Temperature dependence of single-particle properties in nuclear and neutron matter in the Dirac-Brueckner-Hartree-Fock model

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The understanding of the interaction of nucleons in nuclear and neutron-rich matter at non-zero temperature is important for a variety of applications ranging from heavy-ion collisions to nuclear astrophysics. In this paper we apply the Dirac-Brueckner-Hartree-Fock method along with the Bonn B potential to predict single-particle properties in symmetric nuclear matter and pure neutron matter at finite temperature. It is found that temperature effects are generally small but can be significant at low density and momentum.

I. INTRODUCTION

The nuclear equation of state (EoS) at finite temperature is of fundamental importance for heavy-ion (HI) physics as well as nuclear astrophysics, particularly in the final stages in the evolution of a supernova. Knowledge of the finite-temperature EoS can be of great help in the interpretation of experiments aimed at identifying a liquid-gas phase transition. Presently, findings concerning such transition are very model dependent.

When other aspects, such as spin asymmetries of nuclear/neutron matter are included as well, conclusions are even more contradictory. For instance, the influence of finite temperature on the manifestation of ferromagnetic instabilities is an unsettled question. In Ref. [10], phenomenological Skyrme-type interactions are used in a Hartree-Fock scheme. It is found that the critical density for ferromagnetism decreases with temperature. On the other hand, in Ref. [11] the authors report no indication of ferromagnetic instability at any density or temperature based on the Brueckner-Hartree-Fock (BHF) approximation and the Argonne V18 nucleon-nucleon (NN) interaction. The properties of spin-polarized neutron matter at finite temperature are studied in Ref. [13] with two different parameterizations of the Gogny interaction. The results show two qualitatively different behaviors for the two parameterizations. The reasons for these discrepancies must be carefully studied and their origin understood in terms of specific features of the nuclear force and/or the chosen many-body framework.

Previous work on the temperature dependence of the EoS includes the calculations by Baldo and Ferreira who used the Bloch-De Dominicis diagrammatic expansion [14], Brueckner-Hartree-Fock calculations with and without 3BF [3], and the predictions of Ref. [15] based on the Green’s function method. The entropy per particle in symmetric nuclear matter has been studied in Ref. [16] within the self-consistent Green’s function (SCGF) approach, where both particle-particle and hole-hole scatterings are included. The SCGF framework allows direct access to the single-particle spectral function and thus to all the one-body properties of the system. A most recent work by Rios et al. [17] addresses hot neutron matter within the same approach and performs a comparison with other models. Hot asymmetric matter and β-stable matter have been studied by Moustakidis et al. [18, 19] using temperature and momentum dependent effective interactions.

The study of the many EoS-related aspects in both symmetric and neutron matter starting from realistic NN forces and within a microscopic model is still a considerable challenge. It is the purpose of this paper to report the first part of a comprehensive study of temperature dependence of nuclear and neutron-rich matter properties based on the Dirac-Brueckner-Hartree-Fock (DBHF) approach. An earlier calculation with the DBHF method can be found in Ref. [8]. However, our work will go beyond those predictions, as we plan to address additional aspects such as (spin/isospin) asymmetric matter and temperature dependence of in-medium effective cross sections. Previously, we have confronted isospin asymmetries [20, 21, 22] as well as spin asymmetries [23] effects on the equation of state of cold matter. The inclusion of temperature dependence and the simultaneous consideration of all of the above mechanisms will make our microscopic predictions more broadly useful and capable to reach out to the properties of the hot environment present in the latest stage of a supernova collapse or in the collision of heavy nuclei at intermediate energies.

Next, after a review of the main aspects of the formalism, we will show and discuss predictions of the chemical potential and single-particle properties in symmetric and pure neutron matter. We will concentrate here on the properties of the single-particle within the nuclear medium for the following reason: although the nuclear/neutron matter energy density is certainly an important quantity, the single-particle interaction and its temperature dependence, which determine the one-body properties in the medium, are perhaps more relevant for non-equilibrium processes such as relativistic heavy-ion collisions.

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Hot nuclear and neutron matter are infinite fermionic systems where only the strong interactions among nucleons are taken into account. The temperatures typically considered are of a few tens of MeV, relatively small on the scale of nuclear energies. For instance, at densities near the saturation density of nuclear matter, the free Fermi energy, $\epsilon_F$, is approximately 40-50 MeV, and thus a temperature of 20 MeV is still somewhat low, with $T/\epsilon_F \sim 0.5$.

II. FORMALISM

Within the DBHF method, the interactions of the nucleons with the nuclear medium are expressed as self-energy corrections to the nucleon propagator. That is, the nucleons are regarded as “dressed” particles, essentially a gas of non-interacting quasi-fermions. The behavior of the dressed nucleon is determined by the effective nucleon propagator, which obeys the Dyson equation. Relativistic effects lead to an intrinsically density-dependent interaction which is consistent with the contribution from three-body forces (TBF) typically employed in non-relativistic approaches. The advantage of the DBHF approximation is the absence of phenomenological TBF to be extrapolated at higher densities from experiments where temperature is introduced in the occupation density. In fact, it can be shown that the finite-temperature counterpart, namely the Fermi-Dirac distribution from three-body forces (TBF) typically employed in non-relativistic approaches.

In the quasi-particle approximation, the transition to the temperature-dependent case is introduced by replacing the zero-temperature occupation number with its temperature-dependent form. This quantity is determined by the effective single-particle potential and the self-consistent nucleon-nucleon G-matrix, respectively.

The single-particle energy, $\epsilon(k, \rho, T)$, is now temperature dependent. It can be obtained self-consistently with the Dirac states following the same procedure as used in the zero temperature case, but including Eq. (2) in the calculation of the single-particle potential. At each iteration of the self-consistent calculation, the normalization condition

$$\rho = D \int_0^\infty n_{FD}(k, \rho, T) d^3k$$

allows to extract the microscopic chemical potential, $\mu(\rho, T)$. $D$ is a degeneracy factor, equal to 4 for symmetric unpolarized nuclear matter or 2 for unpolarized neutron matter.

In close analogy with the $T = 0$ case, the single-particle potential and the self-consistent nucleon-nucleon G-matrix are related by

$$U(\vec{k}, \rho, T) = \sum_{I, L, S, J} \frac{(2I + 1)(2J + 1)}{(2t + 1)(2s + 1)} \times$$

$$\times \int_0^\infty n_{FD}(k', \rho, T) G_{NN}^{T, L, S, J}(q(\vec{k}, \vec{k}'), P(\vec{k}, \vec{k}')) d^3k'$$

for two nucleons having momenta $\vec{k}_1$ and $\vec{k}_2$, with relative and total momentum given by $\vec{q} = \frac{\vec{k}_1 - \vec{k}_2}{2}$ and $\vec{p} = \vec{k}_1 + \vec{k}_2$, respectively.
III. RESULTS

A. Symmetric Nuclear Matter

We begin by showing the predicted chemical potential in symmetric nuclear matter (SNM), see Fig. 1. Each curve is an isotherm starting from zero temperature and going up to $T = 30$ MeV in steps of 5 MeV ($\mu$ goes down with increasing temperature). The effect of temperature is definitely larger at the lower densities and increases in size with increasing temperature. Our predictions are in fair qualitative agreement with those shown in Ref. [14], with or without the contribution of TBF, which do not seem to have a major effect on the chemical potential.

Next, we show the single-particle potential in SNM, $U(k, \rho, T)$, see Fig. 2. The effect of temperature is much more pronounced at low density (compare left and right panels) and low momenta. The general tendency is to turn slightly more repulsive with increasing temperature, although this trend becomes clear only at the higher temperature. The increased repulsion is the result of a combination of effects. Temperature “smears out” the step function distribution, Eq. (1), so that the interaction probability increases (decreases) at low (high) momenta due to the smaller (larger) occupation probability as compared to the $T = 0$ case. Although Pauli blocking is generally reduced by the onset of temperature (which would suggest increased attraction among the particles), the integral in Eq. (5) receives contributions from $G$-matrix elements at higher momenta (as compared to the zero temperature case), and such contributions tend to be repulsive. In the end, we observe a net effect that is repulsive, except at the lowest temperatures. Consistently with Fig. 2, the temperature dependence of the effective mass is generally small, see Fig. 3, and more noticeable at low density. Thus, in the range of densities and temperatures considered here, we expect only minor effects on the in-medium cross sections, whose behavior is essentially dominated by the effective mass. A slightly
repulsive temperature effect on the DBHF effective mass was found in Ref. [8] as well.

The single-particle energy, not including the rest mass, is shown in Fig. 4 at fixed density and for different temperatures. Fig. 4 confirms that the single-particle interaction is noticeably impacted only at the lowest momenta. In Ref. [8] the equivalent Schroedinger optical potential was constructed from the Dirac self-energies and found to be remarkably insensitive to temperature.

We conclude this set of results by showing a macroscopic quantity, namely the entropy, which is a measure of thermal disorder. Entropy production in multifragmentation events in heavy-ion collisions is a crucial quantity in the determination of the mass fragment distribution. The entropy per particle is shown in Fig. 5 as a function of density and for various temperatures, and in Fig. 6 it is displayed as a function of temperature at a fixed density (close to saturation density). The entropy increases with temperature, as physically reasonable, and decreases substantially with density. At low T, it is expected to approach a linear dependence due to the fact that, for a Fermi liquid, the relation between S and T should be approximately

$$S \approx \frac{\pi^2}{3\rho} N(T = 0)T,$$

in terms of the density of states at the Fermi surface.

Although weak model dependence is not a general feature of thermodynamic quantities, the authors of Ref. [16] demonstrate that different approximations to the entropy, including the quasi-particle approximation in the temperature dependent BHF scheme, differ from each other by 10 to 20% at most. This may be due to cancelations in the difference between the single-particle energy and the chemical potential [16].

B. Neutron Matter

We have done a similar study of hot neutron matter (NM) as well. The chemical potential in NM is shown
FIG. 9: (color online) The single-particle potential in neutron matter as a function of the momentum at different temperatures: \( T = 0 \) (solid black); \( T = 10 \) (dashed blue); \( T = 20 \) (dash-dotted green); \( T = 30 \) (dotted red). The neutron matter Fermi momentum is equal to 0.9 fm\(^{-1}\).

in Fig. 7 as a function of the Fermi momentum. (Of course, the same Fermi momentum corresponds to half the density as compared to SNM.) The microscopic chemical potential, as obtained from the normalization condition Eq. (4), was shown to be in good agreement with the macroscopic one, obtained from the bulk properties through the derivative of the free energy density [17].

The entropy in NM is displayed in Fig. 8. As for the case of SNM, discrepancies between predictions from different models have been found to be small, especially those arising from the use of different NN potential models [17]. In fact, our predictions (based on the Bonn B potential) are close to those shown in Ref. [17] either with CDBONN [24] or Argonne V18 [12]. Concerning different many-body approaches, there are indications that contributions to the entropy from dynamical correlations (which would fragment the quasiparticle peak) are small. Hence, different predictions tend to approach the “dynamical quasiparticle” result [17].

The temperature dependence of the single-particle interaction in hot NM is comparable to, or smaller than, the one encountered in the SNM case. We show a representative case in Fig. 9. As discussed in Section IIIA, we notice, from Fig. 9 and from the left panel in Fig. 2, that the potential tends to become deeper at first and then more shallow as the temperature increases. Also, temperature appears to “wash out” some of the structure in the potential.

IV. SUMMARY AND CONCLUSIONS

We used the Dirac-Brueckner-Hartree-Fock method extended to finite temperatures to predict single-particle properties in hot SNM and NM. For temperatures up to a few tens of MeV the effect of temperature is small except at low densities and momenta. Due to suppression of Pauli blocking, which is most important at low momentum, some temperature-induced modification of (low-energy) in-medium cross sections could be expected. This is an interesting point to be explored further. We also discussed the entropy/particle. When compared with other predictions in the literature, our results confirm the weak model dependence of this quantity.

As usual, we adopt the microscopic approach for our nuclear matter calculations. Concerning our many-body method, we find DBHF to be a good starting point to look beyond the ground state of nuclear matter, which it describes successfully. The main strength of this method is its inherent ability to effectively incorporate crucial TBF contributions [22] yet avoiding the possibility of inconsistency between the parameters of the two- and three-body systems.

We have focussed on the one-body properties of the system, which are of great relevance for the study of energetic heavy-ion collision dynamics. A continuation of this study, including a close look at all thermodynamic quantities, will be the topic of a forthcoming work.

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