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Competition between delta isobars and hyperons and properties of compact stars

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ABSTRACT

The Δ-isobar degrees of freedom are included in the covariant density functional (CDF) theory to study the equation of state (EoS) and composition of dense matter in compact stars. In addition to Δ's we include the full octet of baryons, which allows us to study the interplay between the onset of delta isobars and hyperonic degrees of freedom. Using both the Hartree and Hartree–Fock approximation we find that Δ's appear already at densities slightly above the saturation density of nuclear matter for a wide range of the meson–Δ coupling constants. This delays the appearance of hyperons and significantly affects the gross properties of compact stars. Specifically, Δ's soften the EoS at low densities but stiffen it at high densities. This softening reduces the radius of a canonical $1.4M_\odot$ star by up to 2 km for a reasonably attractive Δ potential in matter, while the stiffening results in larger maximum masses of compact stars. We conclude that the hypernuclear CDF parametrizations that satisfy the $2M_\odot$ maximum mass constraint remain valid when Δ isobars are included, with the important consequence that the resulting stellar radii are shifted toward lower values, which is in agreement with the analysis of neutron star radii.

1. Introduction

Compact stars are unique laboratories for studies of dense hadronic matter [1–6]. The hadronic core of a compact star extends from half up to a few times the nuclear saturation density ρ_0. In the high-density region of the core a number of exotic degrees of freedom are expected to appear in addition to nucleons. Possible new constituents of matter include hyperons [7–30], delta isobars [8,9,31–41], and deconfined quark matter [46–65]. The details of the composition of compact stars at high densities are not fully understood yet. The current observational programs focusing on neutron stars combined with the nuclear physics modeling of their interiors are aimed at resolving the puzzles associated with their EoS and interior composition.

Although the appearance of Δ's in neutron star matter was conjectured long ago [8,31] there has been much less research on their properties in the intervening years as compared to hyperons and quark matter. This may partially be a consequence of Ref. [9] where Δ's were found to appear at densities that are much larger than the typical central densities of neutron stars. Thus, Δ's have been considered largely unimportant in neutron star astrophysics.

Recently, a number of studies of Δ's in neutron star matter appeared which were conducted within the CDF theory in the Hartree approximation, i.e., the so-called relativistic mean-field model [28,29,34–41]. Some of these studies ignore hyperons in order to isolate the effects Δ isobars have on the nucleonic EoS and neutron star properties by choosing a particular set (in some cases several sets) of meson–Δ coupling constants [29,34,39,41]. The universal coupling scheme is typically adopted in these studies. In analogy to hyperons, the Δ degrees of freedom were found to soften the EoS of neutron star matter and to reduce the maximum mass of a compact star. However, a simultaneous treatment of hyperons and Δ's appears to be mandatory in order to assess the overall effect of these new degrees of freedom on dense matter and the gross properties of compact stars.

The Δ degrees of freedom in nuclear dynamics have been studied in a number of alternative settings. Δ's play an important

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role in the studies of nucleon–pion–Δ dynamics, which resume the RPA diagrams including Δ-hole loops with the Δ-hole vertex given by $g'_{N\Delta}$ Landau–Migdal parameter [42–44]. These studies are mainly focused on the pion propagator and dispersion (condensation) in nuclear matter. More recently, Δ's were included in the studies of nuclear matter in the chiral approach where the nuclear density functional is arranged in powers of small parameters (e.g. number of derivatives of the pion field) and Δ's appear in virtual states [45].

The principal aim of this work is to explore, in great detail, the competition between Δ isobar and hyperon populations in dense matter, and to study the impact of Δ populations on the properties of compact stars such as masses and radii. For that purpose we carry out a detailed analysis of the parameter space of the meson–Δ coupling value within the CDF theory at the relativistic Hartree and Hartree–Fock level.

This work is organized as follows. In Sec. 2 we outline the CDF model and its parametrizations. Section 3 presents our results for the EoS of dense matter and its composition. The global properties of compact stars and their internal structures are discussed in this section as well. Finally, a summary of our results is provided in Sec. 4.

2. Theoretical model

2.1. CDF model for stellar matter

We start with a brief outline of our theoretical framework, which is based on the CDF theory treated in the Hartree and Hartree–Fock approximations. The Lagrangian density of the model is given by

$$\mathscr{L} = \mathscr{L}_B + \mathscr{L}_m + \mathscr{L}_{\rm int} + \mathscr{L}_l, \tag{1}$$

where the first term $\mathscr{L}_B$ is the Lagrangian of free baryonic fields ψ_B, with index B labeling the spin-1/2 baryonic octet, which comprises nucleons $N \in \{n, p\}$, hyperons $Y \in \{\Lambda, \Xi^{0,-}, \Sigma^{+,0,-}\}$, and the spin-3/2 zero-strangeness quartet $\Delta \in \{\Delta^{++,+,0,-}\}$. Note that the Δ's are treated as Rarita–Schwinger particles [66]. The second term $\mathscr{L}_m$ represents the Lagrangian of free meson fields ϕ_m, which are labeled according to their parity, spin, isospin and strangeness. In the present model we include the isoscalar–scalar meson σ, which mediates the medium-range attraction between baryons, the isoscalar–vector meson ω, which describes the short range repulsion, the isovector–vector meson ρ, which accounts for the isospin dependence of baryon–baryon interactions, and the π meson which accounts for the long-range baryon–baryon interaction and the tensor force. The two hidden-strangeness mesons, σ^* and ϕ, describe interactions between hyperons. The interaction between the baryons and mesons is described by the third term $\mathscr{L}_{int}$ which has the generic form

$$\mathscr{L}_{\rm int} \equiv g_{mB}\tau_B\bar{\psi}_B\Gamma_m\varphi_m\psi_B, \tag{2}$$

where g_{mB} is the meson–baryon coupling constant, $\tau_B \in \{1, \boldsymbol{\tau}\}$ is the isospin matrix and $\Gamma_m \in \{1, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$ is the relevant (Dirac-matrix) vertex. Finally, the last term $\mathscr{L}_l$ describes the contribution from free leptons; we include electrons (e^-) and muons (μ^-) and neglect the neutrinos which are irrelevant at low temperatures.

Starting from Eq. (2) we carry out the standard procedure for obtaining the density functional in CDF theories. This amounts to finding the equations of motions from the Euler–Lagrange equations of the theory, which for the baryon octet and leptons have the form of the Dirac equation, whereas for the Δ decuplet are given by the Rarita–Schwinger equation. The equations of motion for meson in the mean-field approximation take the form of Klein–Gordon equations. Each of the baryon self-energies is then decomposed in the Dirac space according to

$$\Sigma(k) = \Sigma_S(k) + \gamma_0\Sigma_0(k) + \boldsymbol{\gamma}\cdot\hat{\boldsymbol{k}}\Sigma_V(k) \tag{3}$$

where Σ_S, Σ_0 and Σ_V are the scalar, time and space components of the vector self-energies and $\hat{\boldsymbol{k}}$ is a unit vector along $\boldsymbol{k}$. The energy density functional is then generated by evaluating the baryon self-energies $\Sigma(k)$ in the Hartree (RMF) or Hartree–Fock (RHF) approximations [67–70]. The detailed expressions for self-energies are given, for instance, in Refs. [41,71]. Note that the pion-exchange and the tensor couplings of vector mesons to baryons contribute only to the Fock self-energies. In β-equilibrium the chemical potentials of the particles are related to each other by

$$\mu_B = b_B\mu_n + q_B\mu_e, \tag{4}$$

where b_B and q_B denote the baryon number and electric charge of baryon species B, and μ_n and μ_e are the chemical potentials of neutrons and electrons, respectively. This, together with the field equations and charge neutrality condition allows us to determine the EoS and composition of matter for any given net baryonic density ρ at zero temperature self-consistently.

Once the EoS is determined, the integral parameters, in particular the mass and the radius, of a compact star of given central density can be computed from the Tolman–Oppenheimer–Volkoff (TOV) equations [72,73]. To do so we match smoothly our EoS to an EoS of the inner and outer crusts [74,75] at the crust–core transition density $\rho_0/2$, where ρ_0 denotes the saturation density of ordinary nuclear matter.

2.2. Meson–baryon couplings

We now turn to the procedure of choosing the appropriate values of the coupling constant $g_{m\Delta}$ between the mesons and baryons. These have to be fitted to the experimental (empirical) data of nuclear and hypernuclear systems. In the purely nucleonic sector the meson–nucleon (mN) couplings are given by $g_{mN}(\rho_B) = g_{mN}(\rho_0)f_{mN}(x)$, where $x = \rho_B/\rho_0$, ρ_B is the baryonic density. For the isoscalar channel, one has

$$f_{mN}(x) = a_m\frac{1 + b_m(x + d_m)^2}{1 + c_m(x + d_m)^2}, \quad m = \sigma, \omega, \tag{5}$$

which is subject to constraints $f_{mN}(1) = 1$, $f''_{mN}(0) = 0$ and $f''_{\sigma N}(1) = f''_{\omega N}(1)$. The density dependence for the isovector channels is taken in an exponential form[1]

$$f_{mN}(x) = e^{-a_m(x-1)}, \quad m = \rho, \pi. \tag{6}$$

In the hypernuclear sector, as usual, the vector meson–hyperon couplings are given by the SU(3) flavor symmetric quark model [11,76] whereas the scalar meson–hyperon couplings are determined by their fitting to empirical hypernuclear potentials. We note that the isovector couplings are non-universal and, for example, values $g_{\rho\Sigma}/g_{\rho N} \simeq 1/4$–$1/3$ are required to describe the Σ-atom [77].

[1] For the PKO3 interaction used in this study the masses (in MeV) of nucleon, σ-, ω-, ρ- and π-mesons are 938.9, 525.6677, 783, 769, 138. The coupling constants at the saturation $\rho_0 = 0.153$ fm^{-3} are $g_\sigma = 8.8956$, $g_\omega = 10.8027$, $g_\rho = 2.0302$ and $f_\pi = 0.3929$; the remaining parameters, which describe the density-dependence of couplings can be found in Table 1 of Ref. [85].