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Shape evolution of Ne isotopes and Ne hypernuclei: The interplay of pairing and tensor interactions

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Abstract. We study tensor and pairing effects on the quadruple deformation of neon isotopes based on a deformed Skyrme-Hartree-Fock model with BCS approximation for the pairing channel. We extend the Skyrme-Hartree-Fock formalism for the description of hypernuclei adopting the recently-proposed ESC08b hyperon-nucleon interaction. It is found that the interplay of pairing and tensor interactions is crucial to derive the deformations in several neon isotopes. Especially, the shapes of ^{26,30}Ne are studied in details in comparisons with experimentally observed shapes. Furthermore the deformations of the hypernuclei are compared with the corresponding neon isotopic cores in the presence of tensor force. We find the same shapes with somewhat smaller deformations for single Λ-hypernuclei compared with their core deformations.

1 Introduction

Hyperon interactions are of fundamental interest in nuclear physics, with important impacts on neutron star (NS) physics as well, especially after the discovery of the 2-solar-mass NS [1, 2]. From the comparisons of accurate calculations of hypernuclei properties with the experiments, one can derive various features of hyperon interactions. For a decade, by combining the γ-ray experimental data and theoretical calculations such as the shell model [3] and the clustering approach [4], they succeeded in extracting information on its spin-dependent parts of ΛN interaction. As a result, the most updated YN interaction, Nijmegen soft core potential such as the ESC08b model [5] is proposed. In the present work, we use this ESC08b potential as the realistic hyperon interactions for the microscopic Brueckner-Hartree-Fock (BHF) calculations [2] of infinite hadronic matter. The hypernuclei study is then done in the Skyrme-Hartree-Fock (SHF) model, with an effective ΛN interaction derived from those BHF calculations. More details can be found in Refs. [6, 7] and references therein. By doing this we can perform the structure calculations of heavier hypernuclei than those in the previous studies [3, 4].

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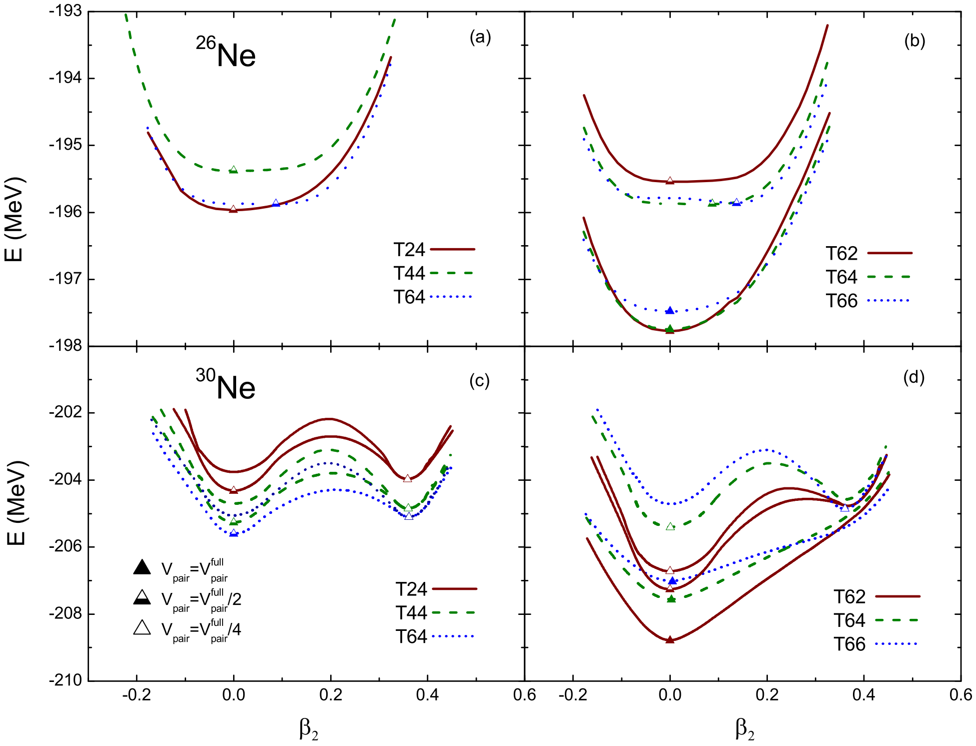

Figure 1. Energy surfaces of ^{26}Ne (upper panels) and ^{30}Ne (lower panels) as a function of the quadruple deformation parameter β_2. The energy minima are indicated with triangles, and three cases of pairing strengths are employed: a strong pairing case with $V_{\text{pair}} = V_{\text{pair}}^{\text{full}}$ (filled symbols) , a medium one with $V_{\text{pair}} = V_{\text{pair}}^{\text{full}}$ /2 (half symbols) and a weak one with V_{pair}=$V_{\text{pair}}^{\text{full}}$ /4 (open symbols). In the left panels, results using 24 (solid line), T44 (dashed line), T64 (dotted line) are shown, and in the right panels, results using T62 (solid line), T64 (dashed line), T66 (dotted line) are shown. Taken from Ref. [6].

We choose the Ne isotope for the core nuclei, since the related hypernuclei have been planned (for example, in the Radioisotope Beam Factory (RIBF)). The Ne isotope itself is quite interesting, and extensive experimental and theoretical studies have been performed recently [8–12]. Thanks to those, we recognize that, both the nucleonic tensor force and the pairing force are necessary for an exact description of most of the isotopic nuclei (especially the neutron-rich ones). In this study, an effective zero-range two-body tensor force is included to generate the Skyrme energy functional as done in some recent Skyrme parameterizations [13–16]. The tensor coupling strengthes used in the present study are listed in Tab. 1 of Ref. [6]. The nucleon pairing is introduced as a BCS-type density-dependent delta force $V(\mathbf{r}) = V_{\text{pair}}\left(1 - \frac{\rho(\mathbf{r})}{\rho_0}\right)$ with $\rho_0 = 0.16\ \text{fm}^{-3}$, where V_{pair} is the pairing strength and $\rho(\mathbf{r})$ is the Hartree-Fock (HF) matter density. Based on the empirical neutron pairing gaps extracted by using the three-point mass difference formula [17] and the experimental binding energies of Ref. [18], we choose $V_{\text{pair}} = 900$ MeV fm^3, which can reproduce reasonably well the gap data for the whole isotopic chain. This value is referred in the following as the full pairing case (labeled as $V_{\text{pair}}^{\text{full}}$).

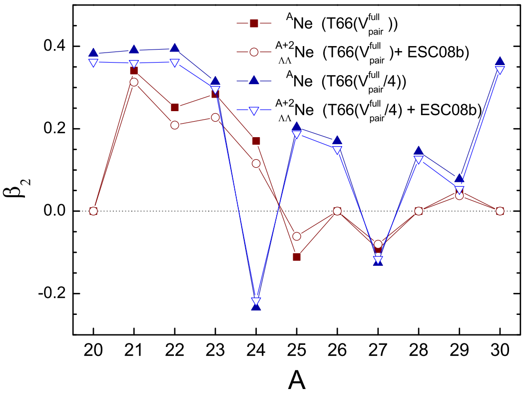

Figure 2. Deformation parameters of the double-lambda hypernuclei (open symbols) with neon isotopic core $^{20-30}$Ne are plotted using the ESC08b potential, with the comparison of those of core nuclei (filled symbols). The calculations are done with T66 for two cases of pairing strengths: a full pairing of $V_{\rm pair} = V_{\rm pair}^{\rm full}$, and a weak pairing of $V_{\rm pair} = V_{\rm pair}^{\rm full}/4$. Taken from Ref. [6].

We plan to study the quadruple deformations of neon isotopes and the corresponding Λ hypernuclei. The paper is organized as follows. In Sec. 2, we present the numerical results and discussions are given as well. Finally, Sec. 3 contains the short summary.

2 Results and Discussions

We first demonstrate how sensitively the shapes of the core nuclei depend on the pairing strength, together with the cooperative tensor correlation. In Fig. 1, the energy surfaces of two nuclei (upper panels for ^{26}Ne and lower panels for ^{30}Ne), with various choices of tensor forces and pairing forces are presented (see the figure caption for the details). Especially, calculations with two weaker cases of pairing are done, namely a medium one with $V_{\rm pair} = V_{\rm pair}^{\rm full}$ /2 and a weak one with $V_{\rm pair}$=$V_{\rm pair}^{\rm full}$ /4 , for the comparison with the full pairing case of $V_{\rm pair} = V_{\rm pair}^{\rm full}$. The neutron pairing gaps in the those two cases are only a few keV, and are regarded as the cases in which we do one variant of calculations with a weakened pairing to study its influence on the nuclear deformation.

For ^{26}Ne, from the comparison of the T62 results with those of T64 and T66, one can see that three cases with $V_{\rm pair} = V_{\rm pair}^{\rm full}$ all give a spherical shape for ^{26}Ne, even with increasingly strong tensor forces. While in the case of $V_{\rm pair} = V_{\rm pair}^{\rm full}/2$, a small tensor coupling in the case of T62 gives a spherical minima, but larger tensor coupling values in cases of T64 and T66 drive clear deformations in the prolate side. Same conclusion can be drawn from the comparison of the T64 results with those of T24 and T44. Therefore, to obtain an experimentally observed prolate shape of ^{26}Ne, a relatively large tensor strength is obviously necessary, together with a weakened pairing between nucleons.

For ^{30}Ne, from the comparison of the T24 results with those of T44 and T64, we see that a stronger tensor coupling makes the energy surface shallower, and at the same time makes the second prolate minimum more pronounced. However, the spherical minimums still win in the case of $V_{\rm pair} = V_{\rm pair}^{\rm full}$, and in the case of $V_{\rm pair} = V_{\rm pair}^{\rm full}$ /2, even in the latter case, a weakened pairing helps to lift largely in energy the spherical minimums. Interesting results are obtained with a further weakened pairing in the case of $V_{\rm pair} = V_{\rm pair}^{\rm full}$ /4. In this circumstance, T24 and T44 with smaller tensor strengthes give still no deformed minima, but T62, T64, T66 with larger tensor couplings finally achieve a large prolate-deformed shape at $\beta_2 \sim 0.35$ for ^{30}Ne, as desired by the experiments. This suggests that it demands the cooperation of a small pairing strength and a large tensor force to obtain a large prolate deformation for ^{30}Ne in this SHF + BCS model. This is consistent with the conclusion drawn in the context of ^{26}Ne.

We then proceed to calculate the corresponding hyperonuclei. In Fig. 2, the deformation parameters of the double-lambda hypernuclei with Ne isotopic cores $^{20-30}$Ne are plotted using the ESC08b potential, with the comparison of the data of those of core nuclei (see the figure caption for the details). Prolately-deformed ground states are successfully realized for ^{26,28,30}Ne as a combined effect of a large tensor force and a weakened pairing in the present model. This fact might be quite meaningful for further improvements of the SHF model or Skyrme parameterizations toward a better description on the shell structures of nuclei in general. We also find an interesting shape inverse of ^{25}Ne from oblate to prolate with the modification of pairing strength. Moreover, for all the isotopes there are smaller deformations with the same shapes for hypernuclei, compared with corresponding core nuclei in both the full pairing and the weak pairing cases.

3 Summary

In summary, we have performed the deformed SHF +BCS model calculations to investigate the effects of tensor and pairing forces on the quadruple deformation of neon isotopes and the corresponding Λ hypernuclei. With selected parameterizations of various tensor, pairing and hyperon-nucleon interactions, we disentangle the interplay of these correlations for the deformation of neon isotopes and the corresponding hypernuclei. We demonstrate that the cooperation of a weakened pairing and a large tensor interaction drives the shape of ^{26}Ne and ^{30}Ne from spherical to prolate, as desired by the recent experiments. In addition, the interplay of tensor force and hyperon force is also studied, and the tensor effect on the deformation of the isotope is found to be larger than that of Λ particles added to the core nucleus with realistic hyperon interactions.

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