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The Effects of Symmetry Energy on the Instability of Matter with Neutrinos Trapping

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Abstract. The effect of symmetry energy on the low density instability, due to density fluctuations, in the matter with neutrino trapping (NT) has been investigated within the extended relativistic mean field models. We not only consider the conventional matter with NT in which lepton fractions are kept fixed, but, also allow the lepton fractions to be density dependent. It is found that the density dependence of the lepton fractions yield smaller size of the instability region and onset of instability is quite sensitive to the behavior of the symmetry energy compared to those for the case with constant lepton fractions.

Keywords:Instability, Relativistic mean field, Neutrinos trapping.
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INTRODUCTION

The nuclear symmetry energy and its density dependence play an important role in understanding variety of phenomena in nuclear and astrophysics (1, 2). Efforts have been made to investigate the correlation between symmetry energy with the neutron star core-crust transition density as well with the onset of the low density instability in the matter without neutrino trapping (NT) which is commonly known as the neutron star matter (3, 4, 5, 6). They found that such correlations are present. The knowledge of the core-crust transition density in neutron star matter is important in pulsar glitches, crust relaxation in cooling and accreting neutrons stars and astroseismology from giant magnetar flares (see Ref. (7). However, correlation between symmetry energy with the low density instability in the matter with NT, rather rarely explored (8).

Conventionally, properties of the matter with NT are calculated by assuming a fixed value for the lepton fractions (8, 9, 10). The core-crust transition density and the onset of the low density instability region and it's size are relatively larger in the case of matter with NT than those for the matter without NT (8). Further, there exists no correlation between symmetry energy and the size of the of instability region for the matter with NT. It seems that such differences in the behavior of low density instability in the matter without and with NT need to be more carefully studied. The assumption of fixed lepton fractions yields rather unphysical predictions for the low density properties of matter with NT (11). It is highly desirable to study appropriately the dependence of the properties of matter with NT at low densities on the behavior of symmetry energy. In this work we undertake such investigation by employing density dependence of lepton fractions for the matter with NT, in contrast to the earlier studies in which lepton fractions ware assumed to be fixed (8). The calculations are done within the framework of extended relativistic mean field models (ERMF).

MATTER WITH NEUTRINO TRAPPING

We describe the matter with NT within the ERMF model. The effective Lagrangian density in the ERMF model reads as (12)

$$\mathcal{L} = \mathcal{L}_N^{\rm free} + \mathcal{L}_{NM}^{\rm lin} + \mathcal{L}_{STD}^{\rm NL} + \mathcal{L}_{MIX}^{\rm NL} + \mathcal{L}_L. \qquad (1)$$

$\mathcal{L}_N^{\rm free}$ describes the free nucleons and their interactions with mesons are described by $\mathcal{L}_{NM}^{\rm lin}$ and $\mathcal{L}_L$ is the Lagrangian density for non-interacting leptons. The Lagrangian densities for standard non-linear mesons self interaction and the mesons mixing self interaction can be written as:

$$\mathcal{L}_{STD}^{\rm NL} = -\frac{\kappa_3}{6M} g_\sigma m_\sigma^2 \sigma^3 - \frac{\kappa_4}{24M^2} g_\sigma^2 m_\sigma^2 \sigma^4$$

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Table 1. Some bulk nuclear matter properties evaluated at saturation density (ρ_0). ρ_0 in fm^{-3}, binding energy per nucleon B/A in MeV, incompressibility K in MeV, symmetry energy $a_{\rm sym}$ in MeV, its slope L in MeV and its incompressibility $K_{\rm sat,2}$ also in MeV.

	SET 1	SET 2	SET 3
ρ_0	0.15	0.15	0.15
B/A	-16.13	-16.14	-16.11
K	249.46	250.15	254.40
$a_{\rm sym}$	30.21	30.51	31.19
L	53.03	62.37	69.87
$K_{\rm sat,2}$	-265.85	-312.97	-360.61

$$+ \quad \frac{1}{24}\zeta_0 g_\omega^2(\omega_\mu\omega^\mu)^2, \tag{2}$$

$$\begin{aligned} \mathcal{L}_{MIX}^{\rm NL} &= \frac{\eta_1}{2M}g_\sigma m_\omega^2\sigma(\omega_\mu\omega^\mu)+\frac{\eta_2}{4M^2}g_\sigma^2 m_\omega^2\sigma^2(\omega_\mu\omega^\mu) \\ &+ \frac{\eta_\rho}{2M}g_\sigma m_\rho^2\sigma(\rho_\mu\rho^\mu)+\frac{\eta_{1\rho}}{4M^2}g_\sigma^2 m_\rho^2\sigma^2(\rho_\mu\rho^\mu) \\ &+ \frac{\eta_{2\rho}}{4M^2}g_\omega^2 m_\rho^2(\omega_\mu\omega^\mu)(\rho_\nu\rho^\nu), \end{aligned} \tag{3}$$

where σ, ω and ρ are the mesons field while g_σ, g_ω and g_ρ are their corresponding coupling constants. m_σ, m_ω, m_ρ and M are the σ, ω, ρ and nucleons masses while κ_3, κ_4, ζ_0, η_1, η_2, η_ρ, $\eta_{1\rho}$ and $\eta_{2\rho}$ are the nonlinear mesons self interaction parameters, respectively.

Three ERMF parameter sets namely SET 1, SET 2 and SET 3 are generated to investigate the correlation between low density instability of matter with NT and their symmetry energy ($a_{\rm sym}$) at saturation density. These parameter sets are obtained in such a way that the quality of the fit to the bulk properties of finite nuclei and nuclear matter are almost the same. Some of the nuclear matter and finite nuclei bulk properties predicted by these parameter sets are listed in Table. 1 and Table. 2. These parameter sets, however, yield slight differences in the poorly known nuclear matter isospin dependent quantities such as $a_{\rm sym}$, its slope L and isovector incompressibility $K_{\rm sat,2}$ (Table. 1). Such variations are due to the presence of more than one mix interaction terms involving ρ mesons.

To determine the abundance of each constituent in matter with NT, the following constraints are used:

- Balance equations for chemical potentials

$$\begin{aligned} \mu_n+\mu_{\nu_e} &= \mu_p+\mu_e, \\ \mu_e-\mu_{\nu_e} &= \mu_\mu+\mu_{\bar{\nu}_\mu}, \end{aligned} \tag{4}$$

Table 2. Some finite nuclei bulk properties that predicted by SET 1, SET 2 and SET 3 parameter sets. Binding energy E in MeV, charge radii r_{ch} and neutron skin $\Delta\, r = r_n$-r_p, both in fm.

	Property	SET 1	SET 2	SET 3
^{40}Ca	E	-340.46	-340.63	-342.34
	r_{ch}	3.41	3.41	3.42
	$\Delta\, r$	-0.05	-0.05	-0.05
^{90}Zr	E	-779.16	-779.07	-781.21
	r_{ch}	4.22	4.23	4.24
	$\Delta\, r$	0.07	0.07	0.07
^{132}Sn	E	-1104.48	-1103.54	-1103.08
	r_{ch}	4.63	4.64	4.65
	$\Delta\, r$	0.23	0.23	0.23
^{208}Pb	E	-1636.48	-1636.26	-1635.85
	r_{ch}	5.48	5.49	5.51
	$\Delta\, r$	0.17	0.17	0.17

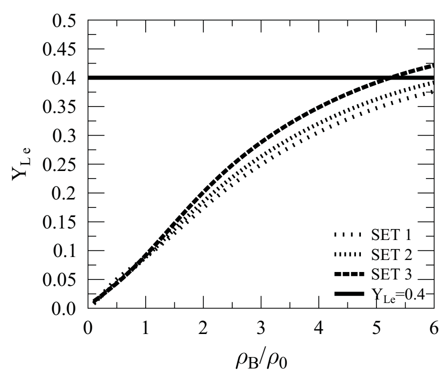

FIGURE 1. Electronic lepton fraction Y_{Le} predicted by SET 1, SET 2 and SET 3 parameter sets as a function of the baryon density. The red solid line corresponds to Y_{Le}= 0.4.

- Charge neutrality

$$\rho_e+\rho_\mu=\rho_p, \tag{5}$$

- Conservation of total density of baryon

$$\rho_B=\rho_n+\rho_p, \tag{6}$$

and for the conventional case, i.e., fixed leptons fractions, the following values are usually adopted (9, 10)

$$\begin{aligned} Y_{Le} &= Y_e+Y_{\nu_e}\approx 0.4, \\ Y_{L\mu} &= Y_m u-Y_{\bar{\nu}_\mu}\approx 0, \end{aligned} \tag{7}$$

while in the case of the density dependence of lepton fractions, we use ρ_{ν_e}=$x(\rho_B)\rho_e$ with $x(\rho_B)$ given as Ref. (11),

$$x(\rho_B) = x_0 \left[1 - \exp\left(-\beta(\rho_B/\rho_0)^{\gamma}\right)\right]. \tag{8}$$

We use , x_0=0.2, β=0.05 and γ=2 so that the Y_{Le}=0.4 at high densities. The electron-lepton fraction Y_{L_e}, therefore, becomes $Y_{L_e} = [1+x(\rho_B)]\,Y_e$. However, for Y_{L_μ} part, we use $\rho_{\bar{\nu}_\mu}$=$x(\rho_B)\rho_\mu$ instead of ρ_{ν_μ}=$x(\rho_B)\rho_\mu$ (11). Thus, similar to Y_{L_e} the density dependence Y_{L_μ} is Y_{L_μ}= $[1-x(\rho_B)]\,Y_\mu$.

In Fig. 1, the Y_{L_e} is plotted as a function of baryon density ρ_B/ρ_0 for parameter sets SET1, SET 2 and SET 3 In contrast to the fixed leptons fractions, the density dependent lepton fractions model yields the quite different behavior for Y_{L_e} at low densities i.e., the value of Y_{L_e} decrease with decreasing density. The small number of leptons at low densities within the density dependent lepton fraction model, to some extent, provides realistic description for proto-neutron star in which neutrinos are trapped in its core but escaped from its surface. The differences in the behavior of Y_{L_e} for different parameter sets ware due to the differences in the density dependence of the symmetry energy and other isospin dependent quantities (seeTable 1). In the next section, we shall demonstrate that the onset of the instability in the matter with NT at low densities caused by the density fluctuations, and the size of the instability region depends sensitively on the behavior of Y_{L_e}.

LOW DENSITY INSTABILITY

The low density instability due to small density fluctuation, where in the thermodynamically framework, commonly is called as mechanical instability (13), can be observed from the negative value of longitudinal dielectric function at zero component of the four-momentum transfer q^μ equal to zero. In relativistic random phase approximation (RPA) approach, this condition is written as (14):

$$\varepsilon_L = \det[1 - D_L(q)\Pi_L(q, q_0 = 0)] \leq 0. \tag{9}$$

The onset of the low density instability can be extracted from this condition. The transition density from the stable to the unstable regions ρ_t is defined as the largest density for which the above condition has a solution. The ρ_t usually used as a good approximation of the edge of the crust of neutron or proto-neutron stars. The explicit form of each element in the longitudinal meson propagator and longitudinal polarization matrices $D_L(q)$ and Π_L can be seen in (14, 6, 8).

In Fig. 2, we plot the transition densities calculated by using SET 1, SET 2 and SET 3 parameter sets as a function of the symmetry energy slope L for matter without

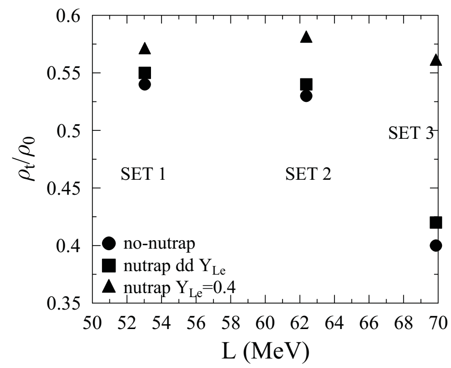

FIGURE 2. Transition densities as a function of the slope of symmetry energy L for matter without NT (no-nutrap), and matter with NT using fixed leptons fractions (nutrap Y_{Le}=0.4) as well as the ones using density dependent leptons fractions (nutrap dd Y_{Le}). The results are obtained by using the SET 1, SET 2 and SET 3 parameter sets.

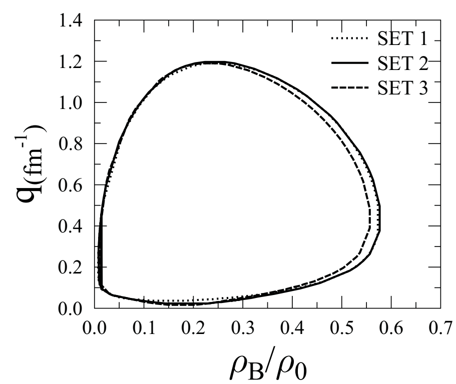

FIGURE 3. Onset of low density instability of matter with NT as functions of the ratio between baryon and saturation densities and the perturbation momentum q using fixed leptons fractions. They are obtained by using SET1, SET2 and SET3 parameter sets.

NT (no-nutrap), and matter with NT having fixed leptons fractions (nutrap Y_{Le}=0.4), and the one obtained by using density dependent leptons fractions (nutrap dd Y_{Le}) are shown. It is obvious that value of ρ_t is systematically higher for the matter with NT having fixed value of Y_{Le} in comparison to those for which the value of Y_{Le} is density dependent as well as for the matter without NT. Furthermore, the matter without NT and the matter with NT in which the Y_{L_e} is density dependent show stronger correlations between ρ_T and L, whereas, the matter with

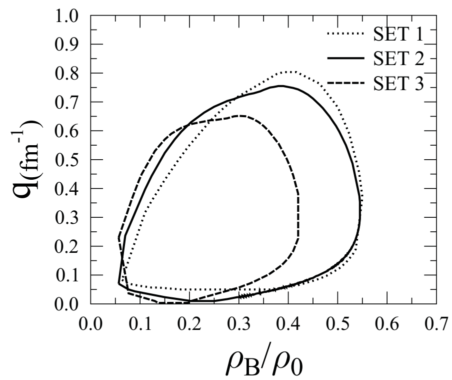

FIGURE 4. The same as Fig. 3 but calculated for the case density dependent leptons fraction.

NT having fixed Y_{L_e} show weaker correlation between ρ_T and L. We also study whether such correlations exist for all the points along the boundary of the low density instability region. The onset of instability for the matter with NT having fixed Y_{L_e} and the one in which Y_{L_e} is density dependent are shown in Figs. Fig. 3 and Fig. 4 respectively. It can be seen from Fig. 3 that the size of the instability region is not very sensitive to the choice of the parameter sets. However, the situation dramatically changes when the leptons fractions in matter with NT is density dependent as can be seen from Fig. 4. The density dependent Y_{L_e} shifts the onset of the instability and reduces the size of the instability region. This reduction of instability region seems strongly sensitive to the density dependence of the symmetry energy which is quite different for the different parameter sets considered. To this end, it is obvious now that the absence of leptons at low densities region of matter is the cause of the appearance of the correlation between size of the onset of instability and $a_{\rm sym}$.

CONCLUSION

We generate 3 ERMF parameter sets i.e., SET 1, SET2 and SET 3 to investigate the correlation between size of the onset low density instability of matter with NT and $a_{\rm sym}$ at saturation density. These parameter sets have similar in quality of fit to the bulk properties of finite nuclei and nuclear matter. We find that the onset of instability and the size of the instability region in the matter with NT are sensitive to the behavior of the symmetry energy when the lepton fractions are density dependent in comparison to those when lepton fractions are kept fixed. Disappearance of leptons at low densities region of the matter is the main source of the appearance of this correlation.

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