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Light exotic Λ-hypernuclei

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The structure of light proton-rich Λ-hypernuclei is addressed in the framework of the Hartree-Fock approach with effective potentials in the Skyrme form. We argue that the ${}^{9}_{\Lambda}$C hypernucleus is bound contrary to its nuclear core ^{8}C. Proton-rich boron, nitrogen and oxygen hypernucleus with unstable cores are shown to remain unbound. We check also $\Lambda\Lambda$ hypernuclei with proton-rich unstable cores.

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1. Introduction

Hypernuclei with proton or neutron excess are of particular interest now in strangeness nuclear physics. These systems loosely studied experimentally as of now can hopefully be produced in heavy ion collisions particularly at the NICA complex developed at JINR [1]. Properties of exotic hypernuclei can shed light on subtle features of the hyperon-nucleon and hyperon-nucleus interactions. A few such properties include the dependence of hyperon-nucleon forces on the nuclear density which are of great importance in the physics of neutron stars with high densities, as well as charge symmetry breaking that may have a noticeable impact on the structure of neutron-rich and proton-rich hypernuclei [2–5]. Due to the glue-like role of the Λ-hyperon, there is a chance to stabilize loosely bound nuclear systems and even get bound hypernuclei with unstable cores.

In this work we study proton-rich hypernuclei in the range $5 \le Z \le 8$ with nucleon cores beyond the proton dripline. It is known that the proton dripline for non-strange nuclei lies right beyond the bound isotopes ^{8}B, ^{9}C, ^{12}N and ^{13}O. Adding a Λ to these bound nuclei evidently produces a bound hypernucleus due to the attractive nature of hyperon-nucleon interaction. It is of interest then to study the hypernuclei $^{8}_{\Lambda}$B, $^{9}_{\Lambda}$C, $^{12}_{\Lambda}$N and $^{13}_{\Lambda}$O having unbound nucleon cores. The goal of this work is to give predictions for the position of the proton dripline on the hypernuclear chart at $5 \le Z \le 8$.

2. Skyrme-Hartree-Fock Approach for Hypernuclei

To study the stability of hypernuclei under consideration we work in the framework of the Hartree-Fock approach with phenomenological Skyrme interactions. Nucleon-nucleon (NN) [6] and hyperon-nucleon (ΛN) [7] Skyrme potentials are taken in the standard form. Various nucleon-nucleon and hyperon-nucleon Skyrme interaction parametrizations with different properties are examined in order to choose which interactions can be best used to describe the hyperon binding energy $B_\Lambda({}^A_\Lambda Z) = B({}^A_\Lambda Z) - B({}^{A-1}Z)$ in light hypernuclei.

In order to verify whether a given hypernucleus is bound with respect to 1 or 2 proton emission, the corresponding values of the separation energy need to be checked. Notably, our approach overbinds the proton-rich nuclei. Particularly, all the cores considered (^{7}B, ^{8}C, ^{11}N and ^{12}O) appear to be bound in the calculation. Therefore, we do not try to determine the proton separation energies directly. On the other hand, we rely on the calculated hyperon binding energies which are compatible with the available data with sufficient accuracy. Proton (or two proton) separation energies S_p (or S_{2p}) in hypernuclei can be calculated using the following relations:

$$S_p({}^A_\Lambda Z) = S_p({}^{A-1}Z) + B_\Lambda({}^A_\Lambda Z) - B_\Lambda({}^{A-1}_\Lambda(Z-1)), \tag{1}$$

$$S_{2p}({}^A_\Lambda Z) = S_{2p}({}^{A-1}Z) + B_\Lambda({}^A_\Lambda Z) - B_\Lambda({}^{A-2}_\Lambda(Z-2)). \tag{2}$$

Here, we emphasize that the values of $S_p({}^{A-1}Z)$ or $S_{2p}({}^{A-1}Z)$ are always taken from experiment, while B_Λ is calculated within the HF approach when there are no experimental data available.

The stability of double Λ-hypernuclei with unbound nuclear cores was also considered in this work. The description of hypernuclei with two Λ-hyperons requires the introduction of the ΛΛ-interaction [8]. The formulas for the proton (or two proton) separation energies S_p (or S_{2p}) in double-Λ hypernuclei read:

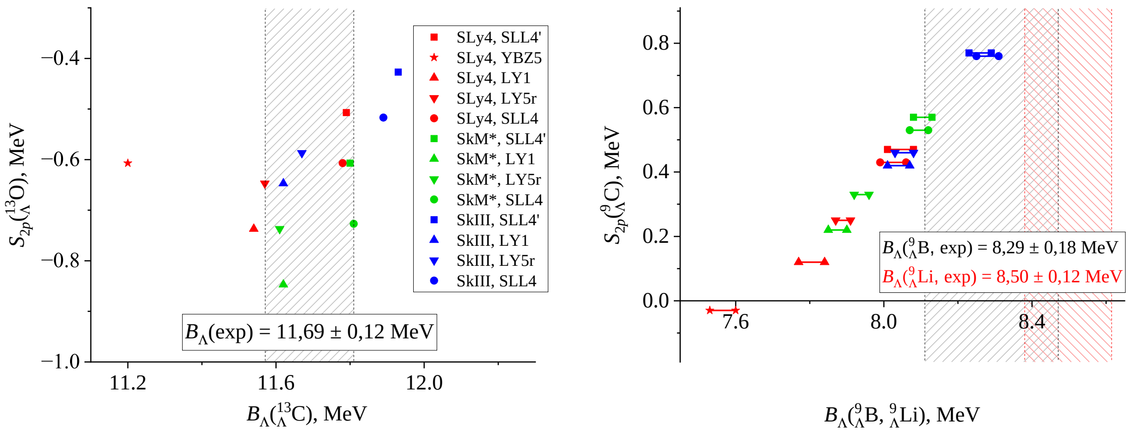

Figure 1: Two-proton separation energies of hypernuclei vs hyperon binding energies in neighbouring hypernuclei: a) $S_{2p}({}^{13}_{\Lambda}\text{O})$ vs $B_{\Lambda}({}^{13}_{\Lambda}\text{C})$, b) $S_{2p}({}^{9}_{\Lambda}\text{C})$ vs $B_{\Lambda}({}^{9}_{\Lambda}\text{B})$ and $B_{\Lambda}({}^{9}_{\Lambda}\text{Li})$. Different points show the calculations with various interaction parametrizations. The hatched areas correspond to experimental B_{Λ} in ${}^{13}_{\Lambda}\text{C}$, ${}^{9}_{\Lambda}\text{B}$ and ${}^{9}_{\Lambda}\text{Li}$. The left and right points in connected pairs on Fig. 1b depict the hyperon binding energies $B_{\Lambda}({}^{9}_{\Lambda}\text{B})$ and $B_{\Lambda}({}^{9}_{\Lambda}\text{Li})$ respectively.

$$S_p({}^{A}_{\Lambda\Lambda}Z) = S_p({}^{A-2}Z) + B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda\Lambda}({}^{A-1}_{\Lambda\Lambda}(Z-1)), \tag{3}$$

$$S_{2p}({}^{A}_{\Lambda\Lambda}Z) = S_{2p}({}^{A-2}Z) + B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda\Lambda}({}^{A-2}_{\Lambda\Lambda}(Z-2)). \tag{4}$$

Here, once again, $S_p({}^{A-2}Z)$ or $S_{2p}({}^{A-2}Z)$ are always taken from experiment, while two hyperon binding energies $B_{\Lambda\Lambda}$ are calculated.

3. Results

Our choice of the Skyrme interaction parametrizations was primarily based on whether the given interaction is able to reproduce the hyperon binding energies of hypernuclei in the studied region. NN-interaction parametrizations SLy4 [9], SkM* [10] and SIII [11] are commonly used in the literature and were found to describe nuclear properties reasonably. For the ΛN force, we mainly considered the parametrizations SLL4, SLL4' [12], LY1 [13], LY5r [14], as well as YBZ5 [15] with a different dependence of the interaction on the nuclear density. In this study, we do not take into account the charge symmetry breaking ΛN interaction.

Fig. 1a shows the calculated values of S_{2p} in the hypernucleus ${}^{13}_{\Lambda}\text{O}$. Its nucleon core ${}^{12}\text{O}$ is known to decay via emission of two protons with $S_{2p} = -1.737 \pm 0.012$ MeV [16]. Different points on the figure represent the calculations with different combinations of NN and ΛN Skyrme interactions. We plotted the S_{2p} value against the hyperon binding energy B_{Λ} in the neighbouring hypernucleus ${}^{13}_{\Lambda}\text{C}$. The comparison of our calculations to the known experimental value $B_{\Lambda} = 11.69 \pm 0.12$ MeV [17] shows that most of the interactions under consideration should indeed provide a realistic estimate for $B_{\Lambda}({}^{13}_{\Lambda}\text{C})$. Considering all of the obtained values being well below zero, we concluded that ${}^{13}_{\Lambda}\text{O}$ is unbound. In the same manner we found that the hypernuclei ${}^{8}_{\Lambda}\text{B}$ and ${}^{12}_{\Lambda}\text{N}$ are also unbound with respect to single proton emission.

The hypernucleus ${}^{9}_{\Lambda}\text{C}$ holds special interest due to its unique proton-to-neutron ratio of 3:1 that cannot be found in any other species across the nuclear or hypernuclear chart. Its nuclear

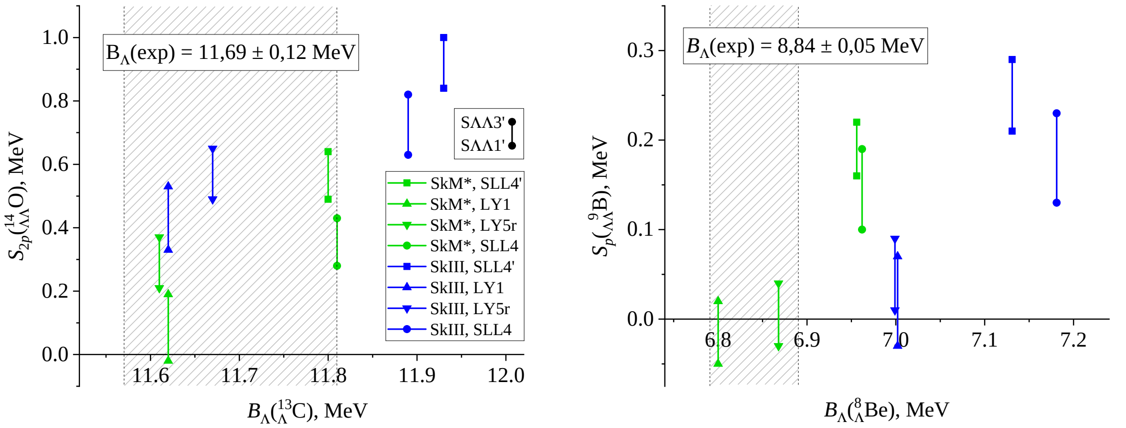

Figure 2: One or two-proton separation energies of hypernuclei vs hyperon binding energies in neighbouring hypernuclei: a) $S_{2p}({}^{14}_{\Lambda\Lambda}\mathrm{O})$ vs $B_\Lambda({}^{13}_{\Lambda}\mathrm{C})$, b) $S_p({}^{9}_{\Lambda\Lambda}\mathrm{B})$ vs $B_\Lambda({}^{8}_{\Lambda}\mathrm{Be})$. See Fig. 1 for notation. The top and bottom points in connected pairs show the predictions made using SΛΛ3' and SΛΛ1' ΛΛ-interaction respectively.

core ^{8}C emits 4 protons while the decay often proceeds in a two-step manner: ${}^{8}\mathrm{C} \rightarrow {}^{6}\mathrm{Be} + 2p$, ${}^{6}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + 2p$. Whereas ^{6}Be is unbound, ${}^{7}_{\Lambda}$Be is known to be bound, meaning the essential decay channel for ${}^{9}_{\Lambda}$C is the two-proton emission ${}^{9}_{\Lambda}\mathrm{C} \rightarrow {}^{7}_{\Lambda}\mathrm{Be} + 2p$. If this channel is closed, the four-proton ${}^{9}_{\Lambda}\mathrm{C} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + 4p$ emission is strictly forbidden. Therefore, the $S_{2p}({}^{9}_{\Lambda}\mathrm{C})$ value should be checked. The values of $S_{2p}({}^{8}\mathrm{C})$ and $B_\Lambda({}^{7}_{\Lambda}\mathrm{Be})$ required for calculations using (2) are both known from experiment ($S_{2p}({}^{8}\mathrm{C}) = -2.111 \pm 0.019$ MeV [16], $B_\Lambda({}^{7}_{\Lambda}\mathrm{Be}) = 5.16 \pm 0.08$ MeV [17]), so we need to calculate only $B_\Lambda({}^{9}_{\Lambda}\mathrm{C})$. Fig. 1b shows the calculated values of $S_{2p}({}^{9}_{\Lambda}\mathrm{C})$ plotted against B_Λ in the neighbouring hypernuclei ${}^{9}_{\Lambda}$B and ${}^{9}_{\Lambda}$Li. Left and right dots in each pair depict the hyperon binding energies $B_\Lambda({}^{9}_{\Lambda}\mathrm{B})$ and $B_\Lambda({}^{9}_{\Lambda}\mathrm{Li})$ respectively. The grey and red shaded areas show the experimental value of $B_\Lambda({}^{9}_{\Lambda}\mathrm{B}) = 8.29 \pm 0.18$ MeV and $B_\Lambda({}^{9}_{\Lambda}\mathrm{Li}) = 8.50 \pm 0.12$ MeV, respectively [17]. We can see that the interactions under consideration tend to underestimate the values of $B_\Lambda({}^{9}_{\Lambda}\mathrm{B})$ and $B_\Lambda({}^{9}_{\Lambda}\mathrm{Li})$. However, the better $B_\Lambda({}^{9}_{\Lambda}\mathrm{B})$ and $B_\Lambda({}^{9}_{\Lambda}\mathrm{Li})$ are described, the stronger is the two-proton binding in $S_{2p}({}^{9}_{\Lambda}\mathrm{C})$, indicating that $S_{2p}({}^{9}_{\Lambda}\mathrm{C}) > 0$. It stands to reason that ${}^{9}_{\Lambda}$C is bound.

Moving to ΛΛ hypernuclei, we conducted our calculations using two ΛΛ-interaction parametrizations: SΛΛ1' and SΛΛ3' [8, 18]. Considering we found ${}^{9}_{\Lambda}$C to be bound, adding another hyperon would evidently produce a bound hypernucleus ${}^{10}_{\Lambda\Lambda}$C. More detailed analysis is required for the other three double-Λ hypernuclei.

Fig. 2a depicts the calculated values of S_{2p} in hypernucleus ${}^{14}_{\Lambda\Lambda}$O. Here each pair of connected points corresponds to a particular combination of NN and ΛN interactions, the upper (lower) point shows the values obtained with the SΛΛ3' (SΛΛ1') ΛΛ-interaction. Most of the parametrizations yield positive values of S_{2p}. The single exception is the SkM* + LY1 + SΛΛ1' combination giving a tiny negative value of −0.02 MeV. We conclude that ${}^{14}_{\Lambda\Lambda}$O is bound with high probability.

A different situation was observed for the hypernucleus ${}^{9}_{\Lambda\Lambda}$B (see Fig. 2b). Like its nucleon core, this hypernucleus has one proton emission as the essential decay mode. The predictive power of the Skyrme-Hartree-Fock approach for boron was probed using the hypernucleus ${}^{8}_{\Lambda}$Be with $B_\Lambda({}^{8}_{\Lambda}\mathrm{Be}) = 8.84 \pm 0.05$ MeV [17] found in experiment. Our predictions for the stability of ${}^{9}_{\Lambda\Lambda}$B appeared to vary depending on the choice of interactions, specifically in the region where $B_\Lambda({}^{8}_{\Lambda}\mathrm{Be})$

is best reproduced. This hypernucleus could serve as a delicate testing ground for exploring finer properties of ΛN and ΛΛ interaction, as small effects may have a great influence on the stability of the hypernucleus.

A similar analysis of ${}^{13}_{\Lambda\Lambda}$N showed that this hyperisotope is unbound.

4. Conclusions

The Skyrme-Hartree-Fock approach was used to give predictions for the stability of light proton-rich Λ-hypernuclei in the region of $5 \leq Z \leq 8$. These predictions were based on the idea that the model can give good estimates for hyperon binding energies used for calculating the proton separation energies in the hypernuclei. The hypernucleus ${}^{9}_{\Lambda}$C was shown to be bound, making it the only known bound nuclide with thrice the amount of protons compared to the number of neutrons. The hypernuclei ${}^{8}_{\Lambda}$B, ${}^{12}_{\Lambda}$N and ${}^{13}_{\Lambda}$O were shown to be unbound. For ΛΛ hypernuclei, ${}^{10}_{\Lambda\Lambda}$C and ${}^{14}_{\Lambda\Lambda}$O were found to be bound, ${}^{13}_{\Lambda\Lambda}$N is unbound and the stability of ${}^{9}_{\Lambda\Lambda}$B remains questionable.

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