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Phase transitions and symmetry energy in nuclear pasta

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Abstract

Cold and isospin-symmetric nuclear matter at sub-saturation densities is known to form the so-called pasta structures, which, in turn, are known to undergo peculiar phase transitions. Here we investigate if such pastas and their phase changes survive in isospin asymmetric nuclear matter, and whether the symmetry energy of such pasta configurations is connected to the isospin content, the morphology of the pasta and to the phase transitions. We find that indeed pastas are formed in isospin asymmetric systems with proton to neutron ratios of $x = 0.3$, 0.4 and 0.5, densities in the range of $0.05\ \text{fm}^{-3} < \rho < 0.08\ \text{fm}^{-3}$, and temperatures $T < 2$ MeV. Using tools (such as the caloric curve, Lindemann coefficient, radial distribution function, Kolmogorov statistic, and Euler functional) on the composition of the pasta, determined the existence of homogeneous structures, tunnels, empty regions, cavities and transitions among these regions. The symmetry energy was observed to attain different values in the different phases showing its dependence on the morphology of the nuclear matter structure.

Keywords: Nuclear pasta; Symmetry energy; Topological transition

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1. Introduction

The effect of the excess of neutrons to protons in the nuclear equation of state (EOS) is characterized by the symmetry energy, $E_{sym}(T,\rho)$, and its importance in phenomena ranging from nuclear structure to astrophysical processes has prompted intense investigations [1,2]. Some of the latest experimental and theoretical studies of the symmetry energy have been at subsaturation densities and warm temperatures [3,4]; the behavior of the symmetry energy at even lower temperatures is still unknown and it is the subject of the present investigation.

Nuclear systems exhibit fascinating complex phenomena at subsaturation densities and warm and cold temperatures. At densities below the saturation density, $\rho_0 = 0.16$ fm^{-3}, and temperatures, say, between 1 MeV and 5 MeV, nuclear systems are well inside a condensed region and can undergo phase transitions.

Experimental reactions [6,5,3] have shown that E_{sym} is affected by the formation of clusters. A recent calculation of the symmetry energy at clustering densities and temperatures [4] obtained good agreement with experimental data, corroborating the Natowitz conjecture [3,7], namely that the asymptotic limit of E_{sym} would not tend to zero at small densities as predicted by mean-field theories.

The problem of estimating the symmetry energy at even lower temperatures is even more challenging. At colder temperatures ($T < 1$ MeV) nuclear systems are theorized to form the so-called "nuclear pasta", which are of interest in the physics of neutron stars [8]. Since neutron star cooling is due mostly to neutrino emission from the core, the interaction between neutrinos and the crust pasta structure is bound to be relevant in the thermal evolution of these stars [9]. An additional challenge of the study of E_{sym} in these cold and sparse systems is that nucleons in the pasta have been found to undergo phase transitions between solid and liquid phases [10] *within the pasta structures* in the context of the classical simulations. Further readings on quantum mechanical simulations of "pasta" can be found in Refs. [11,12].

To study the symmetry energy of such complex systems one must use models capable of exhibiting particle-particle correlations that will lead to clustering phenomena and phase changes. Even though most of the studies of E_{sym} have been based on mean-field approaches [1], the low temperature-low density investigations lie outside the scope of these models as they fail to describe clustering phenomena. To correct for this, some calculations have attempted to include a limited number of cluster species by hand [13–15], by using thermal models [16], or hybrid interpolations between methods with embedded cluster correlations and mean field theories [3].

On the opposite side of the theoretical spectrum, the Classical Molecular Dynamics (CMD) model is able to mimic nuclear systems and yield cluster formation without further parameter adjustments, out of those set at the saturation density (see Section 2.1 for details). This is the model used, for instance, to calculated E_{sym} in the liquid-gas region [4], and to find the solid-liquid phase transition in the pasta [10].

Thus, the questions that occupy us in the present investigation are: do the different phases of the pasta structures found in Ref. [10] survive in non-symmetric nuclear matter in the context of classical simulations? And, how does the symmetry energy behave at low densities and temperatures in this context? *i.e.* within the pasta. In this work we extend the low density calculations of the symmetry energy of Ref. [4] to lower temperatures, and connect them to the morphologic and thermodynamic properties of the pasta found in Ref. [10], but now at proton fractions in the range of 30% to 50%. Our results may be compared with those obtained within the context of other models [17–19].