Stefano Burrello -

Pairing effects in clustered stellar matter

– purpose of the STSM

The aim of this project is to analyze how the non-homogeneity of crust matter and the associated wide distribution of nuclear species, affects the superfluid properties of the crust. Specifically, we plan to introduce pairing correlations both in the cluster and homogeneous matter component of the NSE model and study the effect of different pairing models on the heat capacity of the inner crust.

– description of the work carried out during the STSM,

The host institution has developed [1] a Nuclear Statistical Equilibrium model that computes the equation of state and properties of stellar matter at finite temperature, by calculating the statistical weight of all the possible Wigner-Seitz cell configurations. The free-energy of the different Wigner-Seitz cells is computed in the Thomas-Fermi approximation.

In the present status of the numerical code corresponding to this model, a phenomenological pairing term is included in the cluster energy functional, but no pairing is considered for the free neutrons.

The code was previously used to calculate supernova matter. For this reason the inputs of the code are the temperature, density and proton fraction. For the present application, we have numerically implemented the beta-equilibrium condition. The equation $\mu_n - \mu_p = \mu_e$ is now iteratively solved in order to find, for each density and temperature, the equilibrium proton fraction. We have then calculated the structure of the NS crust for the 10 representative densities in the inner crust first studied in the seminal paper by Negele and Vautherin [2], and for temperatures ranging from 10 KeV to 2 MeV. For each thermodynamic condition, we have extracted the most probable isotope, as well as the full isotopic distribution, the free neutron and proton densities ρ_{gn}, ρ_{gp} and the average energy, entropy and pressure.

Then we have solved the BCS equations with mean field and pairing interaction functionals consistently extracted from a neutron matter BHF calculation [3], in the same conditions of temperature and chemical potentials as derived from the NSE calculation in the different density cells. From this calculation, the functional relation between density and chemical potentials in the presence of superfluidity, as well as the pairing energy associated to the homogeneous gas component, have been obtained.

– description of the main results obtained,

We have found that the relation $\rho_{gq}(\mu_n, \mu_p, T)$ (q=n,p) obtained with the NSE model is almost indistinguishable from the one extracted from BCS. This means that, in all the thermodynamic conditions considered, the presence of pairing for the free nucleons only induces very slight modifications in the relation between density and chemical potential. As a consequence, the pairing contribution from the free particles can be calculated as a perturbation and the associated energy shift can be simply added to the NSE results in the absence of pairing, without explicitly including pairing in the coupled self-consistent NSE equations.

The comparison of the average Wigner-Seitz cell characteristics at the lowest temperature with the HF results of ref. [2] shows that our macroscopic NSE model reproduces well microscopic density functional results, and residual differences can be ascribed to the choice of the effective interaction used. As the temperature increases, the cluster distributions become larger and already at T=100 KeV the single-nucleus approximation is not adequate to describe the composition of the cell. This means that we can expect to have sizeable differences with respect to standard finite temperature HFB calculations, which systematically employ this approximation.

Finally the analysis of the temperature evolution of the inner crust has already revealed interesting features even in the absence of pairing. The use of a table of measured nuclear masses in the NSE model has allowed to show that loosely bound resonances like H7 become increasingly dominant with respect to heavy nuclei in the inner crust as the temperature increases. This result is at variance with standard finite temperature Hartree-Fock, and can be understood from the fact that a mean-field theory does not correctly treat loosely bound light resonances.

– future collaboration with the host institution (if applicable),

This work is a first contact between the applicant and the host institution. The preliminary results obtained are extremely promising, and a second visit is certainly necessary to reach publishable conclusions. The next steps will be

1. the calculation of the specific heat as a function of density and temperature with inclusion of pairing in the free neutron component as a perturbation, as outlined above.
2. the introduction of a pairing correction in the surface of the clusters in the Local Density Approximation.
3. the analysis of the resulting specific heat and the comparison with the results available in the literature where the cluster distribution and the importance of light resonances was not accounted for [4].
4. the study of the influence of the pairing model on the conclusions.

– confirmation of the host institution of the successful execution of the STSM,

I fully agree on the above report. F.Gulminelli

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1. Ad. R. Raduta, F. Aymard, F. Gulminelli, EPJA 50, 24 (2014).
2. J.W. Negele, D. Vautherin, Nucl. Phys. A 207, 298 (1973).
3. S.Burrello, M.Colonna, F.Matera, Phys. Rev. C 89, 057604 (2014).
4. M.Fortin et al., Phys. Rev. C 82, 065804 (2010).

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