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Impact of pairing effects on thermodynamical properties of clustered stellar matter

The aim of the present work has been to further develop a research project, based on the collaboration between the LPC Caen (host institution) and the INFN-LNS and Catania University, which was recently started thanks to the STSM Grant awarded in October 2014.

The project deals with the study of the influence of pairing effects on the properties of the inner crust of compact stars, characterized by the simultaneous presence of clusters and homogeneous matter.

The host institution has in particular developed a Nuclear Statistical Equilibrium model [1] that computes the composition of stellar matter at finite temperature, by calculating the statistical weight of all the possible Wigner-Seitz cell configurations. Thereby has taken into account that, at finite temperature, not only a single representative nucleus but a wide distribution of nuclei has expected to appear, at a given pressure condition. However, previously, NSE model did not consider pairing correlations.

The presence of pairing obviously modifies the functional relation between density and chemical potential for the neutron gas and we have already observed that pairing cannot be introduced perturbatively, but it has to be consistently added in the gas energy functional of the NSE model.

We have then calculated the structure of the neutron star 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 100 keV to 2 MeV. For each thermodynamic condition, including pairing self-consistently in the NSE code, we solved BCS equations for the homogeneous gas component, with mean field and pairing interaction functionals consistently extracted from a neutron matter BHF calculation [3]. So, solving coupled NSE equations also preserving the condition of beta-equilibrium, we have obtained the most probable isotope, as well as the full isotopic distribution, neutron and proton chemical potentials, the free neutron and proton densities and the average energy, entropy and pressure. In this way, we got several interesting results.

The first new relevant result is the appearance of a discontinuity in the gas densities behavior with the temperature. The introduction of pairing correlations in the NSE model changes indeed in a non-continuous way the composition of stellar matter in correspondence of the critical temperature of the system transition from the normal to the superfluid phase, that is exactly where the pairing gap vanishes. This discontinuity has also reflected in the trend shown by chemical potentials and others thermodynamic quantities.

We have also computed the contribution of the gas to the energy density of star matter through the total volume left after excluding the volume of the clusters and we have analyzed the temperature behavior of the total baryonic energy and of its derivative with respect to the temperature. The temperature derivative has been performed numerically following the trajectory of beta-equilibrium or keeping constant the total proton fraction. In this way only the total baryonic density is constant, but the proton/neutron gas densities are not. We have founded that, as it has been already shown in [4], this derivative exhibits a peak corresponding to the transition from the superfluid to the normal fluid in the neutron gas. The temperature location of the peak is anyway very different from the results of [4]. This is due to the difference in the pairing gap adopted in the two models, demonstrating that not only the amplitude but also the shape and the maximum location of the gap are important to determine the peak position in the specific heat.

Moreover, concerning total baryonic density and specific heat, an important effect appears at higher temperature because of beta equilibrium. Keeping beta equilibrium we get, indeed, at higher temperature, a new significant increase of the specific heat with respect to the same curve achieved maintaining the total proton fraction constant. In this region of temperature charge and mass NSE distribution is quite wide and the most probable cluster becomes a light one. The asymmetry of this kind of resonances is higher than that one obtained for heavy clusters and so, implementing beta equilibrium, total proton fraction strongly decreases when the temperature increase, causing this effect.

Finally, we have also introduced, in a perturbative way, a surface correction on clusters energies adopting the Local Density Approximation. We got that the energy shift caused by these in-medium effects has both negative and positive components, and can lead to an increase or to a decrease of the surface tension, depending on the thermodynamic conditions. Anyway, these effects doesn’t seem to be influenced in a strong way by the pairing and appear more important above all for light resonances. We can anticipate that the inclusion of in-medium effects in a self-consistent way in the NSE model should be increasingly important at high baryonic density, where dominate light resonances, and this will lead to a suppression of very asymmetric clusters with respect to more symmetric ones.

We believe that the present work bears new interesting information on the neutron star cooling problem. We are therefore presently completing the different calculations in order to write a joint publication which we hope to fully finalize before summer 2015. We thank COMPSTAR for the support which has allowed developing in a very short time an entirely new and fruitful collaboration between LPC Caen and LNS Catania.

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] A. 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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