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Equation-of-State of Nuclear Matter with Light Clusters

Hermann Wolter[*†]
Faculty of Physics, University of Munich, D-85748 Garching, Germany
E-mail: hermann.wolter@lmu.de

The nuclear equation-of-state (EoS) is an essential ingredient of astrophysical calculations of neutron star structure or core-collapse supernovae, where it is required for a large range of densities (down to densities of about 1/1000 ρ_0), temperatures and charge asymmetries. Because of the latter this also involves the question of the density dependence of the symmetry energy, which is intensely investigated recently in nuclear dynamics and heavy ion collisions. In astrophysical calculations also the composition of the medium in terms of nucleons, light clusters or nuclei embedded in a gas is needed. The low density limit of the nuclear EoS and the symmetry energy is investigated here. It is dominated for not too high temperatures and asymmetries by cluster correlations, which make the symmetry energy finite at zero density, contrary to the behavior of mean field descriptions. We present results for the EoS including cluster correlations in combined quantum statistical (for the medium dependence of the clusters) and generalized Relativistic Mean Field (for the nucleon quasi particle energies) models, from which we obtain the composition and the complete thermodynamical properties. Recently the low-densnity symmetry energy was determined experimentally in a detailed study of central heavy ion collisions at Fermi energies. The comparison of the calculations with the data shows excellent agreement and gives strong support to the importance of clustering at low densities.

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[*] Speaker.
[†] For a list of collaborators see Acknowledgement.

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1. Introduction

The composition and the equation-of-state (EoS) of nuclear matter are widely discussed in several areas of nuclear physics, like for exotic nuclei, and they also attain increasing importance in astrophysics for neutron stars and core-collapse supernovae[1]. For these astrophysical objects, but also partly for exotic nuclei, the EoS is required from almost zero to supersaturation densities, for temperatures from 0 to 100 MeV and for large asymmetries, also including the changing composition in terms of nucleons, light clusters (like deuterons and alpha particles) or heavier nuclei in possibly inhomogeneous phases. At low densities and temperatures cluster correlations will become dominant. In this limit the internal energy should be that of the most bound nuclear cluster existing in this state, e.g. alpha particles or heavier nuclei. At high density these clusters will disolve in the medium and the system will consist of protons and neutros. The description of these clustering processes at low density is the main object of this contribution. This question is closely related to the low density behavior of the nuclear symmetry energy (SE), which generally has been an object of intense investigation in recent years, especially since theoretical predictions vary widely[2]. The SE can be written as the difference of the energy of neutron and symmetric nuclear matter $E_{\mathrm{sym}}(\rho,T) = E_{\mathrm{neutr}}(\rho,T) - E_{\mathrm{nm}}(\rho,T)$. Cluster correlations lead to more binding in symmetric nuclear matter, and the SE should be finite at low densities. Discussion of the SE at higher densities are given in the contribution of W. Trautmann to this conference [3].

Clearly mean field models cannot capture the phenomenon of cluster formation. Suitable approaches are the nuclear statistical equilibrium (NSE) model, cluster-virial expansions [4], and generalized Beth-Uhlenbeck or Quantum Statistical (QS) approaches [5], which are used here. The advantage of this method is that the medium modifications of the clusters at finite density are taken into account. For the nucleon quasiparticle properties for which we employ a RMF model. In Ref. [6] the thermodynamic properties of nuclear matter were derived using this approach. Recently it also has become possible to determine the low density SE in central heavy ion collisions at Fermi energies, where a slowly expanding thermalized hot system is created [7]. We will finally compare the results of our model with these experiments and, in fact, we find a very good agreement [8].

2. Theoretical description of the EoS at low densities

In the QS approach[5] the cluster wave functions are determined in the medium, including the shifts of the nucleon quasiparticle energies and the effect of the Pauli blocking. As a consequence the binding energy of the clusters is weakened with incleasing density and temperature, and finally the clusters are dissolved when the binding energy becomes zero (Mott transition). From these density and temperature dependent binding energies and the corresponding phase shifts the thermodynamical behavior of the system is derived. This approach, however, needs a good model for the nucleon quasiparticle energies as a function of density and temperature. The Relativistic Mean Field (RMF) model has been shown to give reliable results from finite nuclei to heavy ion collisions, in particular when used with density dependent meson-nucleon coupling vertices [9]. We have generalized his model by including as explicit degrees of freedom also light clusters from A=2 to 4 with medium dependent binding energies as given by the QS model. By a combination

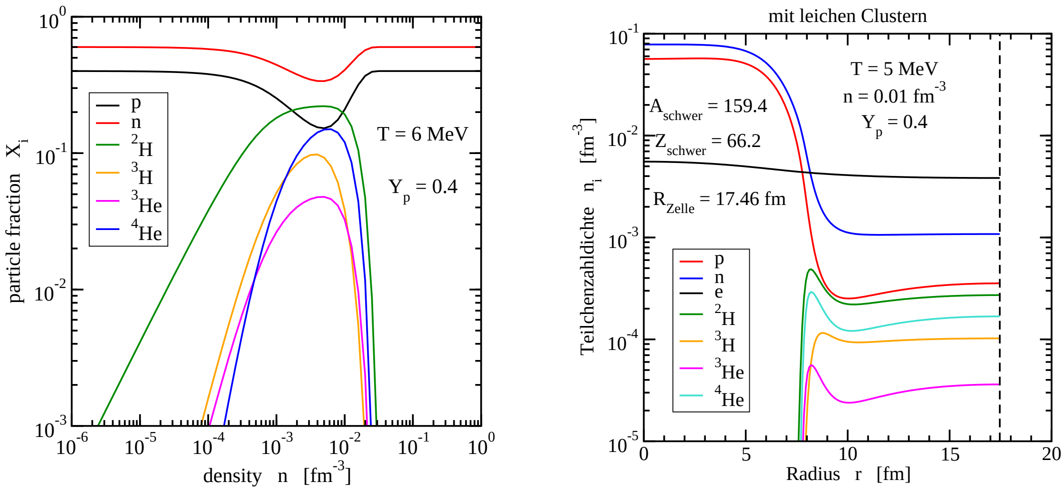

Figure 1: Composition of nuclear matter with clusters: (left) particle fractions for light clusters as a function of baryon density n for T=6 MeV and proton fraction Y_p=0.4. (right) A heavy nucleus embedded in a gas of electrons, nucleons and light clusters calculated in a spherical Wigner-Seitz cell.

of both models we are able to give a realistic description of clustering phenomena in the nuclear medium. The procedure is described in more detail in Ref. [6].

In Fig. 1 (left) we show results of the particle fractions of nucleons and light clusters as a function of density from about 1/1000th to a few times ρ_0 (saturation density) for a slightly asymmetric system (proton fraction Y_p=0.4). Deuterons appear first and then the heavier clusters more or less simultaneously. For about 1/10 ρ_0, the cluster correlations disappear, and the medium consists just of protons and neutron. In this transition region heavier nuclei embedded in the medium should become important. Such nuclei, and possibly lattice-like structures, are expected to be important in the crust of neutron stars. We have investigated such nuclei in a spherical Wigner-Seitz cell approximation, where a heavy nucleus is calculated in interaction with a gas of nucleons, light clusters and electrons for charge neutrality. The composition of the medium in the cell as a function of radius is shown in Fig. 1 (right) for a low density. It is seen that a heavy nucleus of mass about 160 is formed. Light clusters contribute substantially to the gas fraction.

The internal SE per nucleon as the difference of neutron and symmetric nuclear matter is shown by thick curves in Fig. 2 (left) as calculated in the QS model as a function of density for temperatures from 2 to 20 MeV. The thin curves (strongly overlapping and difficult to distinguish) are calculated without cluster correlations, i.e. in the RMF model. It is clearly seen that the SE is enhanced for low densities and temperatures due to the cluster correlations. The T=0 behavior is shown in Fig. 2 (right) for the heavy cluster calculated in the Wigner-Seitz approximation (see the right part of Fig. 1). It is contrasted with an empirical Skyrme-like parametrization of the density dependence of the SE, proposed by Li et al. [2], which has a parameter x to vary the stiffness. As a common feature all parametrizations tend toward zero for zero density, which is clearly not realistic for nuclear matter as a whole. We also note that our RMF parametrization corresponds to a reasonably stiff SE ($x \approx 0$) around saturation density, which is presently favored by fragmentation experiments [3].

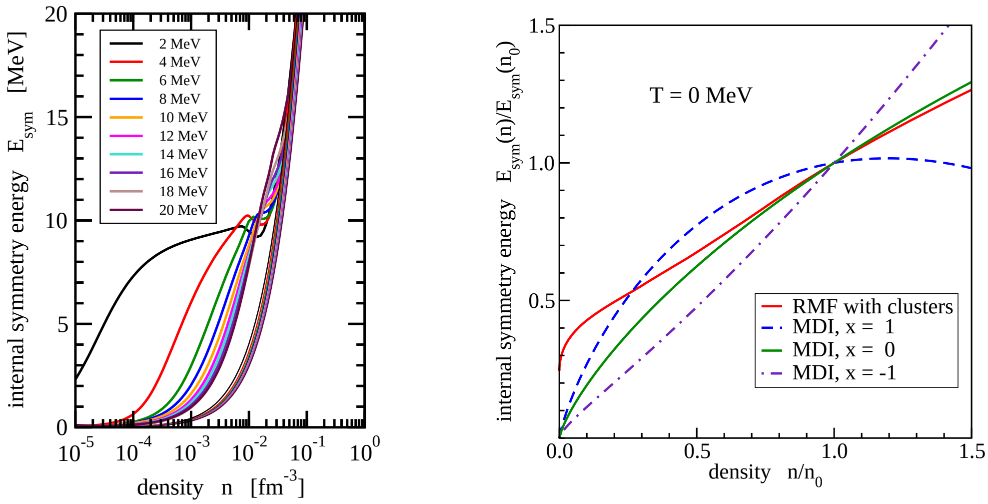

Figure 2: Internal symmetry energy as a function of density: (left) Calculated in the Quantum Statistical model (thick, upper lines) for different temperatures. The thin, lower lines are the results without clusters in the RMF model. (right) E_{sym} scaled at saturation for T=0. Lines labelled MDI are a standard papparametrization of the symmetry energy with asy-stiffnesses varied by the parameter x. The solid, red surve is the result of a calculation including a heavy nucleus embedded in a gas (as in Fig.1 (right)).

3. Comparison to the measured low-density symmetry energy

Is it possible to measure the SE at low density and to confront it to these calculations? Recently, the experimental determination of the SE at very low densities produced in heavy ion collisions of ^{64}Zn on ^{92}Mo and ^{197}Au at 35 MeV per nucleon has been reported [7]. The comparison of the data with our model is given in Ref.[8], where also details of the determination of temperature, density, chemical potential and asymmetry are given. Yields of the light clusters $A \leq 4$ were determined as a function of v_{surf}, the surface velocity before the Coulomb acceleration used as a measure of the time when the particles leave the source under different conditions of density and temperature. The total nucleon densities are of the order of 1/100th to 1/20th ρ_0. An isoscaling analysis of the yield ratios of the two reactions [10] has been employed to determine the free SE F_{sym}. From it the internal SE is calculated with the symmetry entropy taken here in the NSE model. In Fig. 3 the experimentally obtained free and internal SE's are compared to the results of the RMF calculation without clusters and the QS model with clusters [6]. There are large discrepancies in the mean-field approximation (RMF) when cluster formation is neglected. On the other hand, the QS model results correspond nicely to the experimental data.

In conclusion, we have shown that a quantum-statistical model of nuclear matter, that includes the formation of clusters at densities below nuclear saturation, describes quite well the low-density symmetry energy which was extracted from the analysis of heavy-ion collisions. Within such a theoretical approach the composition and the thermodynamic quantities of nuclear matter can be modeled in a large region of densities, temperatures and asymmetries that are required, e.g., in supernova simulations.

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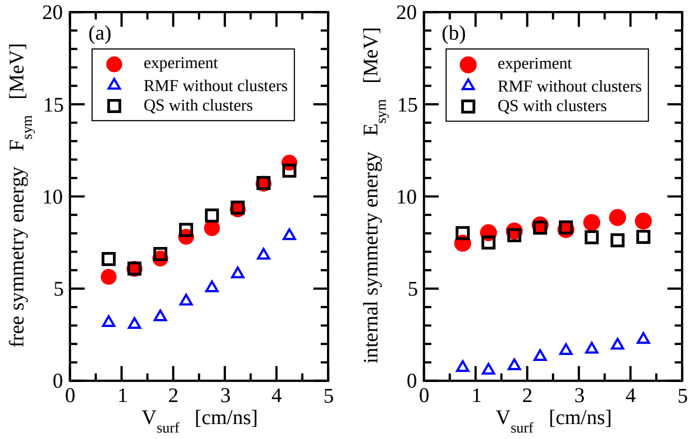

Figure 3: The free (left) and the internal (right) symmetry energy compared to experiment (red dots) as a function of v_{surf} (which is an experimental measure of the time in the heavy ion collision): Blue triangles represent the calulation in the RMF model without clusters, and black squares the calculation in the Quantum Statistical model including medium-modified light clusters.

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