NEUTRON AND PROTON SEPARATION IN DENSE NEUTRON STAR MATTER FOR REALISTIC NUCLEAR MODELS*

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Vanishing of the nuclear symmetry energy implies proton–neutron separation instability in dense nuclear matter. Negative values of the symmetry energy result in disappearance of protons at high densities. The neutron star matter is unstable with respect to formation of domains with high proton concentration immersed in pure neutron matter. We consider bulk separation of protons and neutrons for a number of realistic nuclear models which occurs at densities close to the density of disappearance of protons from the system. The state with separated protons and neutrons strongly influences astrophysical properties of neutron stars.

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The symmetry energy plays a crucial role for the equation of state of the dense matter in neutron stars. Many basic parameters of the neutron star like strong magnetic fields, temperature of the surface or a composition of the matter in the liquid core depend strongly on the behaviour of the symmetry energy.

Various equations of state reproduce the empirical value of the symmetry energy at saturation density, $E_{\mathrm{S}}\,(n_0) = 34 \pm 4$ MeV. At the higher densities there is no empirical values of the symmetry energy. Realistic nuclear matter calculations [1, 2] show that the symmetry energy becomes negative at high densities, and in consequence this leads to the vanishing of protons [3].

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In calculations of the symmetry energy we used

$$E_{\mathrm{S}}(n) = \frac{1}{8} \left. \frac{\partial^2 E(n,x)}{\partial x^2} \right|_{x=1/2},$$

formula derived from the so called parabolic approximation for the energy per particle $E(n,x) = E\left(n, \frac{1}{2}\right) + E_{\mathrm{S}}(n)(2x-1)^2$, where $n = n_N + n_P$ is the baryon number density, which is the sum of neutron and proton baryon number densities. $x = n_P/n$ is the proton fraction of the nuclear matter.

Generally, decreasing with density nuclear symmetry energy makes proton abundance smaller. For some equations of state protons disappear completely at sufficiently high densities. Proton fraction x is calculated from the β-equilibrium conditions, where we take into account neutrons, protons electrons and muons.

The behaviour of the symmetry energy suggests that for higher densities, where protons are still present, the energy of nuclear matter can be lowered by separating protons from neutrons. There are two mechanisms of separation of protons and neutrons in neutron star matter: localization of individual protons in neutron matter [4, 5] and a bulk separation of protons and neutrons. In this paper we focus on the latter possibility. A bulk separation means that pure neutron matter coexists with nucleon matter containing some proton fraction x_{C}.

By performing a standard analysis [6] of small proton and neutron density fluctuations one can obtain the separation instability condition [3]

$$w_0 = \frac{\partial \mu_P}{\partial n_P} - \frac{(\partial \mu_P / \partial n_N)^2}{\partial \mu_N / \partial n_N} < 0 .$$

Here w_0 is the effective proton–proton potential in the long-wavelength limit, μ_N and μ_P are neutron and proton chemical potentials. The function $w_0(n)$ becomes negative at sufficiently high density. The instability corresponds to separation of protons and neutrons. Neutron star matter is unstable with respect to formation of domains with high proton concentration immersed in pure neutron matter.

Bulk separation instability means that the ground state of the neutron star matter in the density range where it occurs is not liquid but most likely periodic (crystalline) due to the Coulomb interaction. Such matter can have elastic properties of a solid, if minority phase forms clusters (bubbles). Actual structure is determined by balance of Coulomb and surface energies. The latter one appears at the interface separating coexisting nuclear phases of different densities and proton fractions. Hence, in the interior of a neutron star could exist a solid core, of a structure similar to that in the inner crust, with cluster, "spaghetti", and "lasagna" phases possible.

We implement the coexistence conditions by constructing isobars [6, 7]. The neutron matter coexists with nucleon matter of density n_{C} containing some proton fraction x_{C} in the pressure range $[P_1, P_2]$. The coexistence requires that the pressure and neutron chemical potential in both phases are the same, $P_N(n_N, x=0) = P_{\mathrm{C}}(n_{\mathrm{C}}, x_{\mathrm{C}})$, $\mu_N(n_N, x=0) = \mu_N(n_{\mathrm{C}}, x_{\mathrm{C}})$. The proton chemical potential have to satisfy inequality $\mu_P(n_N, x=0) > \mu_P(n_{\mathrm{C}}, x_{\mathrm{C}})$, so as to protons do not diffuse into neutron matter. In neutron star matter separation instability occurs at some critical pressure P_1, for which the coexistence conditions are satisfied for the first time. Protons disappear at pressure P_2. Behaviour of the symmetry energy for different models implies vanishing of protons in very different densities, so we obtained very different values of n_{C} and n_N. In this paper we selected seven parametrizations of the realistic nuclear models which satisfy the coexistence conditions. They are from the Skyrme model with parameters (SI', SII', SIII', SL) [8], (where the strongest effect of bulk separation is for SI' parametrization) and three models UV14+TNI, AV14+UVII and UV14+UVII, from [1] (for which the bulk separation occur only for a very small interval of n_N).

We solve the coexistence conditions graphically employing isobars, which are plots of neutron and proton chemical potentials as functions of proton fraction x under constant pressure (see Fig. 1). The fraction of volume occupied by the proton clusters $\alpha = \frac{xn}{x_{\mathrm{C}} n_{\mathrm{C}}}$ is much less than 1% of the total volume of the system. The density of domains with high proton concentration is about 10% less than the density of the neutron background.

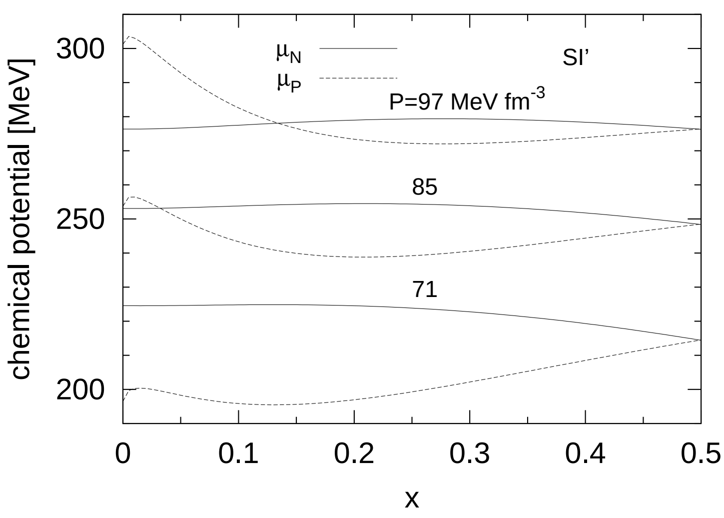

Fig. 1. The Skyrme I' chemical potential of protons (dashed line) and neutrons (solid line) as functions of proton fraction x for indicated values of pressure.

The most important parameters of isobars are given in Table I.

TABLE I

The most important parameters of isobars for four parametrisations of Skyrme model, and three from [1]: UV14+TNI (UV), AV14+UVII (AV) and UV14+UVII (UVU). First part of the table gives the parameters of proton clusters under the pressure P_1, when the coexistence conditions are satisfied for the first time. The second under the pressure P_2, when the protons disappear.

Potential	SI'	SII'	SIII'	SL	UV	AV	UVU
P_1 $[\mathrm{MeV\,fm^{-3}}]$	71	60	78	300	398	3904	2464
x_C	0.205	0.296	0.337	0.250	0.445	0.371	0.078
n_C $[\mathrm{fm^{-3}}]$	0.422	0.397	0.405	0.969	0.957	1.617	1.537
n_N $[\mathrm{fm^{-3}}]$	0.478	0.497	0.480	1.082	1.061	1.668	1.587
α [%]	0.097	0.017	0.003	0.015	0.00013	0.0057	4.502
P_2 $[\mathrm{MeV\,fm^{-3}}]$	97	72	87	355	405	4037	2579
x_C	0.5	0.5	0.5	0.5	0.5	0.5	0.183
n_C $[\mathrm{fm^{-3}}]$	0.438	0.405	0.412	1.003	0.962	1.622	1.529
n_N $[\mathrm{fm^{-3}}]$	0.526	0.528	0.497	1.160	1.069	1.677	1.652

In conclusion, we have shown that for realistic nuclear models the high density behaviour of the nuclear symmetry energy gives the possibility of bulk separation instability in highly asymmetric nuclear matter. The state with separated protons and neutrons implies, in turn, a magnetic instability [9], which generates strong magnetic field in a neutron star [10]. Existence of a solid core influences astrophysical phenomena, *e.g.* pulsar glitches and cooling rates of neutron stars.

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