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Nuclear Matter Properties of Deformed Neutron-Rich Exotic Nuclei

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Abstract. The symmetry energy, the neutron pressure and the asymmetric compressibility of deformed neutron-rich even-even nuclei are calculated on the examples of Kr and Sm isotopes within the coherent density fluctuation model using the symmetry energy as a function of density within the Brueckner energy-density functional. The correlation between the thickness of the neutron skin and the characteristics related with the density dependence of the nuclear symmetry energy is investigated for isotopic chains of these nuclei in the framework of the self-consistent Skyrme-Hartree-Fock plus BCS method. Results for an extended chain of Pb isotopes are also presented. A remarkable difference is found in the trend followed by the different isotopic chains: the studied correlations reveal a smoother behavior in the Pb case than in the other cases. We also notice that the neutron skin thickness obtained for ^{208}Pb with SLy4 force is found to be in a good agreement with recent data. In addition to the interest that this study may have by itself, we give some numerical arguments in proof of the existence of kinks in Ni and Sn isotopic chains that are not present in the Pb chain.

1 Introduction

The ground states of atomic nuclei are characterized by different equilibrium configurations related to corresponding geometrical shapes. The study of the latter, as well as the transition regions between them, has been a subject of a large number of theoretical and experimental studies (for a review, see, for example, Ref. [1] and references therein). The position of the neutron drip line is closely related to the neutron excess and the deformation in nuclei. Deformed nuclei are expected in several regions near the neutron drip line [2, 3]. In some cases, the deformation energy can impact their existence. For instance, it has been predicted that there exist particle-bound even-even nuclei that have, at the same time, negative two-neutron separation energies caused by shape coexistence effects [2]. In fact, the nuclear deformation increases the surface area, thus leading to a larger surface symmetry energy in a neutron-rich nucleus with a deformed shape. Conversely, the precise determination of the surface symmetry energy is important to describe the deformability of neutron-rich systems and also to validate theoretical extrapolations.

Nowadays, the experimental information about the symmetry energy is fairly limited. The need to have information for this quantity in finite nuclei, even theoretically obtained, is a major issue because it allows one to constrain the bulk and surface properties of the nuclear energy-density functionals (EDFs) quite effectively. In our recent work [4] the Brueckner EDF for asymmetric nuclear matter (ANM) [5,6] was applied to calculate nuclear quantities of medium-heavy and heavy Ni, Sn, and Pb nuclei that include surface effects, namely the nuclear symmetry energy s, the neutron pressure p_0, and the asymmetric compressibility ΔK. For this purpose, a theoretical approach that combines the deformed HF+BCS method with Skyrme-type density-dependent effective interactions [7] and the coherent density fluctuation model (CDFM) (suggested and developed in Refs. [8, 9]) was used. We would like to note the capability of the CDFM to be applied as an alternative way to make a transition from the properties of nuclear matter to the properties of finite nuclei. We have found that there exists an approximate linear correlation between the neutron skin thickness ΔR of even-even nuclei from the Ni ($A = 74 - 84$), Sn ($A = 124 - 152$), and Pb ($A = 206 - 214$) isotopic chains and their nuclear symmetry energies. A similar linear correlation between ΔR and p_0 was also found to exist, while the relation between ΔR and ΔK turned out to be less pronounced. The kinks displayed by Ni and Sn isotopes and the lack of such kink in the Pb chain considered [4] were shown to be mainly due to the shell structure of these exotic nuclei but they deserve further analysis within the used theoretical approach.

Another interesting question is to explore how the nuclear symmetry energy changes in the presence of deformation and correlates with the neutron skin thickness within a given isotopic chain. In the present work (see also [10]), an investigation of possible relation between the neutron skin thickness and the same basic nuclear matter properties in deformed finite nuclei is carried out for chains of deformed neutron-rich even-even Kr ($A = 82-96$) (including, as well, the case of some extreme neutron-rich nuclei up to ^{120}Kr) and Sm ($A = 140 - 156$) isotopes, following the theoretical method of Ref. [4]. We also present for comparison results for an extended chain of Pb ($A = 202 - 214$) isotopes. This is motivated by the significant interest (in both experiment [11–13] and theory [14–17]) to study the neutron distribution and rms radius in ^{208}Pb, aiming at precise determinations of the neutron skin in this nucleus. In addition to the interest that this study may have by itself as well as in combination with the previous calculations of Ref. [4], we give some numerical arguments in proof of the existence of kinks in Ni and Sn isotopic chains that are not present in the Pb chain.

2 Theoretical Framework

The quantity $s^{ANM}(\rho)$, which refers to the infinite system and therefore neglects surface effects, is related to the second derivative of the energy per particle $E(\rho,\delta)$ using its Taylor series expansion in terms of the isospin asymmetry $\delta = (\rho_n - \rho_p)/\rho$, where ρ, ρ_n and ρ_p being the baryon, neutron and proton densities, respectively, (see, e.g., [10, 18, 19]):

$$\begin{aligned} s^{ANM}(\rho) &= \frac{1}{2}\left.\frac{\partial^2 E(\rho,\delta)}{\partial\delta^2}\right|_{\delta=0} \\ &= a_4 + \frac{p_0^{ANM}}{\rho_0^2}(\rho-\rho_0) + \frac{\Delta K^{ANM}}{18\rho_0^2}(\rho-\rho_0)^2 + \cdots . \end{aligned} \tag{1}$$

In Eq. (1) the parameter a_4 is the symmetry energy at equilibrium ($\rho = \rho_0$). In ANM the pressure p_0^{ANM} and the curvature ΔK^{ANM} are:

$$p_0^{ANM} = \rho_0^2 \left.\frac{\partial s^{ANM}(\rho)}{\partial\rho}\right|_{\rho=\rho_0}, \tag{2}$$

$$\Delta K^{ANM} = 9\rho_0^2 \left.\frac{\partial^2 s^{ANM}(\rho)}{\partial\rho^2}\right|_{\rho=\rho_0}. \tag{3}$$

In general, the predictions for the symmetry energy vary quite substantially: e.g., $a_4 \equiv s(\rho_0) = 28 - 38$ MeV while an empirical value of $a_4 \approx 29$ MeV has been extracted from finite nuclei by fitting the ground-state energies using the generalized Weizsäcker mass formula (see, e.g., Ref. [20]). By using the experimental pygmy strength, an average value of $a_4 = 32.0 \pm 1.8$ MeV was obtained from the ^{130,132}Sn analysis [21], that is within the acceptable range of values of a_4 to be around 32.5 MeV coming from various experiments using different experimental probes (for a recent status, see, for example, Ref. [22] and references therein).

In Refs. [4, 10] we calculated the symmetry energy, the pressure and the curvature for *finite* nuclei applying the coherent density fluctuation model. In the CDFM the one-body density matrix $\rho(\mathbf{r},\mathbf{r}')$ of the nucleus is written as a coherent superposition of the one-body density matrices $\rho_x(\mathbf{r},\mathbf{r}')$ for spherical "pieces" of nuclear matter called "fluctons" with densities $\rho_x(\mathbf{r}) = \rho_0(x)\Theta(x - |\mathbf{r}|)$, $\rho_0(x) = 3A/4\pi x^3$:

$$\rho(\mathbf{r},\mathbf{r}') = \int_0^\infty dx |f(x)|^2 \rho_x(\mathbf{r},\mathbf{r}') \tag{4}$$

with

$$\begin{aligned} \rho_x(\mathbf{r},\mathbf{r}') &= 3\rho_0(x)\frac{j_1(k_F(x)|\mathbf{r}-\mathbf{r}'|)}{(k_F(x)|\mathbf{r}-\mathbf{r}'|)} \\ &\times \Theta\left(x - \frac{|\mathbf{r}+\mathbf{r}'|}{2}\right), \end{aligned} \tag{5}$$

where j_1 is the first-order spherical Bessel function,

$$k_F(x) = \left(\frac{3\pi^2}{2}\rho_0(x)\right)^{1/3} \equiv \frac{\alpha}{x} \quad (6)$$

with

$$\alpha = \left(\frac{9\pi A}{8}\right)^{1/3} \simeq 1.52A^{1/3} \quad (7)$$

is the Fermi momentum of the nucleons in the "flucton" with a radius x. In Eq. (4) $|f(x)|^2$ is the weight function that in the case of monotonically decreasing local densities ($d\rho(r)/dr \leq 0$) can be obtained using a known density distribution for a given nucleus:

$$|f(x)|^2 = -\frac{1}{\rho_0(x)} \left.\frac{d\rho(r)}{dr}\right|_{r=x} \quad (8)$$

with the normalization $\int_0^\infty dx|f(x)|^2 = 1$.

The main assumption of the CDFM is that properties of *finite nuclei* can be calculated using the corresponding ones for nuclear matter, folding them with the weight function $|f(x)|^2$. Along this line, in the CDFM the symmetry energy for finite nuclei and related quantities are assumed to be infinite superpositions of the corresponding ANM quantities weighted by $|f(x)|^2$:

$$s = \int_0^\infty dx|f(x)|^2 s^{ANM}(x), \quad (9)$$

$$p_0 = \int_0^\infty dx|f(x)|^2 p_0^{ANM}(x), \quad (10)$$

$$\Delta K = \int_0^\infty dx|f(x)|^2 \Delta K^{ANM}(x). \quad (11)$$

The explicit forms of the ANM quantities $s^{ANM}(x)$, $p_0^{ANM}(x)$, and $\Delta K^{ANM}(x)$ in Eqs. (9), (10), and (11) are defined below. They have to be determined within a chosen method for description of the ANM characteristics. In the present work, as well as in Refs. [4, 10], considering the pieces of nuclear matter with density $\rho_0(x)$, we use for the matrix element $V(x)$ of the nuclear Hamiltonian the corresponding ANM energy from the method of Brueckner *et al.* [5, 6]:

$$V(x) = AV_0(x) + V_C - V_{CO}, \quad (12)$$

where

$$\begin{aligned} V_0(x) &= 37.53[(1+\delta)^{5/3} + (1-\delta)^{5/3}]\rho_0^{2/3}(x) \\ &+ b_1\rho_0(x) + b_2\rho_0^{4/3}(x) + b_3\rho_0^{5/3}(x) \\ &+ \delta^2[b_4\rho_0(x) + b_5\rho_0^{4/3}(x) + b_6\rho_0^{5/3}(x)] \quad (13) \end{aligned}$$

with $b_1 = -741.28$, $b_2 = 1179.89$, $b_3 = -467.54$, $b_4 = 148.26$, $b_5 = 372.84$, and $b_6 = -769.57$. In Eq. (12) $V_0(x)$ is the energy per particle in nuclear matter (in MeV) accounting for the neutron-proton asymmetry, V_C is the Coulomb energy of protons in a flucton, and V_{CO} is the Coulomb exchange energy. Thus, using the Brueckner theory, the symmetry energy $s^{ANM}(x)$ and the related quantities for ANM with density $\rho_0(x)$ (the coefficient a_4 in Eq. (1)) have the forms:

$$s^{ANM}(x) = 41.7\rho_0^{2/3}(x) + b_4\rho_0(x) + b_5\rho_0^{4/3}(x) + b_6\rho_0^{5/3}(x), \qquad (14)$$

$$p_0^{ANM}(x) = 27.8\rho_0^{5/3}(x) + b_4\rho_0^2(x) + \frac{4}{3}b_5\rho_0^{7/3}(x) + \frac{5}{3}b_6\rho_0^{8/3}(x), \qquad (15)$$

and

$$\Delta K^{ANM}(x) = -83.4\rho_0^{2/3}(x) + 4b_5\rho_0^{4/3}(x) + 10b_6\rho_0^{5/3}(x). \qquad (16)$$

In our method (see also [4,10]) Eqs. (14), (15), and (16) are used to calculate the corresponding quantities in finite nuclei s, p_0, and ΔK from Eqs. (9), (10), and (11), respectively. We note that in the limit case when $\rho(r) = \rho_0\Theta(R - r)$ and $|f(x)|^2$ becomes a δ function [see Eq. (8)], Eq. (9) reduces to $s^{ANM}(\rho_0) = a_4$.

3 Results of Calculations and Discussion

An illustration of a possible correlation of the neutron-skin thickness ΔR (the difference of the rms radii of neutrons and protons) with the s and p_0 parameters extracted from the density dependence of the symmetry energy around the saturation density for the Kr isotopic chain is given in Figure 1. The symmetry energy and the pressure are calculated within the CDFM according to Eqs. (9) and (10) by using the weight functions (8) calculated from the densities obtained from self-consistent deformed Hartree-Fock calculations using four different Skyrme forces: SLy4, SGII, Sk3, and LNS. It can be seen from Figure 1 that there exists an approximate linear correlation between ΔR and s for the even-even Kr isotopes with $A = 82 - 96$. Similarly to the behavior of ΔR vs s dependence for the cases of Ni and Sn isotopes [4], we observe a smooth growth of the symmetry energy up to the semi-magic nucleus ^{86}Kr ($N = 50$) and then a linear decrease of s while the neutron-skin thickness of the isotopes increases. This linear tendency expressed for Kr isotopes with $A > 86$ is similar for the cases of both oblate and prolate deformed shapes. We note that all Skyrme parametrizations used in the calculations reveal similar behavior; in particular, the average slope of ΔR for various forces is almost the same. In addition, one can see from Figure 1 a stronger deviation between the results for oblate and prolate shape of Kr isotopes in the case of SGII parametrization when displaying the correlation between ΔR and s. This is valid also for the correlation between ΔR and p_0, where more distinguishable results for both types of deformation are present. The neutron skin thickness ΔR for Kr isotopes correlates with p_0 almost linearly, as in the symmetry-energy case, with an inflexion point transition at the semi-magic ^{86}Kr nucleus. In addition, one can see also from Figure 1 that the calculated values for p_0 are smaller in the case of LNS and SLy4 forces than for the other two Skyrme parameter sets. In general, we would like to note that the behavior of deformed Kr isotopes shown in Figure 1 is comparable with the one found for the spherical Ni and Sn isotopes having a magic proton number that we discussed in Ref. [4]. The small differences just indicate that stability patterns are less regular within isotopic chains with a non-magic proton number.

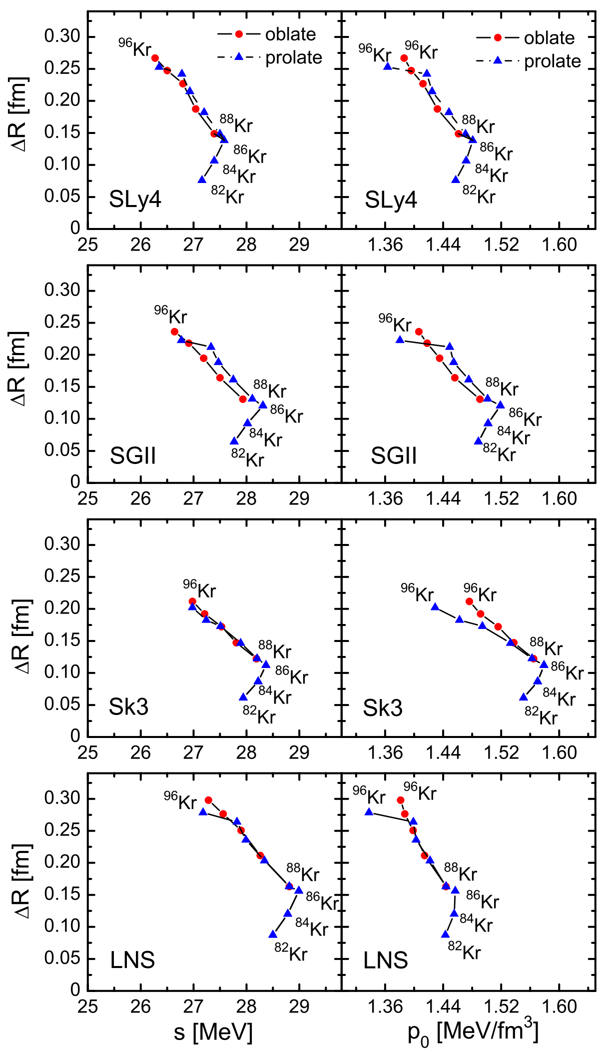

Figure 1. HF+BCS neutron skin thicknesses ΔR for Kr isotopes as a function of the symmetry energy s and the pressure p_0 calculated with SLy4, SGII, Sk3, and LNS forces and for oblate and prolate shapes. The results for oblate and prolate shape for $A = 82, 84$ isotopes are indistinguishable.

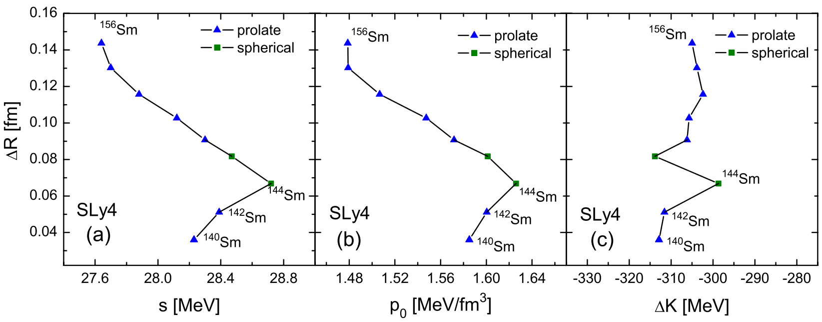

Figure 2. HF+BCS neutron skin thicknesses ΔR for Sm isotopes as a function of the symmetry energy s (a), pressure p_0 (b), and asymmetric compressibility ΔK (c) calculated with SLy4 force.

In Figure 2 we give results for the correlation between the neutron skin thickness and the nuclear matter properties in finite nuclei with SLy4 Skyrme force for a chain of Sm isotopes ($A = 140 - 156$) as a well established example of deformed nuclei. In the calculations, all Sm isotopes are found to have a prolate shape, except for the even-even ^{144}Sm and ^{146}Sm nuclei that are spherical. Similar to the case of Kr isotopes with transition at specific shell closure, we observe a smooth growth of the symmetry energy until the semi-magic nucleus ^{132}Sm ($N = 82$) and then an almost linear decrease of s while the neutron skin thickness of the isotopes increases. An approximate linear correlation between ΔR and p_0 is also shown in Figures 2(b), while Figure 2(c) exhibits a very irregular behavior of ΔR as a function of the asymmetric compressibility ΔK. Nevertheless, the values of ΔK deduced from our calculations are in the interval between –295 and –315 MeV that compare fairly well with the neutron-asymmetry compressibility ($K'_{\Sigma} = -320 \pm 180$ MeV) deduced from the data [23] on the breathing mode giant monopole resonances in the isotopic chains of Sm and Sn nuclei.

The theoretical neutron skin thickness ΔR of Pb nuclei ($A = 202 - 214$) against the parameters of interest, s, p_0, and ΔK, is illustrated in Figure 3. In this work we consider an extended chain of Pb isotopes in comparison to the one analyzed in Ref. [4] by adding two nuclei lighter than ^{206}Pb. Therefore, a more precise study of the corresponding correlations, especially in the transition region at the double-magic ^{208}Pb nucleus, could be made. All predicted correlations manifest an almost linear dependence and no pronounced kink at ^{208}Pb is observed. Similarly to Kr and Sm isotopes presented in this study (and isotopes from Ni and Sn chains described in [4]), the LNS force produces larger symmetry energies s than the other three forces also for Pb nuclei with values exceeding 30 MeV. Another peculiarity of the results obtained with LNS is the almost constant ΔK observed in Figure 3(c). As can be seen from Figure 3, the value of ΔR for ^{208}Pb (0.1452 fm) deduced from the present HF+BCS calculations

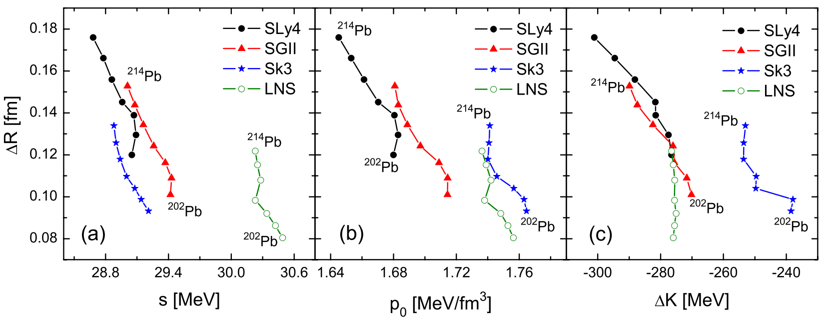

Figure 3. HF+BCS neutron skin thicknesses ΔR for Pb isotopes as a function of the symmetry energy s (a), pressure p_0 (b), and asymmetric compressibility ΔK (c) calculated with SLy4, SGII, Sk3, and LNS force.

with SLy4 force agrees with the recent experimentally extracted skin thickness $(0.156^{+0.025}_{-0.021}$ fm) using its correlation with the dipole polarizability [13].

Following the analysis within the CDFM approach [4], we give in Ref. [10] more detailed study of the weight function $|f(x)|^2$ (that is related to the density and thus, to the structural peculiarities) to understand the kinks observed in the relationships between ΔR and s, as well as ΔR and p_0. The latter were shown to exist [4] in double-magic nuclei in the cases of Ni (at ^{78}Ni) and Sn (at ^{132}Sn) isotopic chains. As one can see in Figures 1 and 2 of the present work, they exist also in the considered cases of Kr (at ^{86}Kr) and Sm (at ^{144}Sm) isotopes. In contrast, such a kink does not exist in the case of Pb isotopic chain (at ^{208}Pb, particularly). Here we would like only to analyze the quantity

$$\Delta s_{\pm} = \frac{s_{A\pm 2} - s_A}{s_A} \tag{17}$$

that is a direct measure of the relative deviation of the symmetry energy with respect to the double-magic nuclei taking them as reference nuclei in each of the chains, where the kinks are expected. The values of Δs_+ and Δs_- are listed in Table 1, where the two numbers for each isotopic chain correspond to the range of integration Δx that contains the peak of $|f(x)|^2$ [10]. One can see first from this Table that the absolute values of Δs_+ and Δs_- for Pb isotopes are comparable with each other, which is not the case for the two other isotopic

Table 1. Relative deviation values of the symmetry energy Δs_+ and Δs_- [Eq. (17)] for the range of integration Δx in Eq. (9) and for Ni, Sn, and Pb isotopes.

	Ni	Sn	Pb
Δs_+	-0.0137	-0.0070	-0.0035
Δs_-	-0.0072	-0.0049	0.0038

chains. Second, and very important is that the Δs_+ value turns out to be negative and Δs_- value to be positive for Pb isotopes at the range of integration Δx, and this is the main difference regarding to the corresponding values (both are negative) in the Ni and Sn chains.

4 Conclusions

A microscopic approach based on deformed HF+BCS calculations with Skyrme forces has been used to investigate possible relationships between the neutron skin thickness of deformed neutron-rich nuclei and the symmetry energy characteristics of nuclear matter for these nuclei. Nuclear matter properties of nuclei from Kr and Sm isotopic chains have been studied by applying the CDFM that provides a transparent and analytic way to calculate the intrinsic quantities by means of a convenient approach to the weight function. The analysis of the nuclear symmetry energy s, the neutron pressure p_0, and the asymmetric compressibility ΔK has been carried out on the basis of the Brueckner EDF for infinite nuclear matter.

For both Kr ($A = 82 - 96$) and Sm ($A = 140 - 156$) isotopic chains we have found that there exists an approximate linear correlation between the neutron skin thickness of these nuclei and their nuclear symmetry energies. Comparing with the spherical case of Ni, Sn, and Pb nuclei described in our previous study [4], we note that the linear correlation observed in the Kr and Sm isotopes is not smooth enough due to their different equilibrium shapes, as well as to the transition regions between them. As known, the latter are difficult to be interpreted as they exhibit a complicated interplay of competing degrees of freedom. Nevertheless, a smoother behavior is observed in Kr isotopes that is a consequence of the stabilization of the oblate shapes along the isotopic chain. As far as Sm isotopes are concerned, the shape evolution from the spherical to the axially deformed configurations in the Sm isotopes causes a less pronounced linearity of the observed correlation between ΔR and s. However, for both classes of deformed nuclei an inflection point transition at specific shell closure, in particular at semi-magic ^{86}Kr and ^{144}Sm nuclei, appears for these correlations of the neutron skins with s and p_0.

We have analyzed in detail the existence of kinks on the example of the Ni and Sn isotopic chains and the lack of such kink for the Pb isotopic chain. From the study in Ref. [4] and the present analysis the kinks displayed by the Ni and Sn can be understood as consequences of particular differences in the structure of these nuclei and the resulting densities and weight functions.

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