

Effects of tensor interaction on pseudospin energy splitting and shell correction

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In the framework of a Skyrme-Hartree-Fock approach combined with Bardeen-Cooper-Schrieffer (BCS) method, the role of the tensor force on the pseudospin energy splitting for tin isotope chain is investigated. The tensor force turns out to obviously affect the pseudospin energy splitting of the spin-unsaturated nuclei. Since the tensor force shifts the single-particle levels, it modifies the single-particle level density and the shell correction energy thereof. The influence of the tensor interaction on shell correction energy is considerable according to our analysis taking a magic nucleus ^{132}Sn as well as a superheavy nucleus $^{298}114$ as examples. This modification of the shell correction energy due to the tensor component affects the stability of the superheavy nuclei.

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I. INTRODUCTION

Properties of exotic nuclei are not only interesting from the viewpoint of nuclear structure, but also have important implications in nuclear astrophysics, such as in nova and supernova explosions, x-ray bursts associated with explosive hydrogen burning, rapid proton capture processes, etc. In view of the recent rapid progress in the discovery of exotic nuclei driven by the advent of the new generation of radioactive ion beam facilities, an important problem is to understand how the shell structure evolves from stable to exotic nuclei, in which the role of the tensor force has received wide attention. The effect of the tensor force on the shell evolution has been explored by Otsuka and his collaborators within the shell model. They found that the tensor force strongly affects the evolution of the single-particle energy level spacing and shell structure [1].

In the case of Skyrme interactions, a zero-range tensor component was actually present in the original papers of Skyrme [2]. However, this component was omitted when realistic Skyrme parameter sets were determined, and it has been systematically neglected for several decades in practical applications. Until very recently, the tensor component was added to the existing Skyrme parametrizations or included by fitting new parametrizations to investigate the contributions of the tensor force to the spin-orbit splitting [3–5], evolution of single-particle energies [5–8], shell evolution [5,9,10], stability of superheavy nuclei [11], binding energy [12,13], nuclear deformability [13,14], properties of excited states [15,16], and the spin and spin-isospin instabilities of nuclear matter [17].

The concept of pseudospin was supported by experimental observations about 40 years ago that the single-nucleon doublet levels with quantum numbers $(n_r, l, j = l + 1/2)$ and $(n_r - 1, l + 2, j = l + 3/2)$ lie very close in energy,

where n_r, l, j are the single-nucleon radial, orbital, and total angular momentum quantum numbers, respectively. This single-nucleon doublet pair can be relabelled as a pseudospin doublet: $(\tilde{n}_r = n_r - 1, \tilde{l} = l + 1, \tilde{j} = \tilde{l} \pm 1/2)$. Then the two states in the doublet are almost degenerate with respect to pseudospin. This symmetry has been used to explain a number of phenomena in nuclear structure including the deformation [18], superdeformation [19], magnetic moment [20,21], and identical bands [22–24]. It is also pointed out that the conservation of the pseudospin symmetry plays an essential role in stabilizing the neutron halo structure and generating the neutron shell effects when the neutron number approaches the neutron drip line [25]. The details about the pseudospin symmetry can be found in Refs. [26–28]. It is interesting to discuss the influence of the tensor force on the pseudospin symmetry. In this work, we shall discuss the effect of the tensor component of the two-body effective interaction on the pseudospin energy splitting by employing a Skyrme-Hartree-Fock approach, taking a long chain of Sn isotopes as an example. In addition, the effect of tensor interaction on shell correction energy will be investigated. The liquid-drop model explains well the gross features of nuclear fission and mass, however, there are systematic deviations from the smooth mass. The shell correction, which is a fluctuation in the binding energy, can be supplemented to the liquid-drop model to improve the description of the nuclear masses and fission barriers [29–35]. For superheavy nuclei, as an important property, the shell correction energy is widely investigated because it is relevant to the stability of a superheavy nucleus. The Strutinsky method [36], which is widely used today, will be employed to extract the shell correction energy here. With the single-particle spectra obtained from the Skyrme-Hartree-Fock approach, the shell correction energies for heavy and superheavy nuclei can be calculated and one can analyze the effect of the tensor force.

This paper is organized as follows. In Sec. II, a brief theoretical method is presented. The effects of the tensor

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interaction on the pseudospin energy splitting and shell correction are discussed in Secs. III and IV, respectively. Finally, a brief summary is provided in Sec. V.

II. TENSOR FORCE IN THE FRAMEWORK OF THE SKYRME INTERACTION

The tensor part of the Skyrme effective interaction is written as [2]

$$v_T = \frac{T}{2} \left[(\sigma_1 \cdot \mathbf{k}')(\sigma_2 \cdot \mathbf{k}') - \frac{1}{3} \mathbf{k}^2 (\sigma_1 \cdot \sigma_2) \right] \delta(\mathbf{r}_1 - \mathbf{r}_2) \\ + \frac{T}{2} \left[(\sigma_1 \cdot \mathbf{k})(\sigma_2 \cdot \mathbf{k}) - \frac{1}{3} (\sigma_1 \cdot \sigma_2) \mathbf{k}^2 \right] \delta(\mathbf{r}_1 - \mathbf{r}_2) \\ + U[(\sigma_1 \cdot \mathbf{k}')\delta(\mathbf{r}_1 - \mathbf{r}_2)(\sigma_2 \cdot \mathbf{k})] \\ - \frac{U}{3} (\sigma_1 \cdot \sigma_2) [\mathbf{k}' \cdot \delta(\mathbf{r}_1 - \mathbf{r}_2) \mathbf{k}], \quad (1)$$

where $\mathbf{k} = (\vec{\nabla}_1 - \vec{\nabla}_2)/(2i)$ acts on the right and $\mathbf{k}' = -(\vec{\nabla}_1 - \vec{\nabla}_2)/(2i)$ acts on the left. T and U provide the intensity of the tensor force in even and odd states of relative motion, respectively. The spin-orbit potential including the tensor contributions is given by [3]

$$U_{s.o.}^{(q)} = \frac{W_0}{2r} \left(2 \frac{d\rho_q}{dr} + \frac{d\rho_{q'}}{dr} \right) + \left(\alpha \frac{J_q}{r} + \beta \frac{J_{q'}}{r} \right), \quad (2)$$

where $q(q')$ denotes the like (unlike) particles and the J_q is the proton or neutron spin-orbit density given as

$$J_q = \frac{1}{4\pi r^3} \sum_i v_i^2 (2j_i + 1) \left[j_i(j_i + 1) - l_i(l_i + 1) - \frac{3}{4} \right] R_i^2(r). \quad (3)$$

where v_i^2 is the Bardeen-Cooper-Schrieffer (BCS) occupation probability of each orbit. The orbital with $j_> = l + 1/2$ gives a positive contribution to J_q while the orbital with $j_< = l - 1/2$ gives a negative contribution to J_q . The strengths of these contributions α and β are expressed as $\alpha = \alpha_C + \alpha_T$ and $\beta = \beta_C + \beta_T$. α_C and β_C are related to the central exchange part of the interaction and can be written in terms of the usual Skyrme parameters

$$\alpha_C = \frac{1}{8}(t_1 - t_2) - \frac{1}{8}(t_1 x_1 + t_2 x_2), \quad (4) \\ \beta_C = -\frac{1}{8}(t_1 x_1 + t_2 x_2).$$

α_T and β_T are related to the tensor part in the following way:

$$\alpha_T = \frac{5}{12}U, \quad \beta_T = \frac{5}{24}(T + U). \quad (5)$$

The central exchange and tensor contributions modify the energy density H by

$$\Delta H = \frac{1}{2}\alpha(J_n^2 + J_p^2) + \beta J_n J_p. \quad (6)$$

One set of the parameters employed in the present work is the same as that in Ref. [3]: $\alpha_T = -170 \text{ MeV fm}^5$ and $\beta_T = 100 \text{ MeV fm}^5$ added perturbatively to the Skyrme force SLy5 [37] (marked by SLy5 + TF), which can fairly well explain the isospin dependence of the experimental energy differences between the single-proton states outside the $Z =$

50 core for Sn isotopes, and the single-neutron states outside the $Z = 82$ core for $Z = 82$ isotones both quantitatively and qualitatively. Recently, Zou *et al.* analyzed the evolution of the spin-orbit splittings in the Ca isotopes and $N = 28$ isotones with this SLy5 + TF and they found that adding the tensor contribution can qualitatively explain in most cases the empirical trends [7].

III. EFFECT OF THE TENSOR FORCE ON THE PSEUDOSPIN ENERGY SPLITTING

Apart from affecting the spin symmetry, the tensor force influences the pseudospin symmetry. The shift of single-particle levels might have different origins and mechanisms. In the present study, we focus on the effect of the tensor force. The calculations are performed in a coordinate space using a box size of 20 fm and a mesh size 0.1 fm. The pairing correlation is accounted in the BCS formalism with an energy gap determined by the observed odd-even mass differences for an open shell and being zero for a closed shell. In addition to the SLy5 + TF, the parameter set T31 including the tensor force (T31 + TF) is employed in the present study, which also explains the experimental energy differences between the $1h_{11/2}$ and $1g_{7/2}$ single-proton states along the Sn isotopes, while the interaction T31 without the tensor component fails to reproduce the trend of the experimental data, as shown in Fig. 1. Note that the calculations with the SLy5 + TF were first performed in Ref. [3] using other pairing formalisms, yet their results coincide with our calculated ones, which is therefore consistent with the conclusion that the pairing effect is negligible for the spin-orbit splitting suggested in Ref. [39]. We display the proton pseudospin energy splitting of $1d(2p_{3/2}, 1f_{5/2})$ and $1f(1g_{7/2}, 2d_{5/2})$ of the Sn isotopes in Fig. 2. The results with the parameter sets SLy5 (SLy5 + TF) and T31 (T31 + TF) show the same trend. The proton spin current does not contribute to isospin dependence of the spin-orbit potential for an isotope chain, however, the neutron spin current is uniquely responsible for the isospin dependence and affected greatly by the sign of the parameter β_T . From $N = 56$ to $N = 64$, J_n is reduced as the $1g_{7/2}$

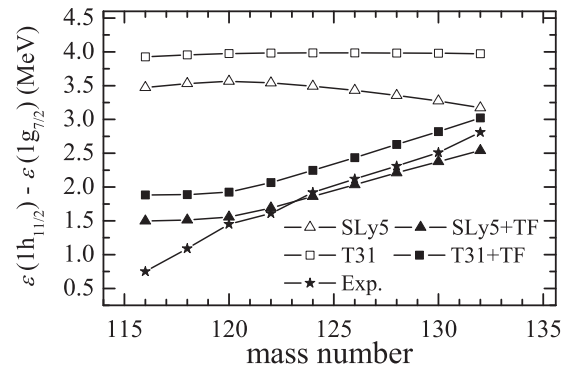


FIG. 1. Energy differences between the $1h_{11/2}$ and $1g_{7/2}$ single-proton states along the Sn isotopes. The experimental data are taken from Ref. [38]. For the proton-rich isotopes, one of or both of these two levels lie on the positive energy states (unbound), so we do not present them here.

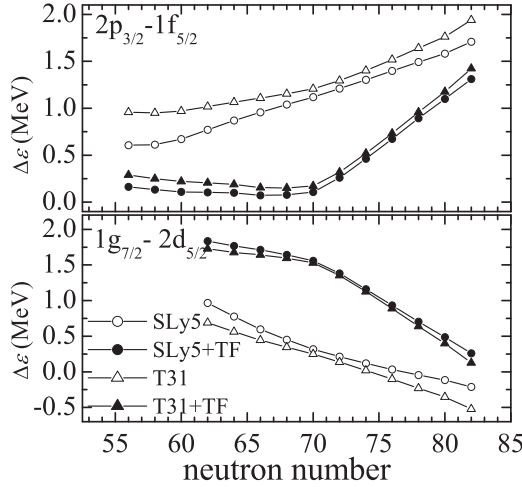


FIG. 2. Proton pseudospin orbit splitting $\Delta\epsilon$ measured by $\epsilon(2p_{3/2}) - \epsilon(1f_{5/2})$ for $1\tilde{d}$ and by $\epsilon(1g_{7/2}) - \epsilon(2d_{5/2})$ for $1\tilde{f}$ in the Sn isotopes.

neutron orbit is gradually filled. Because of a positive value of β_T , the absolute values of the proton spin-orbit splittings are enlarged. Therefore, the energy level of the proton orbit $1f_{5/2}$ is pushed up while that of the $2p_{3/2}$ is pulled down, leading to the reduction of the pseudospin orbit splitting of $1\tilde{d}$. When the neutron number N changes from 66 to 70, the filling of the $2d_{3/2}$ neutron orbit also reduces the pseudospin orbit splitting of $1\tilde{d}$. The pseudospin energy splitting of $1\tilde{f}$ should increase in this region, nevertheless, the lower panel of Fig. 2 shows an opposite trend. The reason for this result is that the centroid of the $1g$ levels shifts down more rapidly than that of the $2d$ levels as the neutron number increases, which submerges the weak isospin dependence of the tensor effect in this region. Moreover, from $N = 72$ to $N = 82$, the $1h_{11/2}$ orbit is gradually filled, which reduces the spin-orbit splitting, so that the $1f_{5/2}$ and $1g_{7/2}$ orbits shift downwards, but the $2p_{3/2}$ and $2d_{5/2}$ shift upward. Accordingly, the pseudospin energy splitting of $1\tilde{d}$ is enhanced, however, that of the $1\tilde{f}$ is reduced as the neutron number increases.

Although the proton spin current does not affect isospin dependence of the spin-orbit potential for a given isotope chain, being spin unsaturated for protons, the filling of the proton orbits affects nucleonic spin-orbit splitting as compared to that without the tensor force. The negative value of α_T and positive value of J_p enhance the absolute value of the spin-orbit potential and hence increase the spin-orbit splitting. From $N = 56$ to $N = 68$, the tensor effects resulting from the proton spin current (α_T term) and neutron spin current (β_T term) affect the spin-orbit splitting in the same way. Consequently, the pseudospin energy splitting of $1\tilde{d}$ is reduced and $1\tilde{f}$ is enlarged evidently compared to those without the tensor force. From $N = 70$ to $N = 82$, the α_T and β_T terms vary in an opposite way, and the contribution of the α_T term is canceled out gradually. Accordingly, the difference of the pseudospin energy splitting between that with and without the tensor force is reduced gradually. On the whole, compared to that without the tensor force, the pseudospin symmetry is recovered to a large extent for

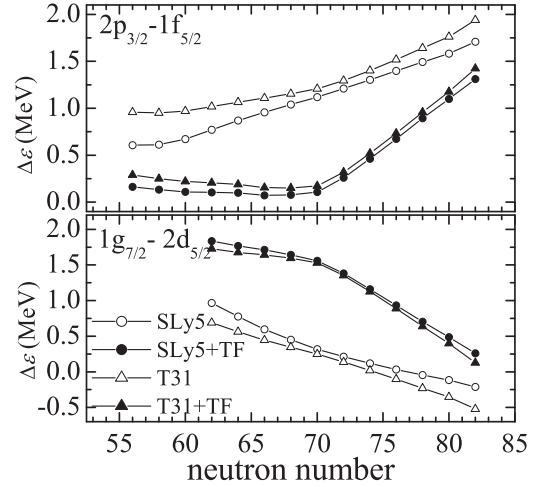


FIG. 3. Same as Fig. 1, but for neutrons.

the pseudospin doublet of $1\tilde{d}$ but is broken for $1\tilde{f}$. The tensor interaction thus brings a distinct change in pseudospin symmetry. For neutrons, the role of the tensor force is more complicated due to the variation of neutron number, but the obvious alternations caused by the tensor component are distinguished, as shown in Fig. 3. The tensor force leads to the energy inversion of some pseudospin doublets, such as $(2p_{3/2}, 1f_{5/2})$ when N varies from $N = 56$ to 60 as can be seen in Fig. 3.

For the pseudospin doublets except $(n\tilde{p}_{1/2}, n\tilde{p}_{3/2})$, such as $(1\tilde{g}_{7/2}, 1\tilde{g}_{9/2})$ and $(1\tilde{h}_{9/2}, 1\tilde{h}_{11/2})$ in the spin-unsaturated heavy nucleus, they are all composed of a $j_+ = l + 1/2$ orbit and a $j_- = l - 1/2$ orbit. Accordingly, their pseudospin symmetry could be affected considerably by the tensor effect because the two orbits are shifted by the tensor component in an opposite direction. For the pseudospin doublets $(n\tilde{p}_{1/2}, n\tilde{p}_{3/2})$, only the $n\tilde{p}_{3/2}$ orbit is shifted due to the tensor force (the $n\tilde{p}_{1/2}$ orbit is not affected due to its zero orbit angular momentum), and hence the tensor force also affects these pseudospin splittings. Our aim is to illustrate the significant influence of the tensor force on the pseudospin symmetry. Because the pseudospin symmetry is affected by the tensor force, a number of phenomena [18–25] being related to this symmetry can be accordingly affected. In addition, the rotation bands of the deformed nuclei based on the single-particle levels should be influenced by the tensor force, which needs investigation but it is not going to be easy because of the breaking of the time reversal symmetry.

IV. EFFECT OF THE TENSOR FORCE ON THE SHELL CORRECTION

Once the single-particle spectra are obtained, the shell correction energies can be calculated. Calculating such a correction requires the subtraction of the “smoothing varying” part of the sum of single-particle energies

$$E_{\text{shell}} = E - \tilde{E} = \sum_{i=1}^{N(Z)} e_i n_i - \int_{-\infty}^{\tilde{\lambda}} e \tilde{g}(e) de, \quad (7)$$

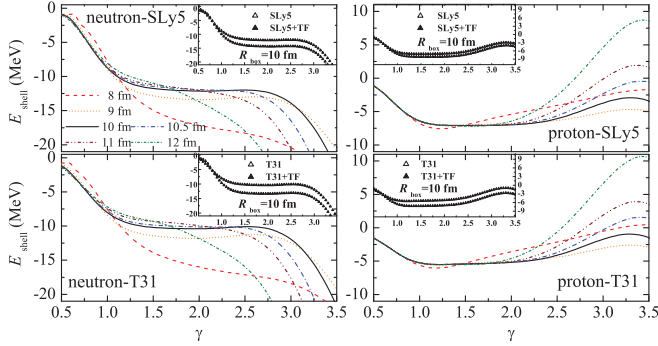


FIG. 4. (Color online) Neutron and proton shell correction energies as a function of the smoothing range γ for ^{132}Sn with different box sizes. The insets display the shell correction energies with and without the tensor component with the box size $R_{\text{box}} = 10$ fm and their coordinate axes are the same as the figures.

where $N(Z)$ is the neutron (proton) number, and e_i are the single-particle energies. The neutrons and protons are treated quite separately. The smoothed Fermi level $\tilde{\lambda}$ is obtained from the equation $N(Z) = \int_{-\infty}^{\tilde{\lambda}} \tilde{g}(e) de$. Taking into account the n_i -fold degeneracies of the single particle orbits, the smoothed level density $\tilde{g}(e)$ takes the form of

$$\tilde{g}(e) = \frac{1}{\gamma} \sum_{i=1}^{\infty} n_i f\left(\frac{e_i - e}{\gamma}\right), \quad (8)$$

where γ is the smoothing range in units of $\hbar\omega_0 = 41A^{-1/3}$ MeV. The folding function is usually taken as $f(x) = \frac{1}{\sqrt{\pi}} e^{-x^2} L_M^{1/2}(x^2)$, where $L_M^{1/2}(x^2)$ is an associated Laguerre polynomial. Here the energy cutoff of the single-particle spectra is selected to be 40 MeV.

It remains to determine the order of the associated Laguerre polynomial M and the smoothing range γ . Ideally, the calculated E_{shell} should not be dependent on the specific values in a broad range of reasonable values, namely, the so-called plateau condition:

$$\frac{\partial E_{\text{shell}}}{\partial \gamma} = 0, \quad \frac{\partial E_{\text{shell}}}{\partial M} = 0. \quad (9)$$

In our calculations, it is found that $M = 3$ is an optimal value just like that in Ref. [40], in which the associated Laguerre polynomial takes the form of $L_3^{1/2}(x^2) = -x^6/6 + 7x^4/4 - 35x^2/8 + 35/16$. Figure 4 presents the neutron and proton shell correction energies as a function of the smoothing range γ taking the nucleus ^{132}Sn as an example, where the Skyrme-Hartree-Fock equations are solved with box sizes of $R_{\text{box}} = 8 \sim 12$ fm with the parameter sets SLy5 and T31. One can find that the plateau condition is well fulfilled within the range $1.5 \leq \gamma \leq 2.7$ for neutrons and $1.2 \leq \gamma \leq 2.0$ for protons in the case of $R_{\text{box}} = 10$ fm. The plateau vanishes gradually as $R_{\text{box}} > 10$ fm. And $R_{\text{box}} = 10$ fm is large enough in our calculations to achieve the convergence for the total binding energy with an accuracy of 0.03%. When $R_{\text{box}} = 10$ fm, the calculated shell correction energies for ^{132}Sn with the parameter sets SLy5 and T31 in the cases with and without the tensor force, are presented in the insets of Fig. 4. This shell correction shows a parameter dependence. Without the tensor

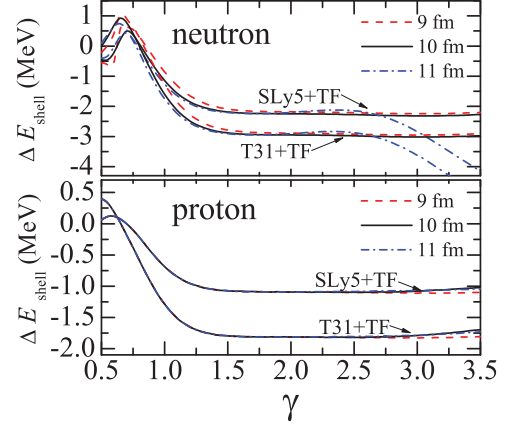


FIG. 5. (Color online) Modification of neutron and proton shell correction energies due to the tensor force as a function of the smoothing range γ for ^{132}Sn .

force, the shell correction energies for neutron (proton) are about -12.0 MeV (-7.0 MeV) and -10.3 MeV (-5.5 MeV) by adopting the parameter sets SLy5 and T31, respectively. The tensor force shifts the single-particle levels, thereby the single-particle level density undergoes a corresponding change, so that the shell correction energy is modified. It can be found that the shell correction energies for both neutrons and protons are reduced by the tensor force, the reason for which is partly because the tensor interaction makes the energy level density near the Fermi surface become lower. In order to show a clearer change in the shell correction energy caused by the tensor force, we plot in Fig. 5 the net effect of the tensor force on the shell correction energy ΔE , namely, the difference between the shell correction energies with and without the tensor force. As can be seen, the ΔE presents a more broad range of γ from 1.5 to 3.5 to fulfill the “plateau condition” with $R_{\text{box}} = 10$ fm. With $R_{\text{box}} = 11$ fm, though the neutron and proton shell correction energies do not show the “plateau” as presented in Fig. 4, the net contribution of the tensor force to the shell correction energies shows the “plateau”, especially for protons and nearly provides the same result as that with $R_{\text{box}} = 10$ fm. This indicates the reliability of our calculations to a large extent. The error caused by the box size can be canceled out to a large extent when one computes the contributions from the tensor force. One can find that due to the tensor force, the neutron shell correction energy is lowered by about 2.3 MeV and 3.0 MeV, and the proton shell correction energy is lowered by about 1.1 MeV and 1.8 MeV with the parameter sets SLy5 + TF and T31 + TF, respectively. In other words, the effect of the tensor force on the shell correction is considerable. By the way, the shell correction energy at the saddle point turns out to be too important to be neglected [41], so the tensor force may play a non-negligible role in fission processes.

Now we turn to the shell correction for superheavy nuclei. The existence of the superheavy island was predicted in the 1960s. However, there is no consensus among theorists with regard to what should be the next doubly magic nucleus beyond ^{208}Pb . Nearly all of modern calculations predict the existence of a closed neutron shell at $N = 184$. However, they differ

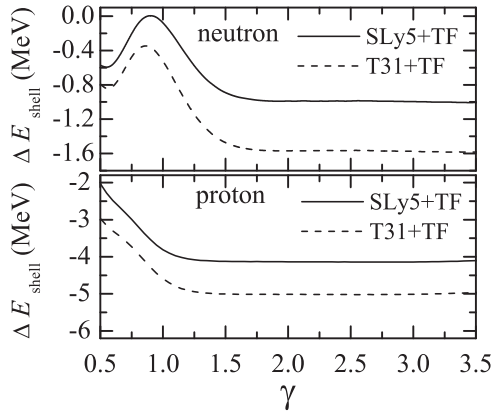


FIG. 6. Modification of neutron and proton shell correction energies due to the tensor force as a function of the smoothing range γ for $^{298}114$.

in predicting the position of the closed proton shell. Modern calculations predict that they appear at $Z = 114, 120, 124$, or 126 [30,42–47] depending on the models employed. We investigate the tensor effect on the shell correction of superheavy nuclei taking $^{298}114$ as an example. The influence of the tensor force on the neutron and proton shell correction energies ($R_{\text{box}} = 12.5$ fm) is illustrated in Fig. 6. With the parameter sets used above, we find that the shell correction energy for protons is altered by $4 \sim 5$ MeV due to the inclusion of the tensor component, and is much larger than the $1.0 \sim 1.6$ MeV for neutrons. This implies that $^{298}114$ becomes more stable due to the presence of the tensor force with the present parameter sets since the shell correction energy can reflect the stability of nuclei. We plot in Fig. 7 the single-particle levels near the Fermi surface to show the effect of the tensor force ($R_{\text{box}} = 20$ fm). As can be seen, the shell gap at $Z = 114$ is obviously enlarged due to the tensor force, and the shell gap at $N = 184$ is changed slightly, which is consistent with the above discussion about the shell correction energy and is agreement with the results in Ref. [11]. The difference between the $4s_{1/2}$ and $2h_{11/2}$ neutron orbits determines the size of the gap at $N = 184$, yet the tensor force only directly affects the $2h_{11/2}$ orbit. In consideration of the fact that the α_T and β_T terms in Eq. (2) take effect in an opposite way, their contributions to the spin-orbit splitting are cancelled out to a certain extent, hence the predicted neutron shell structures is modified only slightly by inclusion of the tensor component. However, for $Z = 114$, the two proton orbits $2f_{5/2}$ and $1i_{13/2}$ shift in an opposite direction due to the tensor component, thus the gap is changed obviously. The discussions here aim at displaying the effect of the tensor force on the structure and stability of the superheavy nucleus. The theoretical results at least imply that the tensor force should play an important role in the shell structure of the superheavy nucleus. We would like to say that many-body approaches with various parameter sets tend to predict different locations of the shell gaps, which perhaps results from the uncompleted knowledge about the tensor force to a large extent.

V. SUMMARY

A detailed investigation for the effect of the tensor force on the pseudospin energy splitting has been carried out taking

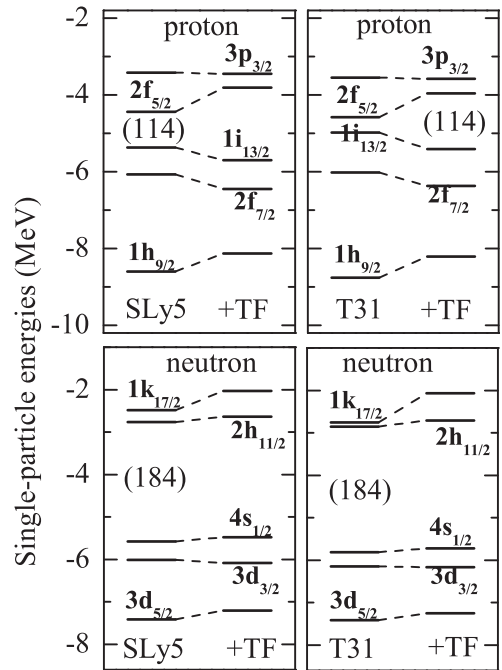


FIG. 7. Single-particle spectra of $^{298}114$ near the Fermi surface. The calculations are performed with (SLy5 + TF and T31 + TF) and without (SLy5 and T31) the tensor interaction in the spin-orbit potential.

the Sn isotope chain as an example in the framework of the Skyrme-Hartree-Fock approach with the parameter sets SLy5 + TF and T31 + TF combined with the BCS method, where the sign of α_T and β_T plays a crucial role. The contributions of the tensor force to the pseudospin symmetry are significant since all pseudospin doublets except $(n\tilde{p}_{1/2}, n\tilde{p}_{3/2})$ are composed of a $j_>$ orbit and a $j_<$ orbit which are affected in an opposite way by the tensor force. For $(n\tilde{p}_{1/2}, n\tilde{p}_{3/2})$, only the $n\tilde{p}_{3/2}$ orbit is shifted due to the tensor force, and hence the tensor force also affects the pseudospin splitting. Thus a lot of phenomena being related to the pseudospin symmetry should be accordingly affected. In addition, the effect of the tensor force on the shell correction energy is calculated taking a magic nucleus ^{132}Sn and a superheavy nucleus $^{298}114$ as examples. It was shown that the influence of the tensor force on the shell correction energy is considerable. For $^{298}114$, the absolute values of calculated proton shell correction energy is enlarged due to the inclusion of the tensor component, which is consistent with the result that the shell gap at $Z = 114$ is obviously enhanced with the present parameter sets. The modification of the shell correction energies by the tensor component are important for superheavy nuclei, which are related to their stability. All the conclusions here actually originate from the shifts of the single-particle levels (i.e., modified spin-orbit splittings) on account of the presence of the tensor force.

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