Neutron Stars Opacity and Proton Fraction

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Background: In neutron stars the nucleons are submitted to extreme conditions. The study of this natural occuring objects can lead to further understanding of the behaviour of nuclear matter in highly asymmetric nuclei. Among the characteristics of neutron stars, its neutrino absorption — associated to structural inhomogeneities — stands out as one of the possible magnitudes linked to an observable.

Purpose: We have carried out a systematic study of this neutrino absorption for different thermodynamic conditions in order to assess the impact that the structure has on it.

Method: We study the dynamics of nucleons in conditions according to the neutron star crust with a semiclassical molecular dynamics model, for different densities, proton fractions and temperature, we calculate the long range opacity and the cluster distribution.

Results: The neutrino absorption, the main mechanism for neutron stars cooldown, takes its highest value for temperatures and densities low compared with the inner crust, and a proton fraction is close to the symmetric case $x = 0.5$.

Conclusions: Within the used model the neutrinos are absorbed mostly close to the surface of the neutron star. Also, for high temperatures, a large cluster still exists, but the appearance of several small-sized clusters smears out the very long range order needed for neutrino absorption.

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A neutron star is an astronomical object with a radius of approximately 10 km and a few solar masses. Its structure can be divided in two parts, according to current models [1]: the crust, 1.5 km thick and with a density of up to half the normal nuclear density $\rho_0$; and the core, where the structure is still unknown and remains highly speculative [2]. According to Ravenhall et al. [3], the neutron star’s crust is composed by the structures known as nuclear pasta.

Most neutron stars are supernovae remnants, that happen when the hot and dense iron core of a dying massive star (known as proto-neutron star) collapses. During the collapse, several nuclear processes take place in the inner core of the star — electron capture, photodisintegration, Urca, etc. These processes have a twofold consequence: not only they largely increase the overall neutron number of the system, but also produce a large amount of neutrinos. These neutrinos flow outward, and its emission is the main mean by which the neutron stars cool down. Therefore, the interaction between the neutrinos and neutron star matter is key to comprehend two aspects of a neutron star history: its genesis and its thermal evolution. The interaction between the neutrinos streaming from the core of the proto-neutron star and its outer layers also plays an important role in reversing the collapse that causes the supernova.

The neutron stars’ crust is composed of neutrons and protons embedded in a degenerate electron gas. Protons and neutrons in the crust are supposedly arranged in structures that differ substantially from the “normal” nuclei — the non-homogeneous phases collectively known as nuclear pasta. The structure of this nuclear pasta is linked to the neutrino opacity of neutron stars’ crust, neutron star quakes, and pulsar glitches. Specifically, the neutron star quakes and pulsar glitches are related to the mechanical properties of the crust matter [4], while the neutrino opacity is due to its morphological properties. The enhancement of the crust’s opacity is because of the coherent scattering, related to the static structure factor of nuclear pasta [5]:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{uniform}} \times S(q).$$

And since neutron stars cooling is associated with neutrino emission from the core, the interaction between the neutrinos and the particular structure of the crust would dramatically affect the thermal history of young neutron stars. These neutrinos are produced mainly due to Urca processes, with an energy of $E \approx 1\,\text{MeV}$, that translates into a wavelength of $\lambda_{\text{Urca}} \approx 15\,\text{fm}$.

Several models have been developed to study nuclear pasta, and they have shown that these structures arise due to the interplay between nuclear and Coulomb forces in an infinite medium. Nevertheless, the dependence of the thermodynamic observables has not been studied in depth. The original works of Ravenhall et al. [3] and Hashimoto et al. [6] used a compressible liquid drop model, and proposed the now known as pasta phases – lasagna, spaghetti and gnocchi. From then on, different approaches have been taken, that we classify roughly as mean field or microscopic.

Mean field works include the Liquid Drop Model, by Lattimer et al. [1], Thomas-Fermi, by Williams and Koonin [7], among others [8][13]. Microscopic models in-
include Quantum Molecular Dynamics, used by Maruyama et al. [14, 15] and by Watanabe et al. [10], Simple Semi-classical Potential, by Horowitz et al. [17] and Classical Molecular Dynamics, used in our previous works [18].

In some recent studies, phases different from the typical nuclear pasta were found. The work by Nakazato et al. [13], inspired by polymer systems, found also gyroid and double-diamond structures, with a compressible liquid drop model. Dorso et al. [15] arrived to pasta phases different from those already mentioned with molecular dynamics, studying mostly its characterization at very low temperatures. In our previous work [19] we found new pasta phases that had the same absorption peak in the wavelength of the Urca neutrinos for symmetrical neutron star matter. All these non homogeneous phases add up to what we shall call Generalized Nuclear Pasta (GNP).

Of the many models used to study neutron stars, the advantages of classical or semiclassical models are the accessibility to position and momentum of all particles at all times and the fact that no specific shape is hardcoded in the model, as happens with most mean field models. This allows the study of the structure of the nuclear medium from a particle-wise point of view. Many models exist with this goal, like quantum molecular dynamics [14], simple-semiclassical potential [17] and classical molecular dynamics [20]. In these models the Pauli repulsion between nucleons of equal isospin is either hard-coded in the interaction or as a separate term [21].

In this work, we study GNP with the classical molecular dynamics model CMD. It has been used in several heavy-ion reaction studies to: help understand experimental data [22]; identify phase-transition signals and other critical phenomena [23–26]; and explore the caloric mental data [22]. To study them further we can see in figure 2 the cluster distribution according to MSTE algorithm [18]. The figure shows that for a proton fraction $x = 0.3$ there are many isolated nucleons that are almost exclusively neutrons. These work as a neutron gas that embeds the underlying proton structure.

Another consequence of the neutron gas is that the proton fraction of the GNP structure is slightly higher than the proton fraction in the simulation cell. We can see from figure 2 that the proton fraction in the large cluster is of about $x = 0.33$, while the macroscopic proton fraction is $x = 0.3$. From figure 3 we can see the mass of the biggest cluster, and note that even for very high temperatures ($T = 2.0\text{ MeV}$) a large cluster appears for every proton fraction.

In figure 4 we can see how these changes affect the absorption in the wavelength range of Urca neutrinos. In said figure we show that as the proton fraction decreases, the absorption decreases as well. For every proton fraction studied, the absorption peak falls rapidly for temperatures higher than $T = 0.8\text{ MeV}$, and it is about 1/4 of the peak absorption at $T = 0.5\text{ MeV}$. However, these conditions are rarely met for neutron stars crust, since its matter is usually highly asymmetric and with high temperatures. The reason why as the proton fraction is reduced, so does the absorption can be understood this way: the backbone structure is due to the proton long range coulombic interaction. When there is one neutron for each proton ($x = 0.5$), the neutron structure follows almost identically that of the proton backbone. However, as the neutron proportion rises, the neutron structure is smeared out and its long range correlation begins to vanish. This effect can be seen in the cluster distribution for $x = 0.3$, where we have many isolated neutrons, that are the embedding neutron gas. These characteristics affect the inhomogeneities that appear in $x = 0.5$, suppressing its long range absorption.

From figure 5 we can see that even for very high temperatures ($T = 2.0\text{ MeV}$) a large cluster appears for every
proton fraction. This large structure is the responsible for the long range interaction. The reason why the opacity gets drastically depressed as the temperature rises therefore is not because the large cluster disappears, but because its structure changes.

According to the neutron stars models [1], as we get deeper into the neutron star: the proton fraction gets lower; the temperature gets higher; and the density gets higher. Therefore, according to the current model, the transparency to neutrinos increases rapidly as we move away from the surface. This means that the neutrino absorption is produced mostly close to the surface of the neutron star. We also found that the structures obtained are no longer those originally proposed, and catalogued as *lasagna*, *spaghetti* and *gnocchi*. Further analysis of the cluster distribution shows that for high temperatures, even though a large cluster exists, there is no absorption in the neutrinos wavelength. This is due to the fact that the system approaches the homogeneous limit.

We expect these results to be qualitatively correct, but quantitatively dependent on the model chosen to describe the neutron star crust. The model we are using in this work has been extensively studied in collisions and heavy ion physics, that is the reason why we have chosen it to describe quantitatively the neutron star matter. We are currently performing a systematic study of the difference
Figure 2: (Color online) Cluster distribution with MSTE algorithm for temperature $T = 2.0 \text{ MeV}$, density $\rho = 0.04 \text{ fm}^{-3}$ and different proton fractions. For the lowest of the studied proton fractions, $x = 0.3$, the large cluster has a slightly larger proton fraction (about 10% higher) and there are many isolated neutrons.

Figure 3: Mass of the largest cluster for $\rho = 0.04 \text{ fm}^{-3}$ for different values of $x$.

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Figure 4: (Color online) Absorption peak in the Urca wavelength for different proton fractions as a function of temperature and density. It can be seen that the absorption decreases drastically for $T > \sim 0.8$ MeV. We also show here that the absorption is affected by the proton fraction, as can be noted by the scales on the color bar.

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