δ meson effects on stellar matter

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(Received 31 May 2004; published 3 November 2004)

The consequences for compact star properties of including the δ mesons in the Lagrangian density of the nonlinear Walecka model are investigated. The equations of state for neutrino free and neutrino trapped with and without the δ mesons are compared. We conclude that the sensitivity to the δ mesons depends on the hadronic contents of the star, i.e., stars with only protons and neutrons behave in a different way than stars with protons, neutrons, and hyperons. Moreover, although the properties of maximum mass stable protoneutron stars with trapped neutrinos are essentially equivalent when the δ meson is included, the neutrino content is affected by its presence.

DOI: 10.1103/PhysRevC.70.058801 PACS number(s): 26.60.+c, 24.10.Jv, 21.65.+f, 21.30.Fe

Recently the authors of Ref. [1] have stressed the importance of including the scalar isovector virtual $\delta(a_0(980))$ field in hadronic effective field theories when asymmetric nuclear matter is studied. Its presence introduces in the isovector channel the structure of relativistic interactions, where a balance between a scalar (attractive) and a vector (repulsive) potential exists. The δ, and ρ mesons give rise to the corresponding attractive and repulsive potentials in the isovector channel. The introduction of the δ meson mainly affects the behavior of the system at high densities, when, due to Lorentz contraction, its contribution is reduced, leading to a harder equation of state (EOS) at densities larger than $\sim 1.5\rho_0$ [1]. According to [2], a formally consistent relativistic effective field model should include on the same footing isoscalar and isovector meson fields.

In a recent work we have considered various parametrizations of the nonlinear Walecka model (NLWM) [3] and density dependent coupling models [4,5] in order to make a comparison of the regions of uniform unstable matter [6]. Relativistic models with different parameters present different features at subnuclear densities of nuclear asymmetric matter which have consequences for the properties of the inner crust of neutron stars or in multifragmentation or isospin fractionation reactions. The parametrizations of these models take generally into account saturation properties of nuclear matter and properties of stable nuclei. Extension of the model for very asymmetric nuclear matter or to finite temperatures may show different behaviors. In particular, the inclusion of the δ meson affects the symmetry energy and consequently the softness of the equation of state and compressibility.

The δ meson plays its role exactly in the isospin channel, which has a fundamental importance in nuclear astrophysics. We may ask which are the consequences of introducing the δ meson in compact stars. Some discussion on this problem has already appeared in [7]. In order to answer this question we compare in the present work the properties of neutron and protoneutron stars with and without the δ meson. In particular, we consider stars with leptons, protons and neutrons, which we call nucleonic stars. We also study the effect of including hyperons and/or a transition to a quark phase. Finally we analyse the effect of the δ meson in the fraction of neutrinos in protoneutron stars with trapped neutrinos.

The Lagrangian density of the NLWM with δ mesons reads [1]

$$\mathcal{L} = \sum_B \overline{\psi}_B[\gamma_\mu(i\partial^\mu - g_{vB}V^\mu - g_{\rho B}\mathbf{t}_B\cdot\vec{b}^\mu) - (M - g_{sB}\phi - g_{\delta B}\mathbf{t}_B\cdot\vec{\delta})]\psi_B + \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - m_s^2\phi^2 - \frac{1}{3}\kappa\phi^3 - \frac{1}{12}\lambda\phi^4\right) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_v^2V_\mu V^\mu - \frac{1}{4}\vec{B}_{\mu\nu}\cdot\vec{B}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{b}_\mu\cdot\vec{b}^\mu + \frac{1}{2}(\partial_\mu\vec{\delta}\partial^\mu\vec{\delta} - m_\delta^2\vec{\delta}^2), \tag{1}$$

with Σ_B extending over the eight baryons and where g_{iB} and m_i are respectively the coupling constants of the mesons $i = s,\ v,\ \rho,\ \delta$ with the hyperons and their masses. Self-interacting terms for the σ-meson are also included, κ and λ denoting the corresponding coupling constants and $\mathbf{t}_B$ is the isospin operator. The set of constants is defined by $g_{sB} = x_{sB}\ g_s$, $g_{vB} = x_{vB}\ g_v$, $g_{\rho B} = x_{\rho B}g_\rho$, $g_{\delta B} = x_{\delta B}\ g_\delta$ and x_{sB}, x_{vB}, $x_{\rho B}$ and $x_{\delta B}$ are equal to 1 for the nucleons. We have chosen $x_s = 0.7$ and $x_\omega = x_\rho = 0.783$ for Λ and assumed that the couplings to the Σ and Ξ are equal to those of the Λ hyperon [8]. For consistency we have taken $x_\delta = x_s$. We also have $g_i = \sqrt{f_i m_i^2}$, $i = s,\ v$, $g_i/2 = \sqrt{f_i m_i^2}$, $i = \rho,\ \delta$, $m_s = 550$ MeV, $m_v = 783$ MeV, $m_\rho = 763$ MeV, and $m_\delta = 980$ MeV. In Table I we display the coupling constants we have used throughout this work. The parameter sets were taken from [1] for which the binding energy is -16.0 MeV at the saturation density $\rho_0 = 0.16\ \mathrm{fm}^{-1}$, the symmetry coefficient is 32.0 MeV, the compression modulus is 240 MeV and the effective mass is $0.75M$, higher than the effective mass of the parametrization used in [6]. It is important to stress that the effective mass at saturation density cannot be too low when the aim is to describe high density matter, as already discussed in [9,10].

The equation of motion for the δ field reads

TABLE I. $NL\delta$ parameter sets.

Parameter	Set I (no δ)	Set II (with δ)
f_s (fm^2)	10.33	10.33
f_v (fm^2)	5.42	5.42
f_ρ (fm^2)	0.95	3.15
f_δ (fm^2)	0.00	2.50
κ	0.033 g_s^3	0.033 g_s^3
λ	−0.0288 g_s^4	−0.0288 g_s^4

$$\delta_3 = \sum_B \frac{g_\delta}{m_\delta^2} t_{3B}\rho_{sB}, \qquad (2)$$

where

$$\rho_{sB} = \frac{1}{\pi^2}\int p^2 dp \frac{M_B^*}{E_B^*}(f_{B+} + f_{B-}),$$

with $E_B^* = \sqrt{\mathbf{p}^2 + M_B^{*2}}$ and the distribution functions given by $f_{B\pm} = 1/\{1+\exp[(E_B^*(\mathbf{p}) \mp \nu_B)/T]\}$, where the effective chemical potential is $\nu_B = \mu_B - g_{vB}V_0 - g_{\rho B}\, t_{3B} b_0$ and the effective masses for the nucleons and hyperons are given by

$$M_B^* = M - g_{sB}\phi_0 - t_{3B} g_{\delta B}\delta_3.$$

The equations of motion for the other fields are the ones usually found in the literature. They can be seen in [9,10], for instance. The energy density and the pressure are also affected by the presence of the new meson. The term $+1/2 m_\delta^2 \delta_3^2$ should be added to the energy density and the $-1/2 m_\delta^2 \delta_3^2$ should be added to the expression of the pressure, both given in [1,6], among other papers.

In this work we study the EOSs for the following cases: (a) pure hadronic matter with nucleons only (pn) either with or without the δ mesons, (b) pure hadronic matter with nucleons and hyperons (pnH) with and without the δ mesons, (c) hadronic matter with nucleons only at low densities, mixed hadronic and quarkionic matter at intermediate densities and pure quark matter at high densities also with and without δ mesons (pnq), and (d) the same as (c) but with the inclusion of hyperons in the hadronic and mixed phases (pnHq). In all cases the leptons were included as free Fermi gases and β stability and charge conservations were imposed. In the cases where the mixed phase was included, charge neutrality was imposed globally and the Gibbs conditions for phase coexistence were enforced. We have also studied the cases where neutrino trapping takes place. If neutrino trapping is imposed to the system, the beta equilibrium condition is altered from $\mu_{B_i} = Q_i^B \mu_n - Q_i^e \mu_e$ to $\mu_{B_i} = Q_i^B \mu_n - Q_i^e(\mu_e - \mu_{\nu_e})$ and the total leptonic number is conserved, i.e., $Y_L = Y_e + Y_{\nu_e} = 0.4$. For the hadronic phase we have always used the NLWM with the parameter sets shown in Table I [1]. For the quark phase we have opted for the MIT bag model [11] with the bag constant given by $B^{1/4} = 180$ MeV and the quark masses given by $m_u = m_d = 5.0$ MeV and $m_s = 150.0$ MeV. All formulas used in the prescriptions for the construction of the mixed phases and for the imposition of neutrino trapping can be easily found in the literature, as in [8,9,12] among others.

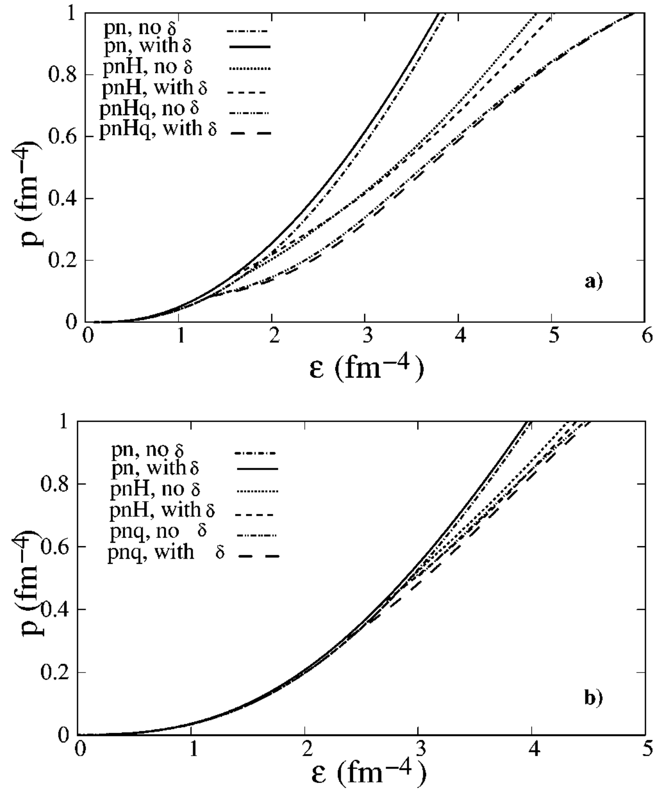

FIG. 1. (a) EOS, $Y_{\nu_e} = 0$; (b) EOS, $Y_L = 0.4$.

In Fig 1 we plot several neutrino free and neutrino-trapped EOSs. The effect of the inclusion of the δ meson is clear from Fig. 1(a): for nucleonic stars the inclusion of the δ meson makes the EOS harder. If hyperons are taken into account the EOS with δ meson suffers a transition to proton-neutron-hyperon phase at lower energies (or densities) and becomes softer. The same is true when quarks are also included. The softer EOSs are the ones which contain a phase transition to a quark phase. These effects are also present, although in a much smaller scale, in the corresponding EOS with trapped neutrinos, Fig. 1(b). The nucleonic phase extends for a larger range of densities and only for energy densities larger than 2 fm^{-4} will the softening due to hyperons and/or quarks come into play.

It is clear that the behavior of the different EOSs affects the properties of compact stars with matter described by each one of them. In Tables II and III we display the stellar properties as obtained from the EOSs discussed at the end of the last section. For this purpose the Tolman-Oppenheimer-Volkoff (TOV) equations [13] for spherically symmetric and static stars were solved. For low baryonic densities at $S=0$ we have used the results of Baym, Pethick and Sutherland [14]. In both tables NA means nonapplicable because there is no mixed phase and NP means that the result is not precise due to the lack of very low density EOS for $S=1$. In Table II no neutrinos were included in the EOSs. In Table III the EOSs were obtained with the imposition of neutrino trapping.

TABLE II. Hadronic and hybrid star properties for the EOSs obtained with the NLWM and the MIT bag model; $B^{1/4}=180$ MeV, $Y_{\nu_e}=0$, and $S=0$.

	Hadrons	$\frac{M_{max}}{M_\odot}$	$\frac{M_{bmax}}{M_\odot}$	R (km)	ε_0 (fm^{-4})	ε_{min} (fm^{-4})	ε_{max} (fm^{-4})
no δ	pn	2.09	2.45	10.88	6.99	NA	NA
with δ	pn	2.15	2.56	11.35	6.52	NA	NA
no δ	pnH	1.72	1.95	10.76	7.41	NA	NA
with δ	pnH	1.71	1.94	11.31	6.71	NA	NA
no δ	pnHq	1.47	1.64	10.58	7.43	1.36	6.22
with δ	pnHq	1.45	1.61	10.49	7.87	1.26	6.31

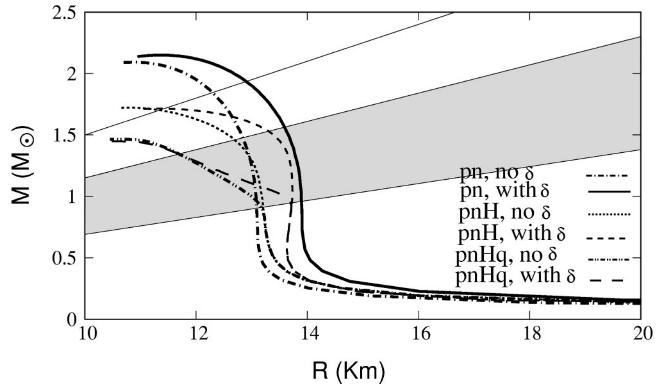

FIG. 2. Compact stars: Mass versus radius.

From Table II one can see that the inclusion of δ in a star with hyperons results in opposite consequences in the star properties if compared with a star only with protons and neutrons, i.e., in a nucleonic star the maximum gravitational and baryonic masses increase with the inclusion of the δ mesons whereas the central energy density decreases. In a pnH star, the masses decrease with the inclusion of the δ and the central energy density increases. In fact, as already discussed, the presence of the δ meson makes the EOSs harder. As a consequence the onset of hyperons or the phase transition to a quark phase occurs at lower densities and the EOS becomes softer than the EOS with no δ meson. So, while a harder EOS like the nucleonic with δ EOS supports a larger mass giving rise to a larger value for the maximum mass of a stable star, a softer EOS like the pnH or pnHq δ EOS supports a smaller mass and the maximum mass of a stable star is smaller.

The comparison between the mass-radius relations, Fig. 2, for the different EOSs is also clarifying. If we consider stars with $M > 0.5 M_\odot$, pn stars with δ-meson have always larger radius for a given mass than the corresponding stars without the δ-meson. This is not anymore true for hyperon or hybrid stars, due to the larger softening undertaken by the EOSs with the δ meson when the onset of hyperons and/or quarks occurs. Still the change of behavior, i.e., δ EOSs with smaller radius for a given mass, only occurs for quite massive stars, namely $M \sim 1.6 M_\odot$ for hyperon stars and $M \sim 1.4 M_\odot$ for hybrid stars. Another point of interest is the determination of neutron star properties by measuring the gravitational redshift of spectral lines produced in neutron star photosphere which provides a direct constraint on the mass-to-radius ratio. Recently a redshift of 0.35 from three different transitions of the spectra of the x-ray binary EXO0748-676 was obtained in [15]. This redshift corresponds to $M/R = 0.15 M_\odot/Km$. In Fig. 2 we have added the line corresponding to this constraint (top straight line), which excludes both hybrid stars (pnHq) either with or without the δ mesons with the parameter sets we have used in the present work. Nevertheless, the 1E 1207.4-5209 neutron star, which is in the center of the supernova remnant PKS 1209-51/52 was also observed and two absorption features in the source spectrum were detected [16]. These features were associated with atomic transitions of once-ionized helium in the neutron star atmosphere with a strong magnetic field. This interpre-

TABLE III. Hadronic and hybrid star properties for the EOSs obtained with the NLWM and the MIT bag model; $B^{1/4}=180$ MeV and $Y_L=0.4$.

	S	Hadrons	$\frac{M_{max}}{M_\odot}$	$\frac{M_{b\,max}}{M_\odot}$	R (km)	ε_0 (fm^{-4})	ε_{min} (fm^{-4})	ε_{max} (fm^{-4})
no δ	0	pn	2.02	2.29	10.66	7.55	NA	NA
with δ	0	pn	2.04	2.31	10.73	7.33	NA	NA
no δ	0	pnq	1.82	2.02	11.62	6.31	2.98	7.68
with δ	0	pnq	1.80	1.99	11.85	6.25	2.33	7.55
no δ	0	pnH	1.89	2.10	10.91	7.06	NA	NA
with δ	0	pnH	1.88	2.09	10.51	7.03	NA	NA
with δ	0	pnHq	1.81	2.00	11.53	6.34	2.30	7.73
with δ	1	pn	2.04	2.28	NP	7.35	NA	NA
with δ	1	pnq	1.78	1.95	NP	6.36	2.25	7.82
with δ	1	pnH	1.86	2.04	NP	6.80	NA	NA
with δ	1	pnHq	1.78	1.94	NP	6.34	2.27	7.76

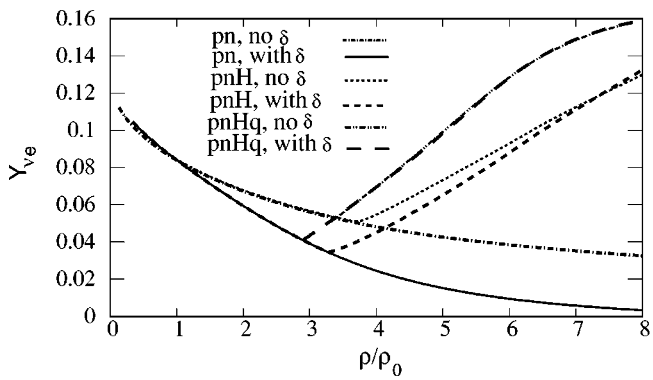

FIG. 3. Neutrino fraction.

tation leads to a readshift of the order of 0.12-0.23, considerably lower than the one in [15]. This readshift imposes another constraint to the mass to radius ratio given by $M/R=0.069M_{\odot}/Km$ to $M/R=0.115M_{\odot}/Km$. We have also added these two lines in Fig. 2. One can see that all the curves presented in this work are consistent with the measurements of [16].

In Table III we present the properties of stars with trapped neutrinos. Notice that the EOSs pnq and pnHq are almost equivalent. Hence, we have compared only three different cases: nucleonic (pn), pnH and pnq stars. With the δ meson we have also calculated the properties of stars with entropy, $S=0$ and $S=1$. This last value is the value which hydrodynamical simulations predict for the neutrino trapped phase [17]. Without the δ mesons we have only considered the $S=0$ results since the effect of temperature is not very important and the main conclusions can be drawn from these results. In fact, properties of maximum mass stable protoneutron stars with trapped neutrinos are essentially equivalent when the δ meson is included. However there is some difference in the neutrino content as can be seen from Fig. 3.

If we consider protoneutron stars in the neutrino trapped phase, formed only by protons and neutrons in equilibrium with leptons (nucleonic EOS), the inclusion of the δ meson has a strong effect on the abundance of neutrinos. Namely, the inclusion of δ reduces a lot the neutrino fraction for $\rho>\rho_0$. This is a direct consequence of the effect of the δ meson on the symmetry energy [1]: for densities $>\rho_0$ the symmetry energy increases faster with density than when δ mesons are not present. A larger symmetry energy reduces the fraction of neutrons and therefore increases the fraction of protons and electrons. If we consider a fixed fraction of leptons, i.e., $Y_{Le}=0.4$, the neutrino fraction will be smaller.

If hyperons are included, the onset of hyperons occurs at lower densities for the EOS with the δ meson. The onset of hyperons is also accompanied with an increase of the neutrino fraction, due to the reduction on the number of electrons. Although the fraction of neutrinos increases faster for the δ EOSs, only for densities greater than $7\rho_0$ will this fraction be larger than the corresponding fraction for the EOS without the δ meson.

The inclusion of a possible phase transition to a quark phase has an important effect on the behavior of both models: the onset of quarks occurs before the onset of hyperons for the present parametrization of hadronic matter. Comparing both models the onset of quarks occurs at lower densities for the δ EOS. Nevertheless the neutrino fractions obtained within both EOS are almost coincident after the onset of quarks in the EOS without the δ meson. This is expected because it is essentially the quark EOS which defines the behavior of the EOS while the hadronic contribution becomes less and less important.

In conclusion, in this work we have studied the effects of the introduction of the δ mesons in the EOS for stellar matter. In particular, a comparison between properties of neutron, hyperon and hybrid stars, possibly with neutrino trapping was done.

It is clear that the inclusion of the δ-meson makes the EOS for nuclear matter harder. However the onset of hyperons and/or quarks in these stars gives rises to a larger softening. In particular maximum stable stars have in these cases lower masses and smaller radius.

The effect of the inclusion of the δ-meson in neutrino trapped EOS is particular noticeable in the neutrino fraction as function of density. In nucleonic stars the inclusion of the δ-meson reduces a lot the neutrino fraction for $\rho>\rho_0$. Smaller neutrino fraction for δ-EOS is still true in hyperon stars up to a quite large density. In hybrid stars, after the onset of the quark phase, neutrino fractions do not depend anymore on the presence of the δ-meson. This will have implications in the cooling of the protoneutron star, since the amount of neutrinos defines whether the star decays into a low mass black hole or into a neutron star.

This work was partially supported by CNPq (Brazil), CAPES (Brazil)/GRICES (Portugal) under project 100/03 and FEDER/FCT (Portugal) under the project POCTI/35308/FIS/2000.

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