PROTON LOCALIZATION IN THE NEUTRON STAR MATTER*,**

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Single proton localization in the neutron matter is studied by means of the self-consistent Hartree-Fock calculations. Ranges of the total density in which the localization is possible are derived and the corresponding proton and neutron density profiles are presented. Perspectives of the full inclusion of spin degrees of freedom are discussed.

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Most of the neutron star (NS) matter is supposed to be composed of neutrons, protons, and electrons has the total density ranging from zero to a few times the nuclear saturation density $\rho_0 \approx 0.17$ fm^{-3} [1]. Densities below ρ_0 can be found in the thin outer part of NS, the NS crust. In this region neutron-rich nuclei are surrounded by a neutron gas. Densities around ρ_0 and above can be present in the core of NS, where nuclei can no longer exist and the nuclear matter (neutrons, a few percent of protons, and electrons to preserve the charge neutrality) is supposed to be almost uniform. Such a matter composition and the density range are the reasons that nuclear theory methods have to be used to describe and understand the NS matter properties.

One of the most intriguing features of the NS is its very strong magnetic field: up to the order of 10^{14} G [2]. This strength comes from the magnetic flux conservation during the progenitor star collapse. It is unclear, if this

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magnetic fields are stable or to what degree they decay [3]. This aspect is crucial for understanding the age of NS. Very little is known about magnetic properties of the NS matter. Pioneering analyses of the spin and isospin stability of nuclear matter can be found in Refs. [4, 5]. Kutschera and Wójcik [5] suggested that localized protons present in the neutron matter can induce its spontaneous magnetic polarization. They studied this problem in the semi-classical Thomas–Fermi approach and indeed obtained the proton localization at specific nuclear matter densities.

This work is an attempt to go further and to perform the full Hartree–Fock self-consistent calculations similar to those described in Ref. [6] but allowing a possibility of the proton localization together with the spin polarization of the NS matter. The calculations are performed in a spherical Wigner–Seitz cell of the radius of several femtometers, with periodic boundary conditions assumed. The Skyrme force is taken to describe the interaction between the nucleons.

In this paper, preliminary results are presented for a simplified problem concerning only the proton localization, *i.e.*, the proton spin is neglected by using states symmetrized with respect to both spin orientations. The parameters of the Skyrme force SLy4 of Ref. [7] were used. This particular interaction is supposed to describe correctly high nuclear densities and systems with large isospin asymmetry. The proton concentration of $Y_{\rm P}$=0.02 was fixed and the calculations were performed for the densities ranging from 0.01 fm^{-3} up to 0.3 fm^{-3}. These conditions were realized by putting one proton and 49 neutrons in the Wigner–Seitz cells with radii varying between 3.4 and 10 fm.

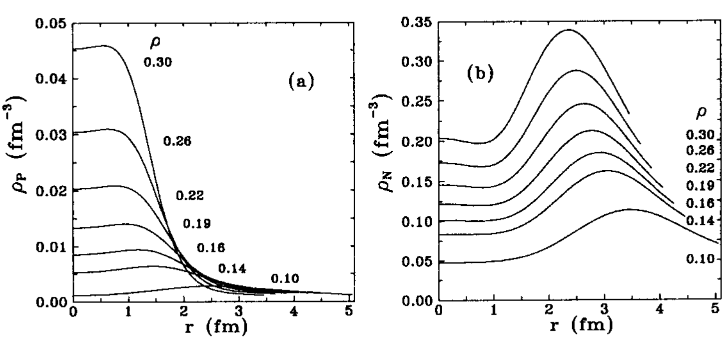

Fig. 1. Proton (a) and neutron (b) density profiles for the single-proton cell with the proton concentration Y_p = 0.02, corresponding to total densities above the nuclear saturation density. The results were obtained using the Skyrme force SLy4 chabanat.

In Figure 1(a) the proton density profiles for total densities larger than ρ_0 are presented. For $\rho > 0.19\ \mathrm{fm}^{-3}$ the proton appears to be well-localized. The density of neutrons around the proton is smaller than that in the surrounding pure neutron matter, see Fig. 1(b). For densities around $0.1\ \mathrm{fm}^{-3}$ the proton and neutron density distributions become almost uniform. The obtained density profiles are strongly perturbed by the boundary conditions assumed at the edge of the Wigner–Seitz cell. This deficiency will be removed in future calculations by using larger cells and larger numbers of neutrons in such a way that a uniform neutron matter can be obtained at large distances.

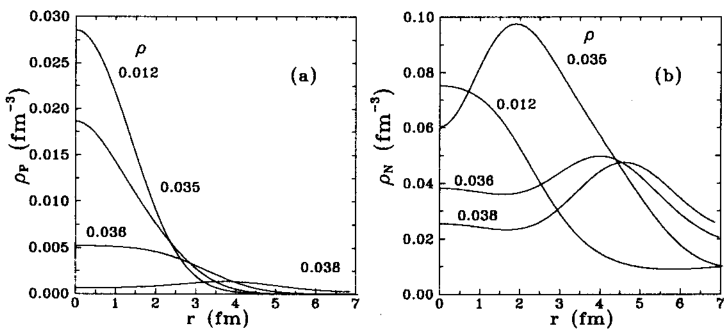

Fig. 2. Same as in Fig. 1, but for the total densities below the nuclear saturation density.

Figure 2 shows the low density regime, $\rho < \rho_0$, for proton (a) and neutron (b) densities. In this case the proton becomes localized when the total density decreases below $\rho \approx 0.04\ \mathrm{fm}^{-3}$. Contrary to the behaviour obtained at large densities, Fig. 1(b), here the neutron density forms a bump around the proton.

The general features of these results agree well with those obtained by Kutschera and Wójcik [5]. This is in spite of the fact that the Skyrme interaction used in the present study was slightly different, and that the self-consistent method was used instead of the semiclassical approximation.

The next stage of this project is to include an exact treatment of the spin degrees of freedom. The single localized proton breaks the time-reversal symmetry of the total wave function and hence the HF method must be modified to allow for such a breaking. This requires an introduction of time-odd spin and current densities [8], and leads to time-odd components in the HF mean-field. Only such extensions allow for spin-spin proton-neutron interactions in the framework of the mean field theory, which may play an important role for the proton localization phenomenon. In the spherical approach, the LS representation has to be used to decouple the spin and the orbital angular momentum degrees of freedom. Moreover, complex radial wave functions have to be considered to enable the construction of the time-odd densities. This work is in progress.

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