(\mathrm{q}=\mathrm{n,p})$ is the nucleonic Skyrme mean field without hyperons and

$$\begin{aligned} \epsilon_{N\Lambda} \approx & -\Big[368-(1717+268\alpha-920\alpha^2)\rho_{\mathrm{N}}-\\ &(2932-776\alpha+2483\alpha^2)\rho_{\mathrm{N}}^2\Big]\rho_{\mathrm{N}}\rho_\Lambda+\\ &\Big[449-2470\rho_{\mathrm{N}}+5834\rho_{\mathrm{N}}^2\Big]\rho_{\mathrm{N}}\rho_\Lambda^{5/3}\,, \end{aligned} \tag{3}$$

$$\begin{aligned} \frac{m_\Lambda^*}{m_\Lambda} \approx 1- & \\ &\Big[1.58+0.12\alpha-0.12\alpha^2+0.54y-0.14y^2\Big]\rho_{\mathrm{N}}+\\ &\Big[4.11+2.11\alpha+2.88\alpha^2+0.35y+1.17y^2\Big]\rho_{\mathrm{N}}^2-\\ &\Big[4.03+7.08\alpha+5.18\alpha^2-0.93y+3.27y^2\Big]\rho_{\mathrm{N}}^3\,, \end{aligned} \tag{4}$$

with $\rho_{\mathrm{N}}=\rho_{\mathrm{n}}+\rho_{\mathrm{p}}$, $\alpha=(\rho_{\mathrm{n}}-\rho_{\mathrm{p}})/\rho_{\mathrm{N}}$, and $y=\rho_\Lambda/\rho_{\mathrm{N}}$. For more details about the above equations, please refer to Ref. [10].

We take into account pairing interactions of nucleons with a BCS approximation which is taken to be a density-dependent delta-force[11],

$$V_{\mathrm{q}}(\boldsymbol{r}_1,\boldsymbol{r}_2)=V_{\mathrm{q}}'\left(1-\frac{\rho_{\mathrm{N}}(r)}{\rho_0}\right)\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\,, \tag{5}$$

where $\rho_{\mathrm{N}}(r)$ is the nucleonic HF density at $\boldsymbol{r}=(\boldsymbol{r}_1+\boldsymbol{r}_2)/2$ and $\rho_0=0.16\ \mathrm{fm}^{-3}$. We use the pairing strength $V_{\mathrm{q}}'=-410\ \mathrm{MeV\,fm}^3$ for both neutrons and protons of light nuclei[12] and $V_{\mathrm{p}}'=-1146\ \mathrm{MeV}\cdot\mathrm{fm}^3$, $V_{\mathrm{n}}'=-999\ \mathrm{MeV}\cdot\mathrm{fm}^3$ for medium-mass and heavy nuclei. A smooth energy cutoff is employed in the BCS calculations[13]. In the case of an odd number of nucleons, the orbit occupied by the odd nucleon is blocked in the BCS calculations, as described in Ref. [14].

3 Results

The nucleus ^{8}Be is known to be strongly deformed due to its double-α structure. As a first step, we study the well-deformed Be and B isotopes and the corresponding Λ hypernuclei by performing the DSHF+BCS and extended DSHF+BCS calculations with SkI4 Skyrme interaction and the microscopic ΛN force.

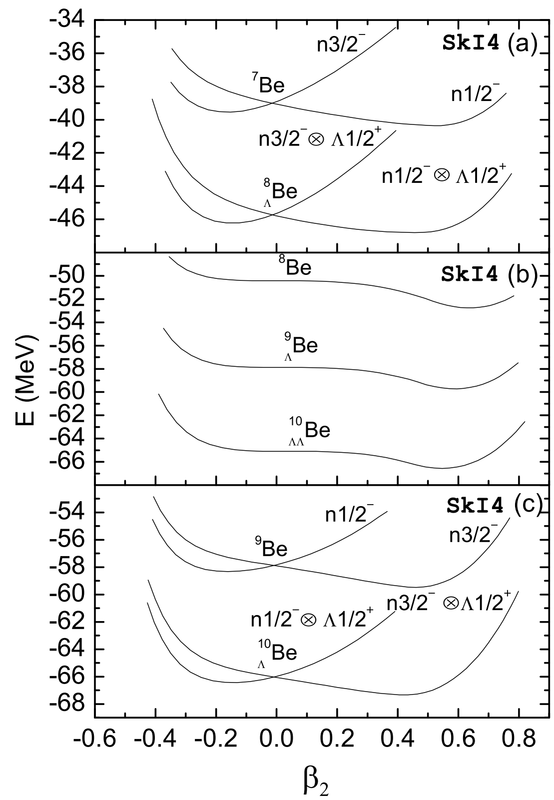

Fig. 1. Self-consistent DSHF calculations with the SkI4 interaction for (a) ^{7}Be and $^{8}_{\Lambda}$Be, (b) ^{8}Be, $^{9}_{\Lambda}$Be, and $^{10}_{\Lambda\Lambda}$Be, and (c) ^{9}Be and $^{10}_{\Lambda}$Be. The abbreviation "n" stands for the neutron configuration.

Figures. 1, 2 show the binding energy surfaces for the core nuclei ^{7,8,9}Be, ^{8,9,10}B and the corresponding hypernuclei with the SkI4 force. For ^{8}Be we got the Λ binding energy,

$$B_\Lambda=E(^{A-1}Z)-E(^{A}_{\Lambda}Z)\,, \tag{6}$$

and the ΛΛ bond energy,

$$\Delta B_{\Lambda\Lambda}=2E(^{A-1}_{\ \ \Lambda}Z)-E(^{A-2}Z)-E(_{\Lambda\Lambda}{}^{A}Z)\,, \tag{7}$$

with $B_\Lambda=6.96$ MeV and $\Delta B_{\Lambda\Lambda}=-0.12$ MeV, respectively, compared with the experimental values of $B_\Lambda=6.71\pm0.04$ MeV[15] or 5.99 ± 0.07 MeV[1], and $\Delta B_{\Lambda\Lambda} = 4.3 \pm 0.4$ MeV[16] or -4.9 ± 0.7 MeV[17]. The relativistic mean-field model of Ref. [18] predicts $\Delta B_{\Lambda\Lambda} \approx 0.3$ MeV for this nucleus. Although there are two experimental reports about the double-Λ hypernucleus ${}^{10}_{\Lambda\Lambda}$Be, more experimental events are desperately needed to confirm the data with better statistics, as discussed in Ref. [19]. In fact a recent measurement of ${}^{6}_{\Lambda\Lambda}$He shows a weakly attractive $\Delta B_{\Lambda\Lambda} \approx +1$ MeV for this nucleus[20]. We remark that the slightly repulsive bond energy is obtained because of no $\Lambda\Lambda$ interaction in our model, since the underlying NSC89 potential does not provide it. Results obtained with the NSC97 potentials including hyperon-hyperon interactions yield similarly small numbers, however[7, 21].

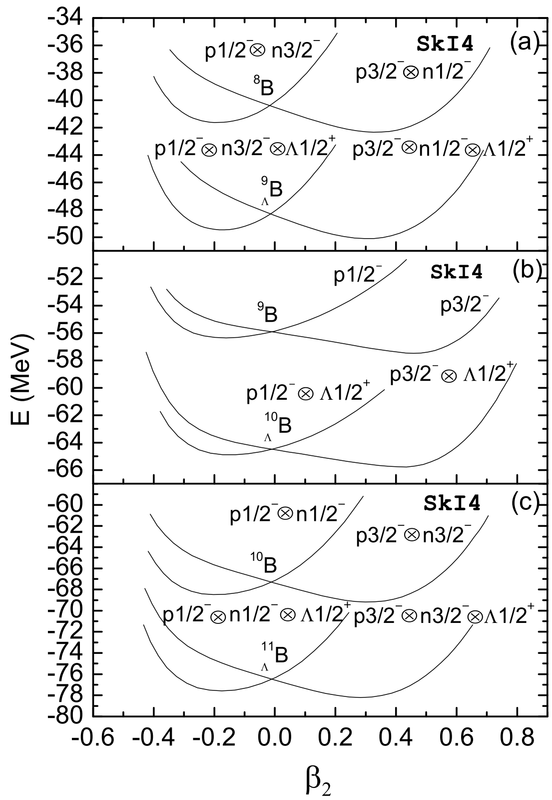

Fig. 2. Self-consistent DSHF calculations with the SkI4 interaction for (a) ^{8}B and ${}^{9}_{\Lambda}$B, (b) ^{9}B and ${}^{10}_{\Lambda}$B, and (c) ^{10}B and ${}^{11}_{\Lambda}$B. The abbreviation "p" stands for the proton configuration.

The predicted deformations of ^{8}Be, ${}^{9}_{\Lambda}$Be and ${}^{10}_{\Lambda\Lambda}$Be are very similar, namely $\beta_2 = 0.63$, $\beta_2 = 0.59$ and $\beta_2 = 0.55$, respectively. The calculations suggest that the core nucleus ^{8}Be and the ${}^{9}_{\Lambda}$Be, ${}^{10}_{\Lambda\Lambda}$Be hypernuclei have similar deformation parameters with the same sign, which agree with the results of Ref. [22]. These results also justify the assumption of the same deformations in the core and the hypernuclei made in the Nilsson model potential [3].

One notes in Fig. 1 that the ground state of ^{7}Be has the quantum number $K^{\pi} = n\frac{1}{2}^{-}$, while $K^{\pi} = n\frac{3}{2}^{-}$ for ^{9}Be. All the core nuclei ^{7,8,9}Be have large prolate deformations, especially ^{8}Be. The corresponding hypernuclei have similar shapes for the ground states. We can see the same phenomena in Fig. 2: the ground states of ^{8,9,10}B and the corresponding hypernuclei are prolate with little difference of the deformation parameter β_2. Our calculations predict that the ground states of ^{9}Be and ^{10}B are prolate, which is consistent with the experimental data of the Q-moments of these nuclei[4].

4 Summary

In summary, we studied deformations of core and hypernuclei of Be and B isotopes using an extended DSHF formalism. To this purpose we introduced the microscopic ΛN interaction of Refs. [6, 7] extended to isospin-asymmetric matter, together with nuclear pairing correlations and SkI4 Skyrme forces.

We found that the calculated large prolate deformations of the p-shell nuclei ^{9}Be and ^{10}B are confirmed by the experimental data of Q moments. The calculated core nuclei and the corresponding hypernuclei have similar deformations with the same sign, which agrees with the calculations of the α-cluster model in Ref. [22]. The obtained Λ binding energies B_{Λ} confront satisfactorily with the experimental values. A proper treatment of deformations is important in the future study of hypernuclei regarding not only the binding energies of hypernuclei B_{Λ} and $B_{\Lambda\Lambda}$, but also the other properties like the fine structure and nonmesonic decays of hypernuclei.

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