COST Action: MP1304 - Exploring fundamental physics with compact stars (NewCompStar)
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Project time period: March 1 – April 30 2016
Project title: Light clusters in stellar matter

STSM report

Purpose of the STSM

The aim of this work was to compare different mechanisms to evaluate the abundances of light particles, at subsaturation densities, considering different proton fractions and temperatures. In particular, we wanted to evaluate the effect of the clusters couplings used in RMF models [1], with the in-medium corrections modelled within an excluded volume prescription, within a framework of Nuclear Statistical Equilibrium (NSE) models, like the Gulminelli and Raduta (GR) model [2], and with a generalized relativistic density functional (gRDF) approach with cluster mass shifts [3].

Description of the work and main results

At subsaturation densities, light clusters, like deuterons, tritons, helions or alpha particles, can appear in stellar matter, and can modify the neutrino transport, affecting the cooling of the proto-neutron star. Eventually, with increasing density, these clusters will dissolve and a transition to uniform matter will occur. In this work, we were interested in comparing different theoretical mechanisms that allow the suppression of these clusters.

We started by comparing the Coexistence Phase (CP), the Compressible Liquid Drop (CLD) approximations, where heavy clusters are also included [4], together with homogeneous matter with only light clusters, for different RMF models, and considering different temperatures and $\beta-$equilibrium matter. We first considered the clusters vector couplings equal to the nucleons, and the scalar couplings equal to zero. We observed that the CP and CLD approaches make the abundances of the light clusters smaller than in the case where we only have homogeneous matter and light clusters, due to the appearance of these heavy clusters. With increasing temperature, the abundances decrease, though the dissolution density will occur at ~ 0.01 fm^{-3}, for all the temperatures considered. We then considered the case of free clusters, that is, both the vector and scalar couplings are equal to zero, and we observed that the clusters reappear at high densities, this effect being bigger with increasing temperature. This means that we do need to consider in-medium effects. Since we were interested in how the dissolution of these light clusters work, and since we saw that the heavy clusters don't affect this result, we considered the simplest approach, where we only have homogeneous matter and light clusters. We also added the ^7H-cluster to our system, and we considered 3 different cases for the clusters couplings: (1) $g_{v_{clus}} = g_{v_{nuc}}$ and

$g_{s_{clus}} = 0$; (2) $g_{v_{clus}} = g_{s_{clus}} = 0$ (as before); and (3) $g_{v_{clus}} = g_{v_{nuc}}$ and $g_{s_{clus}} = g_{s_{nuc}}$. We concluded that these heavy-H clusters need to be added to the model as they are more abundant than the others, for cases (2) and (3).

Besides the abundances, we were also interested in the behaviour of the free energy density, as this thermodynamical quantity is essential in determining the appearance/disappearance of the light clusters: the clusters are present in the system if their free energy is lower than the homogeneous matter, for each density. We concluded that the free energy density decreases with increasing temperature, and that the light clusters indeed lower the free energy of homogeneous matter, by removing its curvature. The range of densities where the light clusters are present will also be smaller with increasing temperature, until they melt, for some critical temperature. Case (3) does not give reasonable results, since the free energy will decrease after some density.

As said above, in the case of free clusters, we do need in-medium effects to suppress the clusters at high densities. We considered the case where we have a mass shift in the clusters, by including an extra term to their effective masses, $\delta B_i = -f_{hm} A_i/\rho_0$, and the effective mass of the gas remains the same. We then compared this method with the one of Typel *et al* [3] and cases (1) and (2), for different temperatures and proton fractions. We observed that we get similar cluster fractions, when comparing cases (1) or (2) with this new approach, while Typel's predicts higher abundances. The dissolution density is also smaller than Typel's. We also see a big effect on the free energy density for this new method, where we see a much more deep lowering of the free energy, though this effect will become smaller with the increase of the temperature. This correction also allows the suppression of the clusters, for all the temperatures and proton fractions considered.

Foreseen publications

We are now preparing a publication with the results already obtained during the STSM.

Future collaboration with the host institution

We intend to continue our collaboration. In fact, we want to consider $\beta-$equilibrium matter, and zero temperature, to calculate the clusters abundances, using this in-medium correction to the mass clusters. We are also interested in calculating the dissolution density by considering two different situations: $B = 0$ and $f - f_{hm} = 0$. Finally, we plan to implement two other corrections to the mass shifts: one to the gas and the other considering a potential instead.

Confirmation of the host institution

See the attached file.

[1] M. Ferreira and C. Providência, Phys. Rev. C **85**, 055811 (2012).
[2] F. Gulminelli and A. R. Raduta, Phys. Rev. C **92**, 055803 (2015).
[3] S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H. H. Wolter, Phys. Rev. C **81**, 015803 (2010).
[4] H. Pais, S. Chiacchiera, and C. Providência, Phys. Rev. C **91**, 055801 (2015).