Neutrino mean free path and in-medium nuclear interaction

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Neutrinos produced during the collapse of a massive star are trapped in a nuclear medium (the proto-neutron star). Typically, neutrino energies (10-100 MeV) are of the order of nuclear giant resonances energies. Hence, neutrino propagation is modified by the possibility of coherent scattering on nucleons. We have compared the predictions of different nuclear interaction models. It turns out that their main discrepancies are related to the density dependence of the k-effective mass as well as to the onset of instabilities as density increases. This last point had led us to a systematic study of instabilities of infinite matter with effective Skyrme-type interactions. We have shown that for such interactions there is always a critical density, above which the system becomes unstable.

A proto-neutron star is formed during the collapse of a massive star. It is mainly composed of electrons, protons and neutrons but its core can contain other particles like hyperons [1]. Neutrinos play a crucial role during the energy liberation phase that follows a supernova collapse [2], as the energy is carried away by neutrino scattering in the newly born neutron star. During the first few seconds of the proto-neutron star, the matter is neutrino rich and the leptonic number is close to that of nuclei. After some tens seconds, at the end of the proto-neutron star, matter is neutrino poor and the neutrino chemical potential is zero. It is important to have an accurate estimate of the mean free path of neutrinos in a nuclear medium where the density is equal or greater to the saturation nuclear matter density, the temperature a few tens of MeV and the proton fraction can reach 30% of the baryonic density [3]. Here, we focus on the properties of nuclear matter for densities between 1 and 3 times ρ_0, the saturation value of symmetric nuclear matter. For such densities we can reasonably assume protons and neutrons as the only hadronic components. Our calculation of the neutrino mean free path is based on equations of state for pure neutron matter and asymmetric nuclear matter, employing effective Skyrme and Gogny nuclear interactions.

We have considered pure neutron matter and asymmetric nuclear matter in β equilibrium and we have calculated cross sections of reactions contributing to the neutrino mean free path. Neutrino scattering off neutrons ($\nu + n \rightarrow \nu' + n'$) is the only contribution in pure neutron matter [4, 5]. In asymmetric matter, neutrinos can also scatter off protons and electrons or be absorbed by neutrons ($\nu + n \rightarrow e^- + p$). We have calculated these processes within the mean field approximation, and also in the framework of the Random Phase Approximation (RPA) [6], to consider the effects of nuclear correlations on the neutrino scattering. Fig. 1 displays our results for pure neutron matter. In Fig. 1(a), the neutrino mean free path is plotted versus the density for temperatures of 5 MeV and 20 MeV. In the case of a free gas with no nuclear interaction (solid line) the mean free path decreases, as expected. Mean field results are also plotted for the Skyrme SLy230a [7] and Gogny D1P [8] interactions (dashed and dotted lines, respectively). The resulting wide range of mean free paths at high density is directly related to the behaviour of the effective mass [6]. The effects of the long range RPA correlations are represented in Fig. 1(b). The ratio between the RPA (λ_n^{RPA}) and mean field (λ_n^{HF}) mean free paths is plotted as a function of the density. Around the saturation density, both interactions predict an increase in the mean free path. However, as the density increases it turns out that spin fluctuations become dominant, reflected in the presence of a spin zero sound mode which eventually produces a strong reduction of the mean free path.

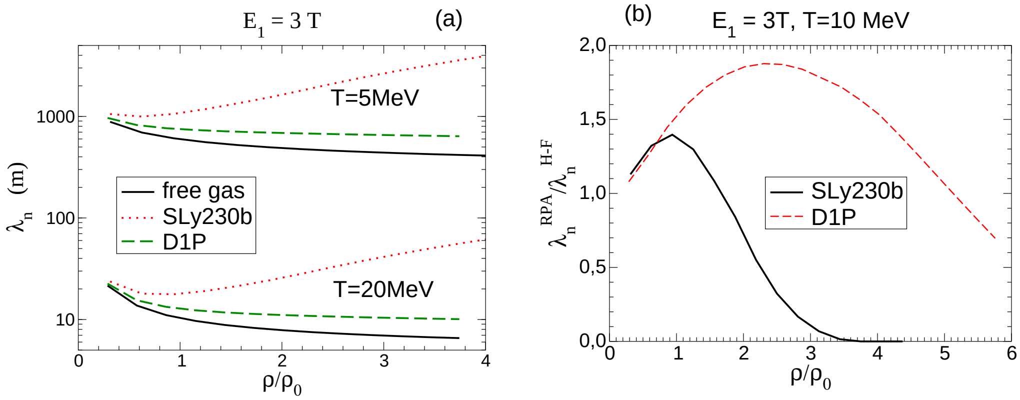

Figure 1. Neutrino mean free path in pure neutron matter versus the density. Several treatments of the nuclear correlations are shown: the mean field approximation (a) and the RPA (b).

For Skyrme type interactions the mean free path vanishes at some density beyond ρ_0, as a consequence of the appearence of spin instabilities. Indeed, at high densities it is energetically favorable for nucleons to completely polarize their spins, and a ferromagnetic transition is always predicted by these interactions. In Fig. 2 we plot the critical density as a function of the proton fraction using several effective interactions. It can be seen that all Skyrme interactions predict ferromagnetism for densities below $\simeq 3.5\rho_0$. In contrast, Gogny type interactions either predict this transition to occur at much higher densities or not occur at all. If a ferromagnetic transition occurs at high densities, we may expect huge modifications of the neutron star properties. For instance, we may observe neutron stars with a ferromagnetic core and a normal neutron liquid around, with a very huge magnetic

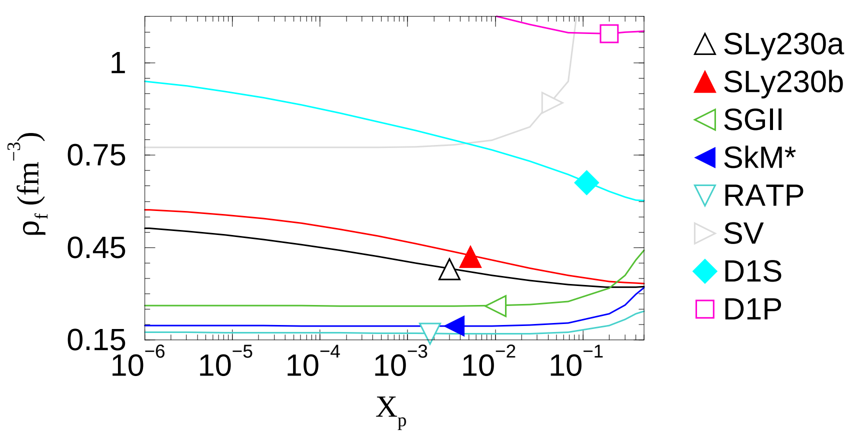

Figure 2. Ferromagnetic phase diagram for Skyrme and Gogny effective interactions.

field on its surface [9]. In this respect, several microscopic calculations based on realistic bare interaction have recently been performed in different frameworks as diffusion Monte Carlo [10] or Brueckner-Hartree-Fock [11, 12]. None of these microscopic calculations confirms the presence of a ferromagnetic instability. This is a strong argument which casts some doubt about the reliability of Skyrme effective interactions beyond saturation density.

We have performed a systematic study of all possible instabilities in symmetric nuclear matter and pure neutron matter predicted by effective Skyrme interactions [13]. The stability conditions are those related to the inequalities that Landau parameters must satisfy. Of course, we impose the interactions to be consistent with currently accepted values for such properties as binding energy, incompressibility, asymmetry energy and surface energy of symmetric nuclear matter at the saturation point. Starting from a general Skyrme interaction with ten parameters, it is possible to show that seven parameters or combinations of parameters can be determined by some of the above mentioned empirical inputs. The problem is thus reduced to the study of instabilities in terms of three parameters, which we choose as $t_1x_1 \equiv x$, $t_2x_2 \equiv y$, and $t_3x_3 \equiv z$. For a given value of the density, the Landau inequalities define in the (x, y, z)-space a volume or stability domain. Outside this domain, one or more of the Landau inequalities are violated. As an example, in Fig. 3 are plotted these domains in the (x, y) plane for z =0 and several values of the density. No instabilities appear for densities below the value associated to each contour. The volume of the stability domain decreases when the density increases, and there is a density where no solution exists satisfying the stability conditions. This figure shows that for any Skyrme interaction, there is a critical density beyond which nuclear matter is necessarily unstable.This result is robust because it is independent of the value of z and of slight modifications of the experimental constraints around their accepted values. The value of this critical density does not exceed 3.5-4 times ρ_0 for a resonable choice of the empirical inputs. The stability domains are well identified and it would be worthwhile to look inside them for Skyrme parametrizations that can also describe accurately finite nuclei.

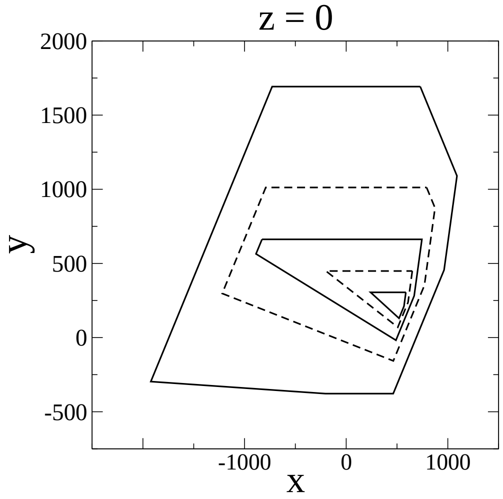

Figure 3. Stability domains in the (x, y) plane for z =0 and for several densities: the largest area (external solid line) is for ρ_0, the next one (dashed line) is for $1.5\rho_0$, and so on in steps of $0.5\rho_0$.

As a conclusion, this discussion in an illustration that an accurate prediction of the neutrino mean free path must also include an accurate understanding of some nuclear properties like the k-effective mass and the onset of instabilities.

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