Structure and Dynamics of Dense Nuclear Matter

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REPORT

Short Term Scientific Mission
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PURPOSE OF THE SHORT TERM SCIENTIFIC MISSION

In past years, the Authors of Refs. [1, 2] have developed a procedure to determine the effective interaction in nuclear matter using the Correlated Basis Functions formalism (CBF) and cluster expansion technique. This approach combines the flexibility of perturbation theory on the basis of eigenstates of the non interacting system with a realistic description of short range correlations in coordinate space.

The reliability and accuracy of this scheme, previously applied in neutron matter and compared in Ref. [3] with the results of G-matrix perturbation theory, have been thoroughly investigated by focusing on the fermion hard-sphere system [4, 5], the properties of which have been extensively analysed within perturbative approaches yielding exact results in the low-density limit.

Within the CBF effective interaction approach a systematic investigation of the quasiparticle properties, in-medium scattering cross section and resulting transport coefficients, evaluated exploiting the Abrikosov Khalatnikov formalism, has been carried out in a common project with Prof. Artur Polls form the Department of Structure and Constituents of Matter, University of Barcelona. This project was partially supported by NewCompStar Action through a Short Term Scientific Mission in Fall 2014.

Having established the robustness and the accuracy of the formalism, the next natural step of the project is the application to the description of dense matter of astrophysical interest. This Short Term Scientific Mission was aimed at calculating the self-energy of unpolarized neutron matter and the resulting single particle properties, such as the momentum distribution and the effective mass, following the procedure of Ref. [4].

The enhancement of the effective mass, resulting form the expansion of the self-energy up to second order in the CBF effective interaction, is expected to play a relevant role in the determination of the transport coefficients needed for astrophysical applications. In spite of the fact that the occurrence of this enhancement has been known for over thirty years [6], all existing calculations of the transport coefficients are in fact based on the predictions of first order perturbation theory, which amounts to using the Hartee-Fock approximation.

DESCRIPTION OF THE WORK AND MAIN RESULTS

The fundamental element of this project has been the determination of the two-point Green's function, which has been computed carrying out a perturbative expansion to the self-energy up to second order in CBF effective interaction. This calculation employs the most recent version of the nuclear matter effective interaction, discussed in Ref .[7], which includes an accurate treatment of the contributions of three-nucleon clusters and three-nucleon interactions.

In order to develop a common formalism suitable for describing nuclear matter with different composition, we consider nuclear matter as a mixture of different species, labeled by the index $\lambda = 1, \ldots, 4$, corresponding to spin-up protons, spin-down protons, spin-up neutrons and spin-down neutrons respectively. Within this formalism, the total density is given by

$$\rho = \sum_{\lambda} \rho_{\lambda} \tag{1}$$

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and it is possible to define the relative density $x_\lambda \equiv \rho_\lambda/\rho$, which can be set to $x_1 = x_2 = x_3 = x_4 = 1/4$ in order to describe spin-isospin symmetric nuclear matter, to $x_1 = x_2 = 0$ and $x_3 = x_4 = 1/2$ to describe spin-symmetric neutron matter, or to $x_1 = x_2 = x_3 = 0$ and $x_4 = 1$ (or $x_1 = x_2 = x_4 = 0$ and $x_3 = 1$) to describe fully spin-polarized neutron matter.

The expansion of the self-energy at first order in perturbation theory and the resulting properties of nuclear matter have been employed as a benchmark to test the formalism. The self-energy, evaluated at Hartree-Fock level, the diagrammatic representation of which can be found in Fig. 1a, has been employed to calculate the energy per particle of symmetric nuclear matter and unpolarized neutron matter. These results reproduce the ground-state energy of the corresponding systems, by definition of the CBF effective interaction. The resulting spectra and corresponding effective masses, as expected, are in agreement with the results of previous implementation of the CBF effective interaction.

Then the formalism has been employed to compute the second order contributions to the self-energy, which can be represented by the diagrams of Fig. 1b and 1c.

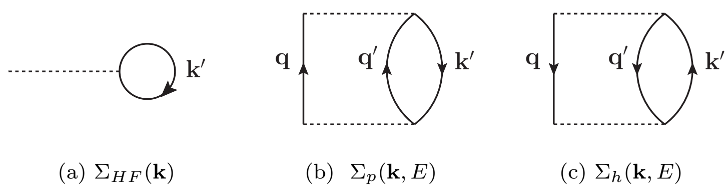


FIG. 1: Diagrammatic representation of the direct part of the first and second order contributions to the irreducible self-energy. Panels (a), (b) and (c) correspond to the Hartree-Fock, polarization and correlation terms, respectively.

Following the approach of Ref. [4], the imaginary and real part of the second order self-energy have been evaluated numerically using the multidimensional integration routines provided by the CUBA library [8]. The numerical evaluation of these objects is quite demanding from the computational point of view, especially for the real part of the self-energy. However, the reconstruction of the complete energy and momentum dependency of the self-energy on a broad range of values is essential for the determination of more dynamical properties of the system, such as the spectral functions. We are currently working on code optimization, in order to reduce the computing time. Preliminary results for the off-shell imaginary and real part are shown in Fig. 2 and Fig. 3 for different value of momenta for low-density neutron matter only.

The same analysis has been extended to spin-polarized neutron matter, employing as a first approximation, the same effective interaction determined for unpolarized neutron matter. The equation of state of polarized neutron matter for asymmetric populations of spin-up and spin-down particles, described by the asymmetry polarization parameter

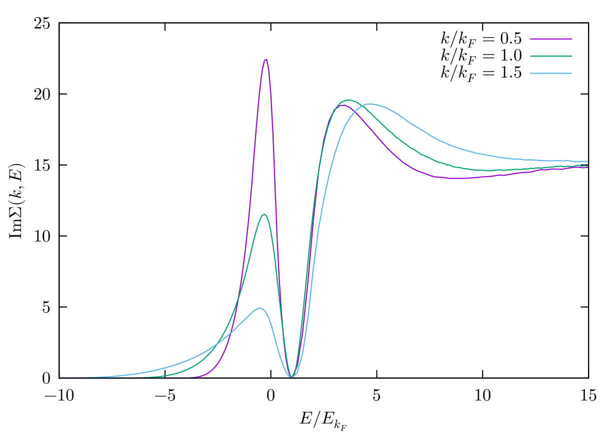


FIG. 2: The imaginary part of the self-energy as a function of the ratio E/E_{k_F} for $k/k_F = 0.5$, 1.0 and 1.5 for unpolarized neutron matter, where E_{k_F} is the Fermi energy and k_F is the Fermi momentum. The density of the system corresponds to a quarter of the saturation density of symmetric nuclear matter ρ_0, $\rho = \rho_0/4$.

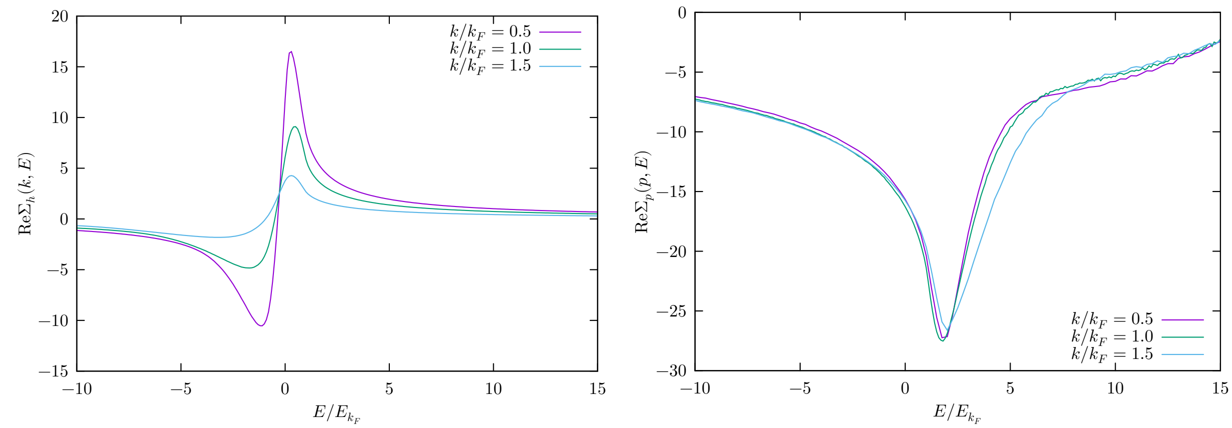


FIG. 3: The real part of the self-energy as a function of the ratio E/E_{k_F} for $k/k_F = 0.5$, 1.0 and 1.5, where E_{k_F} is the Fermi energy and k_F is the Fermi momentum, for unpolarized neutron matter at density $\rho = \rho_0/4$, ρ_0 being the saturation density of symmetric nuclear matter. Left panel correspond to the real part of the contribution of the diagram in Fig. 1b and the right panel to the real part of diagram in Fig. 1c.

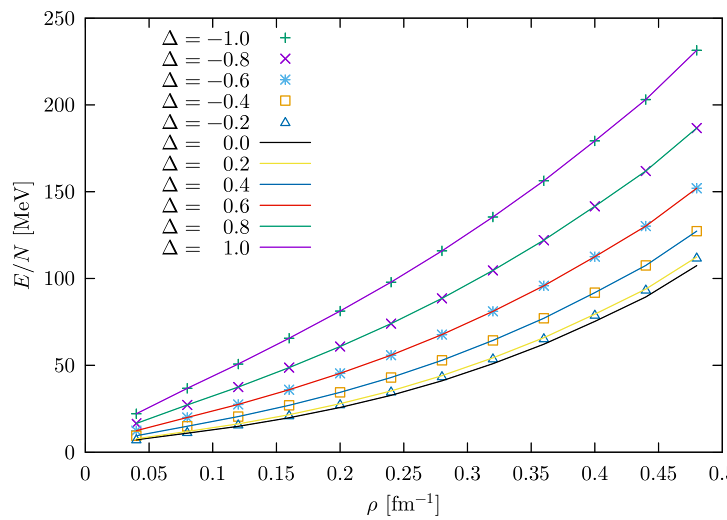


FIG. 4: The energy per particle of spin-polarized neutron matter for different populations of spin-up and spin-down neutrons. Fully spin-polarized neutron matter corresponds to $\Delta = 1$, describing spin-up polarization, and $\Delta = -1$, describing spin down polarization, while the black line, with $\Delta = 0$, corresponds to unpolarized neutron matter.

$\Delta = (\rho_3 - \rho_4)/(\rho_3 + \rho_4)$, can be found in Fig. 4.

In Fig. 5 the effective mass of unpolarized neutron matter ($\Delta = 0$) and fully spin-polarized neutron matter ($|\Delta| = 1$) are compared. Because the polarized system is more weakly interacting, the correction to the effective mass is smaller resulting in a ratio $m^\star/m$ closer to 1.

Employing the Hartree-Fock approximation for the self-energy, we have computed the effective mass of unpolarized neutron matter, which is one of the inputs for the calculation of transport parameters, together with the in-medium scattering cross-section [3, 10]. The latter has been evaluated at Born approximation using the CBF effective interaction. The results for shear viscosity and thermal conductivity are reported in Fig. 6a and Fig. 6b for unpolarized and fully spin-polarized neutron matter, as a function of density. It turns out that the polarized system has larger shear viscosity and thermal conductivity, consistently with the fact that it is closer to a weakly interacting Fermi gas [11].

The analysis of the effect of second order corrections to the transport coefficients will be possible as soon as the calculation of the energy dependence of the real part of the self-energy will be under control. A paper discussing these results, for both unpolarized and spin-polarized neutron matter, will be written.

The project has been carried out in Barcelona with Prof. Artur Polls from the host institution (University of

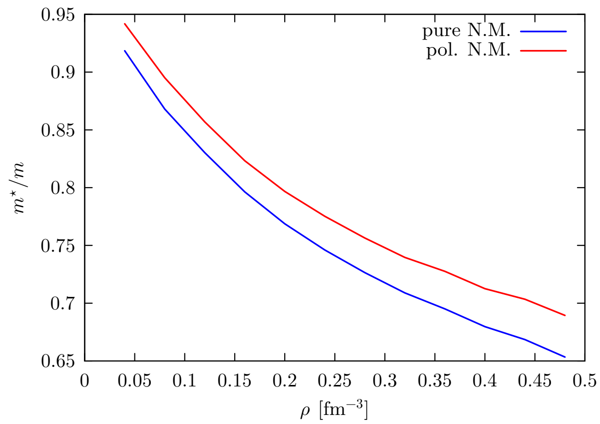
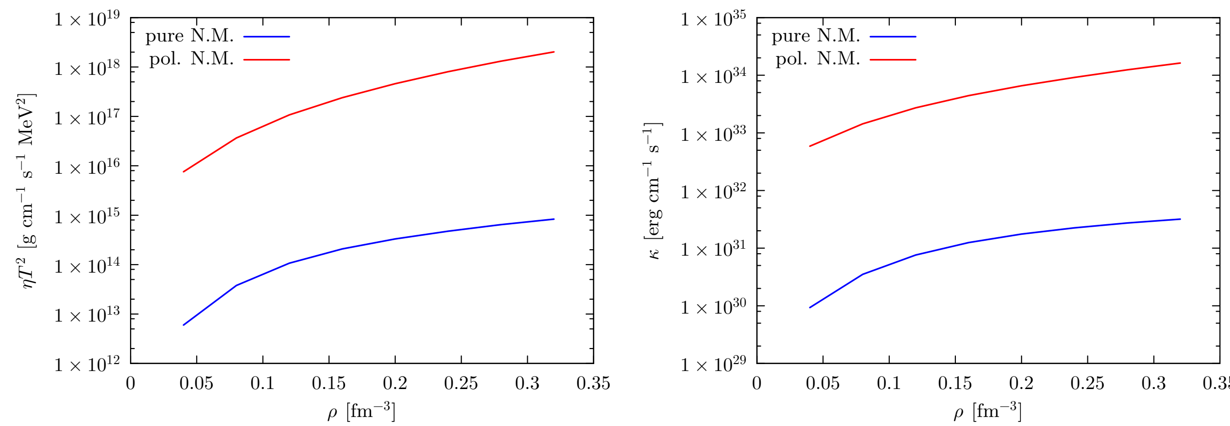


FIG. 5: Density depence of the ratio $m^\star/m$ for unpolarized neutron matter (blu line) e fully spin-polarized neutron matter (red line), obtained form the perturbative expansion of the self-energy up to first order in CBF effective interaction.



(a) The shear viscosity ηT^2 (b) The thermal conductivity κT

FIG. 6: Density dependence of transport coefficients for unpolarized neutron matter (blu line) e fully spin-polarized neutron matter (red line). In the left panel (a) results for the shear viscosity ηT^2 are shown, in the right panel (b) for the thermal conductivity κT.

Barcelona), in collaboration with Prof. Omar Benhar (INFN and "Sapienza" University, Roma), and Dr. Alessandro Lovato (Argonne National Laboratory).

FUTURE PROSPECTS

The advantage of the CBF effective interaction, being determined through a microscopic approach, consists in the capability of providing a consistent description of neutrino emission, scattering an absorption in nuclear matter and allows for taking into account both short and long range correlation effects. The latter mainly determine the response in low-momentum transfer regime, where the collective modes of the system are excited.

The response of neutron star matter to weak interactions is the fundamental ingredient to evaluate its opacity to neutrinos—parametrised in terms of the neutrino mean free path—involved in simulations of supernovae explosions and description of neutron star cooling processes. The natural follow-up of the collaboration will be, then, the application of the CBF effective interaction to the calculation of density- and spin-density response functions at low-momentum transfer, following the lines dictated in Ref. [7], to describe neutrino interactions with nuclear matter.

The obvious second step of the project, which does not involve any further conceptual difficulties, will be the generalisation of the formalism to the description of a system of neutrons, protons and leptons in β-equilibrium, which provides a more realistic model of neutron star matter.

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