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Symmetry Energy, its Components and Nuclear Structure Properties at Finite Temperature

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We study the temperature dependence of the nuclear symmetry energy (NSE), of its volume and surface components and their ratio using two approaches. In the first one the results of these quantities for finite nuclei are obtained within the coherent density fluctuation model (CDFM) that includes effects of nucleon-nucleon correlations. The CDFM weight function is calculated using the temperature-dependent proton and neutron densities obtained by the HFBTHO code that solves the nuclear Skyrme-Hartree-Fock-Bogoliubov problem by using the cylindrical transformed deformed harmonic-oscillator basis. In the second approach, based on the local density approximation (LDA), alternative ways to calculate the symmetry energy coefficient within the LDA are proposed. The Skyrme energy-density functional for nuclear matter is used. We present and discuss the values of the T-dependent volume and surface contributions to the NSE and their ratio for the Ni, Sn, and Pb isotopic chains around the double-magic ^{78}Ni, ^{132}Sn, and ^{208}Pb nuclei. The results are compared with estimations made previously for the behavior of the NSE components and their ratio at zero temperature and 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. Some of our results for T-dependent proton and neutron rms radii as well as for the sizes of neutron skins in hot nuclei are also presented.

INTRODUCTION

The nuclear symmetry energy (NSE) essentially characterizes the isospin-dependent part of the equation of state (EOS) of asymmetric nuclear matter (ANM). The study of its density (ρ) and temperature (T) dependence is an important task in nuclear physics (see, e.g. [1–3]). The transition from ANM to finite nuclei is a natural and important way to learn more about the NSE, which is poorly constrained by experimental data on ground-state nuclear properties. Using approaches like the local-density approximation (LDA) [4–7] and the coherent density fluctuation model (CDFM) [8, 9], knowledge of EOS can give information about the properties of finite systems. The CDFM is a natural extension of the Fermi gas model and is based on the delta-function limit of the generator coordinate method [9, 10]. The model includes nucleon-nucleon correlations of a collective type. It allowed us to make the transition from nuclear matter to finite nuclei in the studies of the NSE for spherical [11] and deformed [12] nuclei, as well as for Mg isotopes [13] using the Brueckner energy-density functional (EDF) for asymmetric nuclear matter [14].

In our work [15] 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 using a self-consistent Skyrme HFB method that used the cylindrical transformed deformed harmonic-oscillator basis (HFBTHO) [16, 17] with the above-mentioned forces.

In our work [18] the volume and surface contributions to

the NSE and their ratio were calculated within the CDFM using two EDF's, namely the Brueckner [14] and Skyrme (see Ref. [19]) ones. The CDFM weight function was obtained by means of the proton and neutron densities calculated using the self-consistent deformed HF+BCS method with density-dependent Skyrme interactions. The results in the cases of Ni, Sn, and Pb isotopic chains were compared with those of other theoretical methods and from other approaches that used experimental data on binding energies, excitation energies to isobaric analog states (IAS), and neutron-skin thicknesses. We note that in [18] the values obtained for the volume and surface components of the NSE and their ratio for the case of $T = 0$ MeV.

The first aim of the present work (see also [20]) 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 that treated them as cold systems [18]. At the same time, the results obtained using 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. [21]).

The second aim of our work (see also [15]) is to calculate the T-dependent NSE for the nuclei from the mentioned isotopic chains, their proton and neutron rms radii as well as the sizes of neutron skins using an alternative method based on the LDA, the Skyrme EDF and the HFBTHO code.

THE FORMALISM AND RESULTS WITHIN THE CDFM

The expression for the nuclear energy given in the droplet model can be written as [22, 23]:

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

In Eq. (1) B ≃ 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 in the liquid model (see Ref. [22], where it is defined by S^{S*}).

In our previous work [15] we studied the temperature dependence of the NSE, $S(T)$. For the aims of the present study we will rewrite the symmetry energy [the third term in the right-hand side of Eq. (1)] in the form

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

where

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

with

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

In the case of infinite nuclear matter, where $A \to \infty$ and $S^S / S^V \to 0$, we have $S(T) = S^V(T)$. Also at large A Eq. (3) can be written in the known form (see Ref. [24]):

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

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:

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

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

In what follows we use essentially the CDFM scheme to calculate the NSE and its components (see Refs. [8, 9, 18]) in which the one-body density matrix $\rho(\mathbf{r},\mathbf{r}')$ is a coherent superposition of the one-body density ma-

trices $\rho_x(\mathbf{r},\mathbf{r}')$ 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:

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

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

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

We have shown in our previous work [11, 12, 18] that the NSE in the CDFM for temperature $T = 0$ MeV can be obtained in the form:

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

where the symmetry energy for the ANM that depends on the density $S[\rho(x)]$ has to be determined using a chosen EDF (in [18] Brueckner and Skyrme EDF's have been used).

Correspondingly, we calculated the pressure (p_0) and the curvature (ΔK) within the CDFM at $T = 0$ MeV from the expression:

$$p_0 = \int_0^\infty dx|\mathcal{F}(x)|^2 p_0^{ANM}(x), \quad (11)$$

$$\Delta K = \int_0^\infty dx|\mathcal{F}(x)|^2 \Delta K^{ANM}(x), \quad (12)$$

where

$$p_0^{ANM}(x) = \rho_0^2\frac{\partial S[\rho(x)]}{\partial\rho}\bigg|_{\rho=\rho_0}, \quad (13)$$

$$\Delta K^{ANM}(x) = 9\rho_0^2\frac{\partial^2 S[\rho(x)]}{\partial\rho^2}\bigg|_{\rho=\rho_0}. \quad (14)$$

In the present work the T-dependent NSE $S(T)$, the pressure p_0 and the curvature ΔK are calculated by expressions similar to Eqs. (10) - (12), correspondingly, but containing T-dependent quantities. The NSE has the form

$$S(T) = \int_0^\infty dx|\mathcal{F}(x,T)|^2 S[\rho(x,T)]. \quad (15)$$

In Eq. (15) the weight function $|F(x, T)|^2$ depends on the temperature through the temperature-dependent total density distribution $\rho_{\text{total}}(r, T)$:

$$|\mathcal{F}(x,T)|^2 = -\frac{1}{\rho_0(x)}\frac{d\rho_{total}(r,T)}{dr}\bigg|_{r=x}, \quad (16)$$

where

$$\rho_{\text{total}}(r,T) = \rho_p(r,T) + \rho_n(r,T). \quad (17)$$

In Eq.(17) $\rho_p(r, T)$ and $\rho_n(r, T)$ are the proton and neutron T-dependent densities that in our work [15] were calculated using the HFB method with transformed harmonic-oscillator basis and the HFBTHO code [16].

Following Refs. [18, 25–28] an approximate expression for the ratio $\kappa(T)$ can be written in terms of the CDFM:

$$\kappa(T) = \frac{3}{R\rho_0}\int_0^\infty dx|\mathcal{F}(x,T)|^2 x\rho_0(x)\left\{\frac{S(\rho_0)}{S[\rho(x,T)]} - 1\right\}, \quad (18)$$

Where $|F(x, T)|^2$ is determined by Eq. (16), $R = r_0A^{1/3}$ [28] 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. [18]. In what follows, we use as an example the commonly employed power parametrization for the density dependence of the symmetry energy (e.g., [27, 28])

$$S[\rho(x,T)] = S^V(T)\left[\frac{\rho(x,T)}{\rho_0}\right]^\gamma. \quad (19)$$

There exist various estimates for the value of the parameter γ. For instance, in Ref. [28] $\gamma = 0.5 \pm 0.1$ and in Ref. [27] $0.54 \leq \gamma \leq 0.77$. The estimates in Ref. [29] (Table 2) of the NSE based on different cases within the chiral effective field theory and from other predictions lead to values of $\gamma = 0.60 \pm 0.05$ (N^2LO), $\gamma = 0.55 \pm 0.03$ (N^3LO), $\gamma = 0.55$ (DBHF) and 0.79 (APR [30]). Another estimate of $\gamma = 0.72 \pm 0.19$ is also given in Ref. [31].

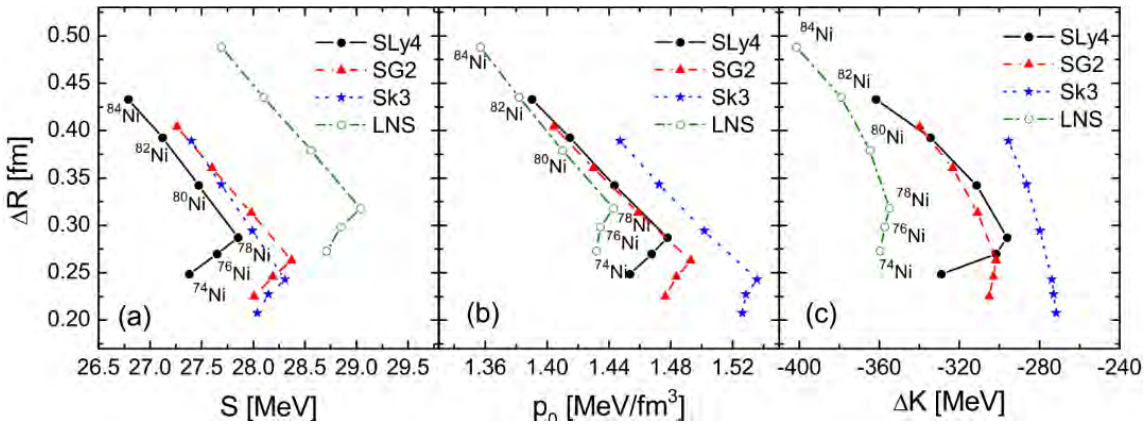

Fig. 1: HF+BCS neutron skin thicknesses ΔR for Ni isotopes as a function of the symmetry energy s (a), pressure p_0 (b), and asymmetric compressibility ΔK (c) calculated with SLy4, SG2, Sk3, and LNS forces.

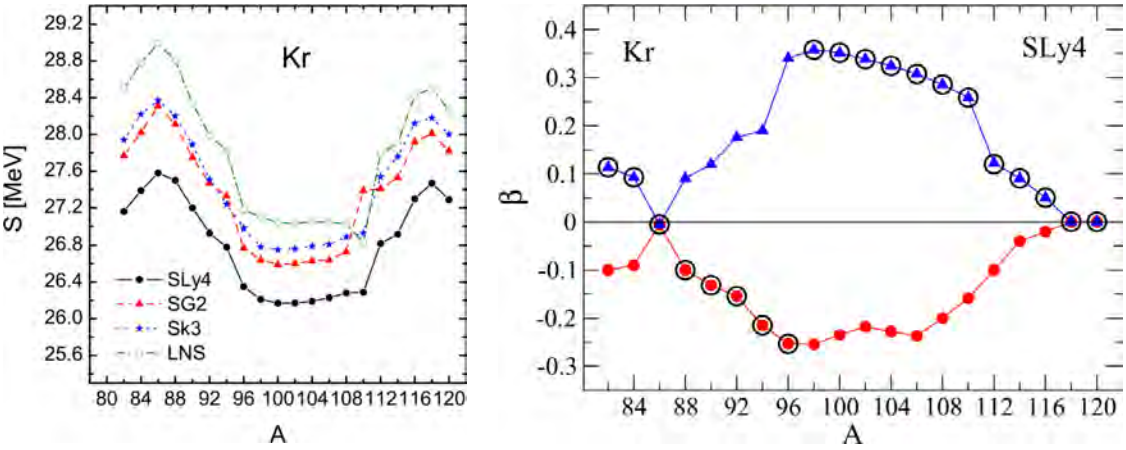

Fig. 2: Left: The symmetry energies s for Kr isotopes (A = 82-120) calculated with SLy4, SGII, Sk3, and LNS forces. Right: The quadrupole parameter β as a function of the mass number A for the even-even Kr isotopes (A = 82-120) in the case of SLy4 force.

In Fig. 1 we give the results in the case of $T = 0$ MeV for the neutron-skin thickness ΔR of the Ni isotopic chain and its correlations with S, p_0, and ΔK obtained in our work [11] using the CDFM and the deformed self-consistent mean-field Skyrme HF+BCS method using SLy4, SG2, Sk3, and LNS forces. It is seen from Fig. 1(a) that there exists an approximate linear correlation between ΔR and S for the even-even Ni isotopes with A = 74-84. A smooth growth of the NSE until the double-magic ^{78}Ni (N = 50) and then a linear decrease of S while the skin thickness increases can be seen. A similar approximate linear correlation between ΔR and p_0 for the Ni isotopes (Fig. 1(b)) and a less strong correlation between ΔR and ΔK (Fig. 1(c)) is observed.

In Fig. 2 (left) the NSE S is given as a function of A for the whole Kr isotopic chain (A = 82-120). One can observe peaks of S at the semi-magic ^{86}Kr (N = 50) and ^{118}Kr (N = 82) nuclei. A flat area is found surrounded by the transitional regions with A = 88-96 and A = 110-116. These results are closely related to the estimate of the quadrupole parameter $\beta = \sqrt{\pi/5}Q/\left(A\langle r^2\rangle^{1/2}\right)$ (Q being the mass quadrupole moment and $\langle r^2\rangle^{1/2}$ the nucleus rms radius) as a function of the mass number A (see Fig. 2 (right)). One can see that the semi-magic ^{86}KR and ^{118}Kr isotopes are spherical, while the open-shell Kr isotopes within this chain possess two equilibrium shapes, oblate and prolate. The transitional regions from spherical to well deformed shapes correspond to transitions from the peaks to the valley in the symmetry energy.

In Fig. 3 are given, as an example, the results for the T-dependent NSE $S(T)$, its volume $S^V(T)$ and surface $S^S(T)$ components, as well as their ratio $\kappa(T) = S^V(T)/S^S(T)$ for the Ni chain obtained in the calculations using relationships (15)-(19) with the weight function $|F(x, T)|^2$ from Eqs. (16)-(17). The T-dependent proton $\rho_p(r, T)$,

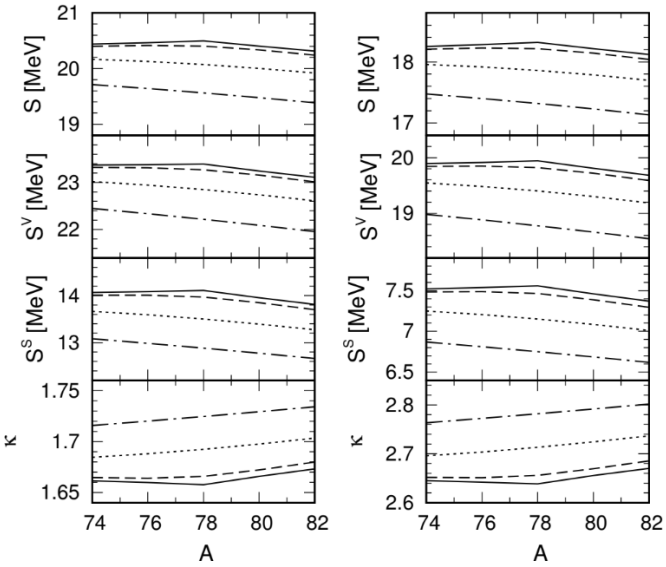

Fig. 3: Mass dependence of the NSE $S(T)$, its volume $S^V(T)$ and surface $S^S(T)$ components and their ratio $\kappa(T)$ for nuclei from the Ni isotopic chain at temperatures $T = 0$ MeV (solid line), $T = 1$ MeV (dashed line), $T = 2$ MeV (dotted line), and $T = 3$ MeV (dash-dotted line) calculated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

neutron $\rho_n(r, T)$ and the total $\rho_{\text{total}}(r, T)$ [Eq. (17)] density distributions were calculated using the HFBTHO code from [16] with the Skyrme EDF for the SkM* and SLy4 forces. The results are presented for two values of the parameter $\gamma = 0.3$ and 0.4. As can be seen, the calculations in the case of $\gamma = 0.4$ for $\kappa(T)$ are compatible with the published values of κ extracted from nuclear properties presented in [28] ($2.0 \le \kappa \le 2.8$), such as the isobaric analog states and skins [25] and masses and skins [26]. 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. Within each isotopic chain the quantities S, S^V, and S^S decrease with increasing mass number, whereas κ increases for both Skyrme forces and for any T ranging from 0 MeV to 3 MeV. The studied quantities are sensitive to the values of the parameter γ used to parameterize $S[\rho(r, T)]$ in Eq/ (19). In the case of $\gamma = 0.3$ our results are in agreement with those from Ref. [28] ($1.6 \le \kappa \le 2.0$). We note also that there are "kinks" in the curves of $S(T)$, $S^V(T)$, and $S^S(T)$, and $\kappa(T)$ for $T = 0$ MeV in the case of the double closed-shell nucleus ^{78}Ni. A "kink" is also observed for $T = 0$ MeV in the case of ^{132}Sn in the Sn chain, while no "kinks" are seen in the Pb chain.

In our work [20] a comparison with results using alternative parametrizations of the density dependence of the symmetry energy (e.g., from Refs. [32, 33]) has been presented.

THE FORMALISM AND RESULTS USING THE LDA

In this Section we present results of our studies (see also Ref. [15]) using the LDA of the T-dependence of NSE [here noted by $e_{sym}(A, T)$] and other nuclear structure properties for even-even Ni, Sn, and Pb nuclei. The Skyrme EDF with SkM* and Sly4 forces is used. The main ingredients of our calculations are the T-dependent proton and neutron density distributions, as well as the kinetic energy densities. Our results for the densities and the related quantities obtained through the HFBTHO code are given in Ref. [15].

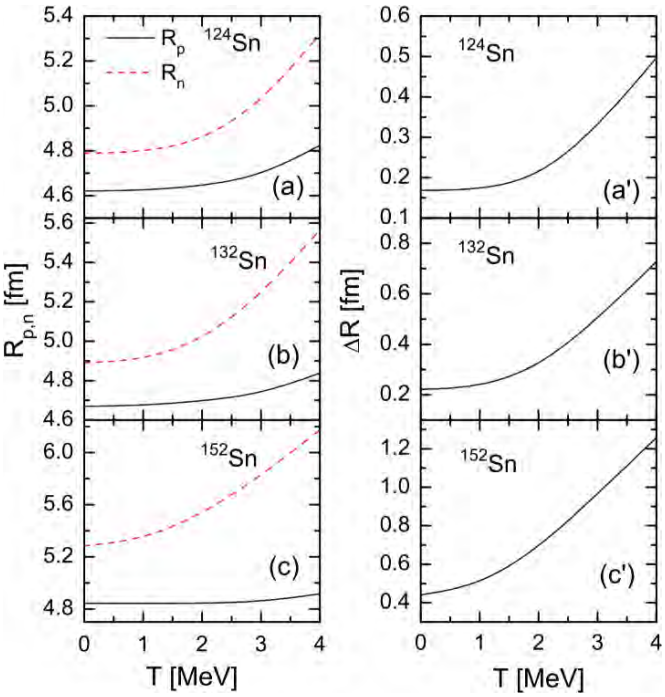

Fig. 4: Left: Proton R_p (solid line) and neutron R_n (dashed line) radius of ^{124}Sn, ^{132}Sn, and ^{152}Sn isotopes with respect to the temperature T calculated with SLy4 interaction. Right: Neutron skin thickness ΔR for the same Sn isotopes as a function of T.

Here we present in Fig. 4, as an example, the T-dependent proton and neutron rms radii and the corresponding neutron skin thickness in the case of $^{124, 132, 152}$Sn nuclei. It can be seen that the effect of temperature leads mainly to a substantial increase of the neutron radii and skins.

Concerning the NSE, here we give one of our approaches that is based on the following expression for $e_{sym}(A, T)$:

$$I^2 e_{sym}(A,T) = \int d\vec{r} \left[\frac{\mathcal{E}(\rho_A(r),\delta,T)}{A} - \frac{\mathcal{E}(\rho_{A_1}(r),\delta=0,T)}{A_1} \right], \quad (20)$$

where $I = (N-Z)/A$, $\delta(r) = [\rho_n(r)-\rho_p(r)]/\rho(r)$ and $\varepsilon(r, T)$ is the total energy density of the system obtained in our case from the Skyrme EDF for infinite homogeneous nuclear matter. The second term in the right-hand side of Eq. (20) is analogous for the isotope with $A_1 = 2Z$ ($N_1 = Z = A_1/2$). For example, for the Ni isotopic chain the nucleus A_1 is the doubly-closed shell nucleus ^{56}Ni ($Z = N_1 = 28$), while for the Sn isotopic chain the nucleus with mass number A_1 is the doubly-closed shell nucleus ^{100}Sn ($Z = N_1 = 50$). Thus, both ^{56}Ni and ^{100}Sn isotopes play a role of reference nuclei. For the case of the Pb chain we use again ^{100}Sn as a reference nucleus because there do not exist appropriate bound nuclei for the purpose.

The results for the NSE $e_{sym}(A, T)$ obtained by using Eq.(20) for several nuclei from Ni (A = 70-82), Sn (A = 124-140) and Pb (A = 206-214) isotopic chains with the SkM* force are presented in Fig.5. The NSE exhibits almost flat behavior for the double-magic ^{78}Ni and ^{132}Sn nuclei. In general, for all isotopic chains considered and for both Skyrme forces used in the calculations, the symmetry energy coefficient decreases smoothly with increase of the mass number in the same temperature interval. Concluding, the results for $e_{sym}(A, T)$ calculated in our work (see also Ref. [15]) for various isotopes are in good agreement with theoretical predictions for some specific nuclei reported by other authors. At the same time, however, in our paper [15] we pointed out the dependence of the results for $e_{sym}(A, T)$ on various definitions of this quantity.

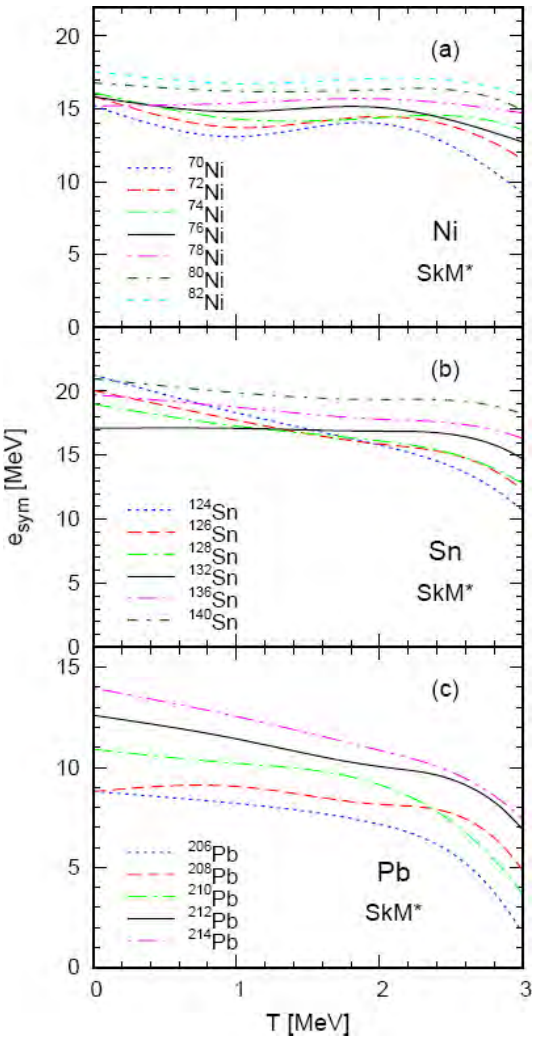

Fig. 5: Temperature dependence of the symmetry energy coefficient e_{sym} obtained by using Eq. (20) for several nuclei from Ni (A = 70–82) (a), Sn (A = 124–140) (b), and Pb (A = 206–214) (c) isotopic chains with SkM* force. The nucleon densities and kinetic energy densities used to calculate e_{sym} are consistently derived from the HFBTHO code.

CONCLUSIONS

In Section II of the present work we presented the results of 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 was based on the local density approximation. It used the coherent density fluctuation model [8, 9] with T-dependent proton $\rho_p(r, T)$, neutron $\rho_n(r, T)$, and total $\rho_{\text{total}}(r, T) = \rho_p(r, T) + \rho_n(r, T)$ density distributions. The latter were calculated using the self-consistent Skyrme HFB method using the cylindrical transformed harmonic-oscillator basis (HFBTHO) [16, 17] and the corresponding code with SkM* and SLy4 Skyrme forces. The quantities of interest were calculated for the isotopic chains of Ni, Sn, and Pb nuclei.

The main results of Section II (see also [20]) 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) The quantities $S(T)$, $S^V(T)$, $S^S(T)$, and $\kappa(T)$ are sensitive to the values of the parameter γ used to parametrize $S[\rho(x, T)]$ in Eq. (19). 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. [18]), for the T-dependent NSE [15] and are compatible with the available experimental data.

(iv) In the cases of double-magic ^{78}Ni and ^{132}Sn nuclei we observed "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.

We note that the kinks disappear as T increases, demonstrating its close relationship with the shell structure.

The results presented in Section III (see also [15]), and obtained in an approach using the LDA, the Skyrme EDF and HFBTHO code, can be summarized as follows:

(i) The increase of the temperature leads mainly to a substantial growth of the neutron radius and skin thickness.

(ii) For the Ni, Sn, and Pb isotopic chains and for both Skyrme forces (SkM* and SLy4) used in the calculations, the symmetry energy coefficient decreases smoothly with the increase of the mass number in the considered temperature interval.

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