Finite temperature pasta matter with the TDHF approximation *

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Core-collapse supernova are relevant, e.g., for the synthesis of heavy nuclei and the formation of neutron stars. In such explosions, densities up to the nuclear saturation density as well as temperatures up to about $40\,\mathrm{MeV}$ are reached. If the mean nuclear density reaches about 10% of the nuclear saturation density, the matter forms rods to lower its surface energy. A further increase of density leads to slabs and even to inverted pasta, where the low density gas phase has the shape of the described pasta phases. Pasta shapes can be relevant e.g. for neutrino scattering which is important for the heat transport in a supernova or proto-neutron star.

The pasta matter is investigated here with the time-dependent Hartree-Fock approximation (TDHF) with the code explained in [1]. The wave functions on a 3d grid with periodic boundary conditions are evolved in time with finite time steps of $\Delta t = 0.1\,\mathrm{fm/c}$. For the present calculation a cubic box was taken with a lattice spacing of $1\,\mathrm{fm}$ and a box length of $16\,\mathrm{fm}$.

As initial conditions α-particles are distributed randomly in space keeping a minimal distance between them and in momentum space with a Maxwell-Boltzmann distribution. Free background neutrons are added as plane wave states with Fermi distribution of momenta. The setups are evolved in time until topological stability is reached. Then the temperature is roughly estimated with a Fermi gas approximation.

Fig. 1 exemplifies the emerging shapes, ordered by the mean density at which they appear. At low mean densities nearly spherical nuclei and "rods", infinitely long in one dimension, are found. "Rod(2)" and "rod(3)" are shapes where two or three rods are connected pointing in perpendicular directions. Note that for the slab shape which is doubly periodic and the rod(3) shape the gas and liquid phases are topologically identical. For higher volume fractions, the corresponding bubble shapes appear. All shapes can be uniquely classified by two simple scalar measures of the surface profile (Minkowski scalars), namely the integral mean curvature and the Euler number [2].

Figure 2 shows the map of the resulting pasta shapes. For the lowest temperature the shapes are well ordered. Pasta shapes exist for high temperatures at low densities. But the temperature for the transition to uniform matter decreases with increasing density.

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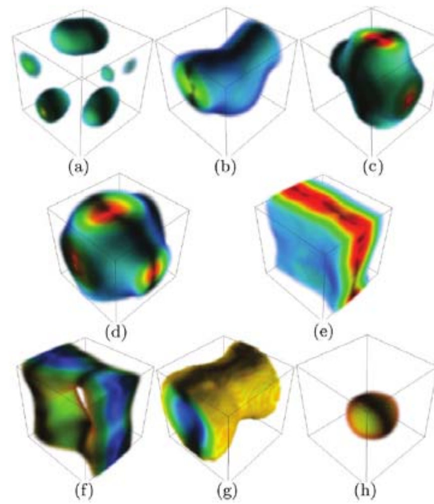

Figure 1: Shapes of pasta structures. Bubble shape illustrations show gas phase, indicated by the color-scale [from $0.03\,\mathrm{fm}$ (blue/light gray) to $0.12\,\mathrm{fm}$ (red/dark gray)]. (a) Sphere. (b) Rod. (c) Rod(2). (d) Rod(3). (e) Slab. (f) Rod(2) bubble. (g) Rod bubble. (h) Sphere bubble. This figure is taken from Ref. [2].

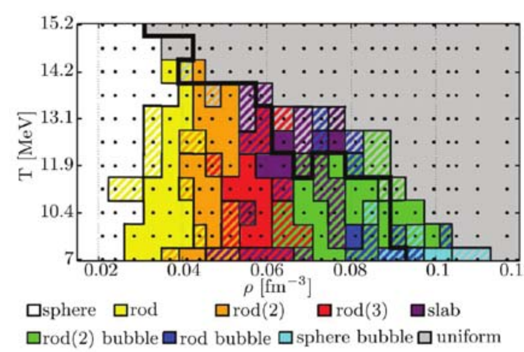

Figure 2: Map of pasta shapes for various temperatures and mean densities. Each dot represents two calculations. This figure is taken from Ref. [2].

References

[1] J. A. Maruhn, P.-G. Reinhard, P. D. Stevenson, and A. S. Umar, Comp. Phys. Comm. **to appear** (2014),arXiv:1310.5946

[2] B. Schuetrumpf, M. A. Klatt, K. Iida, J. A. Maruhn, K. Mecke, and P.-G. Reinhard, Phys. Rev. C **87**, 055805 (2013)