COST Action: MP1304 - Exploring fundamental physics with compact stars (NewCompStar)
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Project title: A comparison of equation of state models with different cluster suppression mechanisms

STSM report

Purpose of the STSM

The aim of the present work was to compare the predictions of equation of state (EoS) models with different cluster suppression mechanisms. In particular, we considered the generalized relativistic density functional (gRDF) approach with cluster mass shifts [1] and a model using the excluded-volume mechanism [2]. We explored the density and temperature dependence of the light and heavy clusters abundances and of different thermodynamic properties.

Description of the work and main results

In order to model the transition from clustered matter at subsaturation densities to uniform matter at densities above nuclear saturation and the dissolution of nuclei with increasing temperature, a suppression mechanism for cluster formation has to be implemented in theoretical approaches for the EoS.

A widely used heuristic approach is the excluded-volume mechanism that is based on a geometric picture where every particle is treated as a rigid sphere of finite radius. E.g., in Ref. [3], an ensemble of nucleons and nuclei is considered in statistical equilibrium. Interactions between the nucleons, using a relativistic mean-field (RMF) model, and particular excluded-volume corrections for the nuclei are implemented there.

An alternative approach to model the dissolution of clusters introduces medium-dependent mass shifts. For light nuclei (^{2}H, ^{3}H, ^{3}He, ^{4}He), they are extracted from microscopic calculations of few-body correlations in dense matter and are implemented in a parametrized form in density functionals. For heavy nuclei, suitable extensions of these parametrizations can be used. This method is realized, e.g., in the generalized relativistic density functional (gRDF) approach [1, 4, 5], which is an extension of a conventional RMF model with density dependent couplings [6]. It is based on a grand canonical approach where all thermodynamic quantities are derived from a grand canonical potential density that itself depends on the temperature and the set of chemical potentials of all particles. In this model light and heavy clusters are treated as quasiparticles similar as nucleons. They all contribute as sources for the meson fields. Like the nucleons, light and heavy clusters get a mean-field self-energy leading to a modified effective mass and medium shifts of the chemical potentials.

In order to attribute the differences in the EoS to the different cluster descriptions, it is important to compare models that use the same approach for the interaction in the nucleonic component. Thus we selected two models that are based on the same parametrization (DD2) of the RMF interaction.

For both descriptions, the HS model with excluded volume of Ref. [3] and the gRDF model with cluster mass shifts [1], EoS tables are available in the CompOSE format (http://compose.obspm.fr/). They include thermodynamic properties and information on the chemical composition of matter with a full distribution of light and heavy nuclei. The tables cover broad ranges in density, temperature, and isospin asymmetry, which are relevant in astrophysical applications. We used these available tables to compare the formation and dissolution of light and heavy clusters and their effect on thermodynamic quantities.

In a first step, we compared the HS model with a generalized excluded-volume approach developed by the host [S. Typel, to appear in Eur. Phys. J. A] and with the gRDF model with mass shifts from the formalism point of view in order to understand the main differences. In the HS model, two different available volume fractions are defined, one for the nucleons and another for the nuclei, whereas for the generalized excluded-volume model, the available volume fractions of the particles are considered in a symmetric way. In the HS model, unlike in the gRDF model, the bound nucleons do not contribute to the source term of the meson fields. Hence nuclei do not give a contribution to the mesonic mean fields and the dissolution of clusters at large densities is mimicked only by the excluded-volume mechanism. Mass shifts of the clusters do not appear in the HS model. The temperature-dependence of the degeneracy factors is also treated differently in the models.

For the comparison of the models, we considered stellar matter in $\beta-$equilibrium. We investigated not only the density dependence of the cluster suppression, but also the temperature dependence. For that purpose, we extracted the average baryon number, $< A >$, the average proton number, $< Z >$, and the average mass fraction, X_{heavy}, of the heavy clusters from the available tables. For low temperatures and densities, the two models behave rather similarly. The main differences, which we observed for low temperatures and higher densities, were that the heavy nuclei dissolve more abruptly in the HS model with increasing density, and nuclei with higher mass numbers survive up to this point. The highest average mass numbers, $< A >$, are reached already at baryon number densities of approx. 10^{-3} fm^{-3} in the gRDF model, and the dissolution proceeds more smoothly. When studying the evolution of the heavy clusters with the temperature for fixed values of the baryon density, the mass fraction X_{heavy} drops suddenly in the gRDF model when a temperature of $T \sim 10$ MeV is approached from below. In the HS model, heavy clusters survive to much higher temperatures before they are artificially suppressed at about $T = 50$ MeV. A similar cutoff is introduced for the light clusters in the HS model. In contrast, light clusters, with the exception of the deuteron, can be found at high temperatures in the gRDF model. At temperatures below approx. $T = 10$ MeV, the differences for light clusters are less pronounced.

We were also interested in comparing the thermodynamic quantities of the two different EoS models. There were no distinct differences when we looked at the free energy, pressure and entropy. When comparing these results with the ones without clusters, we did observe, as expected, a decrease in the free energy when clusters are present. That effect is particularly enhanced for $T \leq 1$ MeV.

Foreseen publications

First results of this STSM were already presented at the OPUS7 meeting on November 19 in Warsaw, Poland. We are presently preparing an article with a summary of our investigation, including details of the formalism and the obtained numerical results collected in a number of figures.

Future collaboration with the host institution

It is planned to continue the collaboration between the University of Coimbra and the GSI Helmholtzzentrumm für Schwerionenforschung in Darmstadt. On the one hand, we want to supplement the present work with a detailed comparison of the heavy cluster distributions in the nuclear chart. On the other hand, a further comparison with other models for the cluster description at subsaturation densities is envisaged, e.g., in the framework of a future STSM with the University of Caen in France.

Confirmation of the host institution

See the attached file.

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[1] S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H. H. Wolter, Phys. Rev. C **81**, 015803 (2010).

[2] M. Hempel and J. Schaffner-Bielich, Nucl. Phys. A **837**, 210 (2010).

[3] M. Hempel, J. Schaffner-Bielich, S. Typel, and G. Röpke, Phys. Rev. C **84**, 055804 (2011).

[4] M. Voskresenskaya and S. Typel, Nucl. Phys. A **887**, 42 (2012).

[5] S. Typel, arXiv:1504.01571[nucl-th] (2015).

[6] S. Typel and H. H. Wolter, Nucl. Phys. A **656**, 331 (1999).