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Temperature Dependence of the Volume and Surface Contributions to the Nuclear Symmetry Energy within the Coherent Density Fluctuation Model

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Abstract. The temperature dependence of the volume and surface components of the nuclear symmetry energy (NSE) and their ratio are investigated in the framework of the local density approximation (LDA). The results of these quantities for finite nuclei are obtained within the coherent density fluctuation model (CDFM) and the Skyrme energy-density functional for nuclear matter. The CDFM weight function is obtained using the temperature-dependent proton and neutron densities calculated through the HFBTHO code that solves the nuclear Skyrme-Hartree-Fock-Bogoliubov problem by using the cylindrical transformed deformed harmonic-oscillator basis. We present and discuss the values of the T-dependent volume and surface contributions to the NSE and their ratio obtained for the Ni, Sn, and Pb isotopic chains around double-magic ^{78}Ni, ^{132}Sn, and ^{208}Pb nuclei. The results are compared with estimations made previously for zero temperature showing the behavior of the NSE components and their ratio. The comparison is made also with our previous results for the T-dependent NSE. We confirm the existence of "kinks" at $T = 0$ MeV for the double closed-shell nuclei ^{78}Ni and ^{132}Sn and the lack of "kinks" for the Pb isotopes.

1 Introduction

The nuclear symmetry energy is an important ingredient of the nuclear equation of state (EOS) in a wide range of densities and temperatures (see, e.g., [1–3]). Using approaches like the local-density approximation [4–7] and the coherent density fluctuation model [8, 9], the knowledge of EOS can give information about the properties of finite systems. The CDFM allowed us to make the

transition from nuclear matter to finite nuclei in the studies of the NSE for spherical [10] and deformed [11] nuclei, as well as for Mg isotopes [12] using the Brueckner energy-density functional (EDF) of asymmetric nuclear matter (ANM) [13].

In our previous work [14] we used a similar method to investigate the T-dependence of the NSE for isotopic chains of even-even Ni, Sn, and Pb nuclei following the LDA [4–7] and using instead of the Brueckner EDF, the Skyrme EDF with SkM* and SLy4 forces. The T-dependent local densities $\rho(r,T)$ and kinetic energy densities $\tau(r,T)$ were calculated within a self-consistent Skyrme HFB method using the cylindrical transformed deformed harmonic-oscillator basis (HFBTHO) [15, 16] with the mentioned forces.

In our work [17] the volume and surface contributions to the NSE and their ratio were calculated within the CDFM using two EDF's, namely the Brueckner [13] and Skyrme (see Ref. [18]) ones. The CDFM weight function was obtained by means of the proton and neutron densities obtained from the self-consistent deformed HF+BCS method with density-dependent Skyrme interactions. The obtained results in the cases of Ni, Sn, and Pb isotopic chains were compared with results of other theoretical methods and with those from other approaches which used experimental data on binding energies, excitation energies to isobaric analog states (IAS), neutron-skin thicknesses and with results of other theoretical methods. We note that in [17] the obtained values of the volume and surface components of NSE and their ratio concern the case at $T = 0$ MeV.

The aim of the present work (see also [19]) is to evaluate the above mentioned quantities for temperatures different from zero. The T-dependent local density distributions $\rho_p(r,T)$ and $\rho_n(r,T)$ computed by the HFBTHO code are used to calculate the T-dependent CDFM weight function. Such an investigation of the thermal evolution of the NSE components and their ratio for isotopes belonging to the Ni, Sn, and Pb chains around the double-magic nuclei, will extend our previous analysis of these nuclei considering them as cold systems [17]. At the same time, the obtained results within the CDFM provide additional information on the thermal mapping of the volume and surface symmetry energies that has been poorly investigated till now (e.g., Ref. [20]).

2 Theoretical Formalism

The expression for the nuclear energy given in the droplet model can be written as [21, 22]:

$$E(A,Z) = -BA + E_S A^{2/3} + S^V A \frac{(1-2Z/A)^2}{1+S^S A^{-1/3}/S^V} + E_C \frac{Z^2}{A^{1/3}} + E_{dif}\frac{Z^2}{A} + E_{ex}\frac{Z^{4/3}}{A^{1/3}} + a\Delta A^{-1/2} \quad (1)$$

In Eq. (1) $B \simeq 16$ MeV is the binding energy per particle of bulk symmetric matter at saturation. E_S, E_C, E_{dif}, and E_{ex} are coefficients that correspond to the

surface energy of symmetric matter, the Coulomb energy of a uniformly charged sphere, the diffuseness correction and the exchange correction to the Coulomb energy, while the last term gives the pairing corrections (Δ is a constant and $a = +1$ for odd-odd nuclei, 0 for odd-even and -1 for even-even nuclei). S^V is the volume symmetry energy parameter and S^S is the modified surface symmetry energy one in the liquid model (see Ref. [21], where it is defined by S^{S*}).

In our previous work [14] we studied the temperature dependence of the NSE $S(T)$. For the aims of the present work we will rewrite the symmetry energy (the third term in the right-hand side of Eq. (1) in the form

$$S(T)\frac{(N-Z)^2}{A} \tag{2}$$

where

$$S(T) = \frac{S^V(T)}{1+\dfrac{S^S(T)}{S^V(T)}A^{-1/3}} = \frac{S^V(T)}{1+A^{-1/3}/\kappa(T)} \tag{3}$$

with

$$\kappa(T) \equiv \frac{S^V(T)}{S^S(T)}. \tag{4}$$

In the case of nuclear matter, where $A \longrightarrow \infty$ and $S^S/S^V \longrightarrow 0$, we have $S(T) = S^V(T)$. Also at large A Eq. (3) can be written in the known form (see Ref. [23]):

$$S(T) = \frac{S^V(T)}{1+\dfrac{S^S(T)}{S^V(T)}A^{-1/3}} \simeq c_3 - \frac{c_4}{A^{1/3}}, \tag{5}$$

where $c_3 = S^V$ and $c_4 = S^S$. From Eq. (3) the relations of $S^V(T)$ and $S^S(T)$ with $S(T)$ can be found:

$$S^V(T) = S(T)\left(1+\frac{1}{\kappa(T)A^{1/3}}\right), \tag{6}$$

$$S^S(T) = \frac{S(T)}{\kappa(T)}\left(1+\frac{1}{\kappa(T)A^{1/3}}\right). \tag{7}$$

In what follows we use essentially the CDFM scheme to calculate the NSE and its components (see Refs. [8, 9, 17]) in which the one-body density matrix $\rho(\mathbf{r},\mathbf{r}')$ is a coherent superposition of the one-body density matrices $\rho_x(\mathbf{r},\mathbf{r}')$ for spherical "pieces" of nuclear matter ("fluctons") with densities $\rho_x(\mathbf{r}) = \rho_0(x)\Theta(x-|\mathbf{r}|)$ and $\rho_0(x) = 3A/4\pi x^3$. The density distribution in the CDFM has the form:

$$\rho(\mathbf{r}) = \int_0^\infty dx|\mathcal{F}(x)|^2\rho_0(x)\Theta(x-|\mathbf{r}|). \tag{8}$$

It follows from (8) that in the case of monotonically decreasing local density ($d\rho/dr \leq 0$) the weight function $|\mathcal{F}(x)|^2$ can be obtained from a known density (theoretically or experimentally obtained):

$$|\mathcal{F}(x)|^2 = -\frac{1}{\rho_0(x)} \left.\frac{d\rho(r)}{dr}\right|_{r=x}. \tag{9}$$

We have shown in our previous works [10,11,17] that the NSE in the CDFM for temperature $T = 0$ can be obtained in the form:

$$S = \int_0^\infty dx |\mathcal{F}(x)|^2 S[\rho(x)], \tag{10}$$

where the symmetry energy for the ANM that depends on the density $S[\rho(x)]$ has to be determined using a chosen EDF (in [17] Brueckner and Skyrme EDF's have been used).

In this work the T-dependent NSE $S(T)$ is calculated by the expressions similar to Eq. (10) but containing T-dependent quantities:

$$S(T) = \int_0^\infty dx |\mathcal{F}(x,T)|^2 S[\rho(x,T)]. \tag{11}$$

In Eq. (11) the weight function $|\mathcal{F}(x,T)|^2$ depends on the temperature through the temperature-dependent total density distribution $\rho_{total}(r,T)$:

$$|\mathcal{F}(x,T)|^2 = -\frac{1}{\rho_0(x)} \left.\frac{d\rho_{total}(r,T)}{dr}\right|_{r=x}, \tag{12}$$

where

$$\rho_{total}(r,T) = \rho_p(r,T) + \rho_n(r,T), \tag{13}$$

$\rho_p(r,T)$ and $\rho_n(r,T)$ being the proton and neutron T-dependent densities that in our work [14] were calculated using the HFB method with transformed harmonic-oscillator basis and the HFBTHO code [15].

Following Refs. [17, 24–26] an approximate expression for the ratio $\kappa(T)$ can be written within the CDFM:

$$\kappa(T) = \frac{3}{R\rho_0} \int_0^\infty dx |\mathcal{F}(x,T)|^2 x\rho_0(x) \left\{ \frac{S(\rho_0)}{S[\rho(x,T)]} - 1 \right\}, \tag{14}$$

where $|\mathcal{F}(x,T)|^2$ is determined by Eq. (12), $R = r_0 A^{1/3}$ [26] and $S(\rho_0)$ is the NSE at equilibrium nuclear matter density ρ_0 and $T = 0$ MeV. For instance, the values of $S(\rho_0)$ for different Skyrme forces in the Skyrme EDF are given in Table II of Ref. [17]. In what follows we use the commonly employed power parametrization for the density dependence of the symmetry energy (e.g., [25, 26])

$$S[\rho(x,T)] = S^V(T) \left[\frac{\rho(x,T)}{\rho_0}\right]^\gamma. \tag{15}$$

There exist various estimations for the value of the parameter γ. For instance, in Ref. [26] $\gamma = 0.5 \pm 0.1$ and in Ref. [25] $0.54 \leq \gamma \leq 0.77$. The estimations in Ref. [27] (given in Table 2 there) of the NSE based on different cases within the chiral effective field theory and from other predictions are $\gamma = 0.60 \pm 0.05$ (N^{2}LO), $\gamma = 0.55 \pm 0.03$ (N^{3}LO), $\gamma = 0.55$ (DBHF) and 0.79 (APR [28]). Another estimation of $\gamma = 0.72 \pm 0.19$ is also given in Ref. [29].

Using Eq. (15) (and having in mind that $S(\rho_0) = S^V$), Eqs. (11) and (14) can be re-written as follows:

$$S(T) = S(\rho_0) \int_0^\infty dx |\mathcal{F}(x,T)|^2 \left[\frac{\rho(x,T)}{\rho_0}\right]^\gamma , \tag{16}$$

$$\kappa(T) \equiv \frac{S^V(T)}{S^S(T)} = \frac{3}{R\rho_0} \int_0^\infty dx |\mathcal{F}(x,T)|^2 x\rho_0(x) \left\{ \left[\frac{\rho_0}{\rho(x,T)}\right]^\gamma - 1 \right\} . \tag{17}$$

3 Results of Calculations and Discussion

The calculations of the T-dependent nuclear symmetry energy $S(T)$, its volume $S^V(T)$ and surface $S^S(T)$ components, as well as their ratio $\kappa(T) = S^V(T)/S^S(T)$ were performed using the relationships (11), (14)-(17) with the

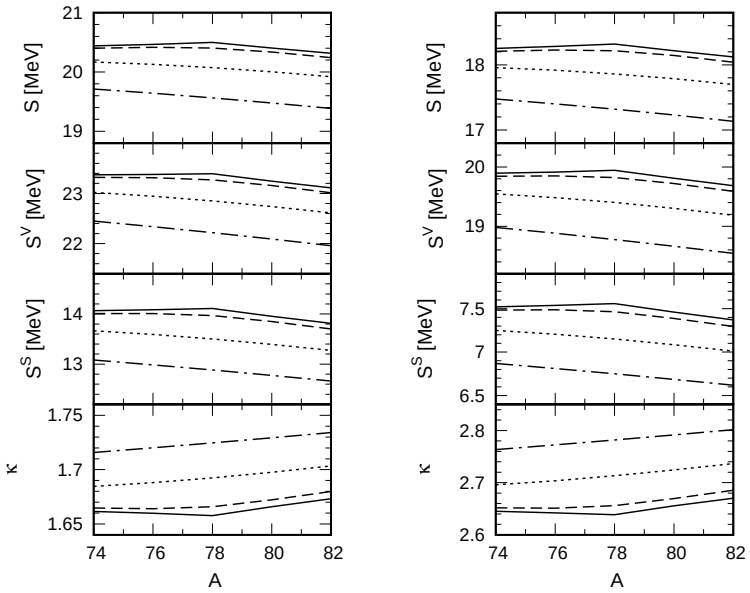

Figure 1. Mass dependence of the NSE $S(T)$, its volume $S^V(T)$ and surface $S^S(T)$ components and their ratio $\kappa(T)$ for nuclei from the Ni isotopic chain at temperatures $T = 0$ MeV (solid line), $T = 1$ MeV (dashed line), $T = 2$ MeV (dotted line), and $T = 3$ MeV (dash-dotted line) calculated with SkM* Skyrme interaction for values of the parameter $\gamma = 0.3$ (left panel) and $\gamma = 0.4$ (right panel).

weight function $|\mathcal{F}(x,T)|^2$ from Eqs. (12) and (13). The T-dependent proton $\rho_p(r,T)$ and neutron $\rho_n(r,T)$ density distributions, as well as the total density $\rho_{total}(r,T)$ [Eq. (13)] were calculated using the HFBTHO code from Ref. [15] with the Skyrme EDF for SkM* and SLy4 forces. We note that in the calculations of $S(T)$ [Eq. (16)] and $\kappa(T)$ [Eq. (17)] we use the weight function $|\mathcal{F}(x,T)|^2$ from Eq. (12), where the density distributions for finite nuclei are used. The quantity $S[\rho(x,T)]$ in Eqs. (11) and (14) is the symmetry energy for asymmetric nuclear matter chosen in the parametrized form of Eq. (15). Our calculations are performed for the Ni, Sn, and Pb isotopic chains.

Studying the T-dependence of the mentioned quantities we observed (as can be seen below) a certain sensitivity of the results to the value of the parameter γ in Eq. (15). In order to make a choice of its value we imposed the following physical conditions: i) the obtained results for the considered quantities at $T = 0$ MeV to be equal or close to those obtained for the same quantities in our previous works for the NSE, its components and their ratio (Ref. [14, 17]), and ii) their values for $T = 0$ MeV to be compatible with the available experimental data (see, e.g., the corresponding references in [17]).

In Figures 1 and 2 the results for $S(T)$, $S^V(T)$, $S^S(T)$, and $\kappa = S^V(T)/S^S(T)$ are given as functions of the mass number A for the isotopic chains of Ni and Pb nuclei for temperatures $T = 0$–3 MeV calculated using the SkM* and SLy4 Skyrme forces. The results are presented for two values of the parameter

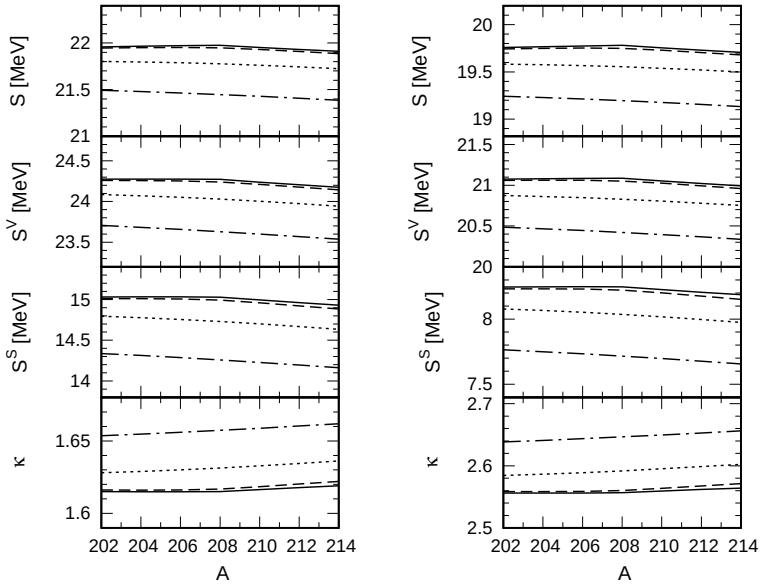

Figure 2. Same as in Figure 1, but for nuclei from the Pb isotopic chain and with SLy4 Skyrme interaction.

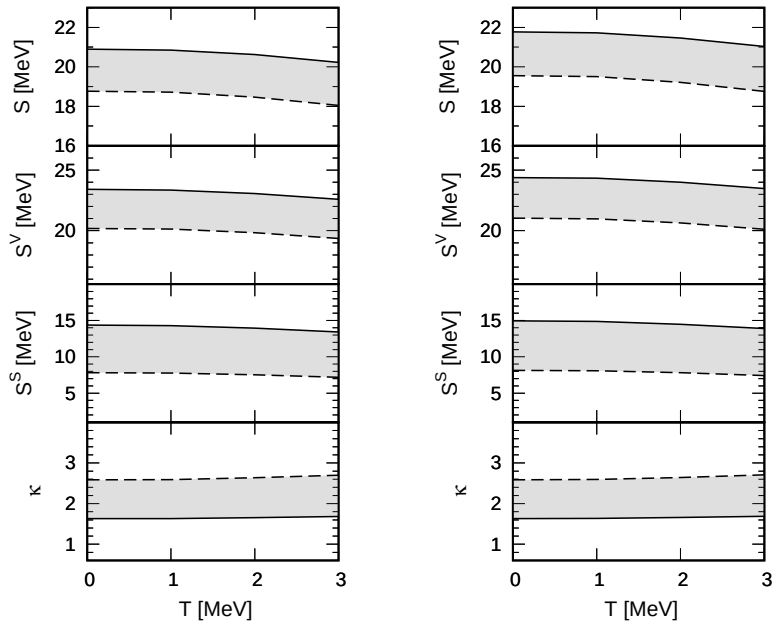

Figure 3. Temperature dependence of the NSE $S(T)$, its volume $S^V(T)$ and surface $S^S(T)$ components, and their ratio $\kappa(T)$ obtained for values of the parameter $\gamma = 0.3$ (solid line) and $\gamma = 0.4$ (dashed line) with SkM* (left panel) and SLy4 (right panel) forces for ^{132}Sn nucleus.

$\gamma = 0.3$ and 0.4. The reason for this choice is related to the physical criterion mentioned above. It can be seen that at $T = 0$ MeV and $\gamma = 0.4$ the value of κ is around 2.6. This result is in agreement with our previous result obtained in the case of the Brueckner EDF in Ref. [17], namely $2.10 \leq \kappa \leq 2.90$. The latter is compatible with the published values of κ extracted from nuclear properties presented in Ref. [26] from the IAS and skins ($2.6 \leq \kappa \leq 3.0$) and from masses and skins [24] ($2.0 \leq \kappa \leq 2.8$). In the case of $\gamma = 0.3$ our result for $T = 0$ MeV is $\kappa = 1.65$ that is in agreement with the analyses of data in Ref. [26] ($1.6 \leq \kappa \leq 2.0$), as well as with the results of our work [17] in the case of Skyrme EDF, namely, for the Ni isotopic chain $1.5 \leq \kappa \leq 1.7$ and for the Pb isotopic chain $1.65 \leq \kappa \leq 1.75$, all obtained with SLy4 and SGII forces.

Before making the comparison of our results for $S(T)$ at $T = 0$ MeV with our previous ones from Ref. [14] (there the NSE is denoted by e_{sym}) we mention that though the latter are in good agreement with theoretical predictions for some specific nuclei reported by other authors, we showed that they depend on the suggested definitions of this quantity. The comparison of the results in the present work for S at $T = 0$ MeV with those from our work Ref. [14] (the latter illustrated there in Figure 12) shows that they agree with our present values of

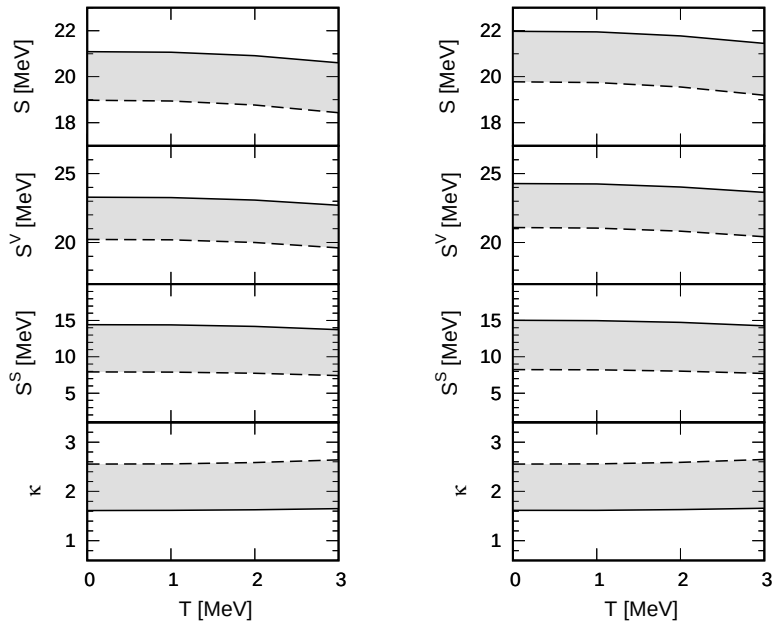

Figure 4. Same as in Figure 3, but for ^{208}Pb nucleus.

S within the range of $\gamma = 0.3$–0.4, except in the case of Pb with SLy4 force, where the present results are somewhat lower.

It can be seen from Figures 1 and 2 that the quantities $S(T)$, $S^V(T)$, and $S^S(T)$ decrease with increasing temperatures ($T = 0$–3 MeV), while $\kappa(T)$ slowly increases when T increases. This is true for both Skyrme forces (SkM* and SLy4) and for the two isotopic chains of the Ni and Pb nuclei. Here we would like to note that the values of γ between 0.3 and 0.4 that give an agreement of the studied quantities with data, as well as with our previous results for $T = 0$ MeV, are in the lower part of the estimated limits of the values of γ (e.g., in the case of $\gamma = 0.5 \pm 0.1$ [26]). It can be seen also from Figures 1 and 2 that there are "kinks" in the curves of $S(T)$, $S^V(T)$, $S^S(T)$, and $\kappa(T)$ for $T = 0$ MeV in the case of the double closed-shell nucleus ^{78}Ni and no "kinks" in the Pb chain. This had been observed also in our previous work for $S(T)$ [14], as well as for its volume and surface components and their ratio κ at $T = 0$ MeV in Ref. [17].

In Figures 3 and 4 are given the results for the T-dependence of $S(T)$, $S^V(T)$, $S^S(T)$, and $\kappa(T)$ for the double-magic ^{132}Sn and ^{208}Pb nuclei obtained using both SkM* and SLy4 Skyrme forces. The results are presented by grey areas between the curves for the values of the parameter $\gamma = 0.3$ and $\gamma = 0.4$. It can be seen that $S(T)$, $S^V(T)$, and $S^S(T)$ decrease, while $\kappa(T)$ slowly increases with the increase of the temperature for both Skyrme forces.

4 Conclusions

In the present work we perform calculations of the temperature dependence of the NSE $S(T)$, its volume $S^V(T)$ and surface $S^S(T)$ components, as well as their ratio $\kappa(T) = S^V(T)/S^S(T)$. Our method is based on the local density approximation. It uses the coherent density fluctuation model [8, 9] with T-dependent proton $\rho_p(r,T)$, neutron $\rho_n(r,T)$, and total $\rho_{total}(r,T) = \rho_p(r,T) + \rho_n(r,T)$ density distributions. The latter are calculated within the self-consistent Skyrme HFB method using the cylindrical transformed harmonic-oscillator basis (HFBTHO) [15,16] and the corresponding code with SkM* and SLy4 Skyrme forces. The quantities of interest are calculated for the isotopic chains of Ni, Sn, and Pb nuclei.

The main results of the present work (see also [19]) can be summarized as follows:

(i) With increasing T, the quantities S, S^V, and S^S decrease, while κ slightly increases for all the isotopes in the three chains and for both Skyrme forces.

(ii) Within each isotopic chain, as a function of the mass number, the quantities S, S^V, and S^S decrease with increasing A, whereas κ increases for both Skyrme forces and for any T ranging from 0 MeV to 3 MeV.

(iii) $S(T)$, $S^V(T)$, $S^S(T)$, and $\kappa(T)$ are sensitive to the values of the parameter γ used to parametrize $S[\rho(x,T)]$ in Eq. (15). The results obtained with values of γ between 0.3 and 0.4 agree with our previous results in the case of $T = 0$ MeV obtained for the components of NSE and their ratio (Ref. [17]), for the T-dependent NSE [14] and are compatible with the available experimental data.

(iv) In the cases of double-magic ^{78}Ni and ^{132}Sn nuclei we observe "kinks" for $T = 0$ MeV in the curves of $S(T)$, $S^V(T)$, $S^S(T)$, and $\kappa(T)$, but not in the case of Pb isotopes. This effect was also found in our previous works. It is also worth mentioning how the kinks are blurred and eventually disappear as T increases, demonstrating its close relationship with the shell structure.

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