Quarkyonic matter in relativistic mean-field formalism

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I. INTRODUCTION

The outcome of the analysis of observational data (GW190814) that the neutron star's mass can be greater than or equal to 2 $M_\odot$ has proven to be a powerful constraint on the dense matter equation of state. One of the most successful and prominent theoretical perspectives to obtain the equation of state (EOS) for the investigation of various properties of a dense star is relativistic mean-field (RMF) formalism. The entire spectrum of the EOS from the stiffest to the softest region can be obtained with the help of existing RMF parameter sets in the literature, which corresponds to a different order of coupling factors between mesons and nucleons and has its own merits in terms of satisfying the various astrophysical observational constraints. The composition of the neutron star cores has also been a secret and topic of debate in the last few years. Although, we can infer a broad idea about the neutron star interiors using the astrophysical observations, but it is far from reach to find out the exact creation of the dense star on the basis of observational data. There are a lot of hypothesis available in the literature regarding the availability of free quarks, hyperons, delta isobars, or the phenomenon of kaon condensation in the interior shell of a neutron star. The presence of exotic particles inside the neutron star happens to soften the EOS which in turn will affect the observables, e.g., reduce the mass and tidal deformability of the star. Quark matter may appear due to a hadronic-quark transition in the core of a hybrid star. Quarkyonic matter is an approach in which both quarks and nucleons appear as quasiparticles in a crossover transition, and provides an explicit realization of early ideas concerning quark matter.

II. FORMALISM

We adopted the newly developed RMF parameter set by Kumar *et al.* named as "IOPB-I" [1] and for which the corresponding Lagrangian density representing the hadronic matter for a neutron star subsequent to mean-field approximation can be written as

$$\begin{aligned}
\mathcal{L}_{NM} = & \sum_{j=p,n} \bar{\psi}_j \Big\{ \gamma_\mu (i\partial^\mu - g_\omega \omega^\mu - \frac{1}{2} g_\rho \vec{\tau}\cdot\vec{\rho}^\mu) \\
& -(M - g_\sigma \sigma) \Big\} \psi_j + \bar{\phi}_l \,(i\gamma_\mu \partial^\mu - m_e)\phi_l \\
& -\frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2}\partial^\mu \sigma \, \partial_\mu \sigma + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu \\
& +\frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} \vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} \\
& +\frac{1}{2} m_\rho^2 \rho^\mu \cdot \rho_\mu + \frac{\zeta_0}{4!} g_\omega^2 (\omega^\mu \omega_\mu)^2 \\
& -g_\sigma \frac{m_\sigma^2}{M} \left(\frac{\kappa_3}{3!} + \frac{\kappa_4}{4!} \frac{g_\sigma}{M} \sigma \right) \sigma^3 \\
& +\Lambda_\omega g_\omega^2 g_\rho^2 (\omega^\mu \omega_\mu)(\vec{\rho}^\mu \cdot \vec{\rho}_\mu), \qquad (1)
\end{aligned}$$

With the addition of up and down quarks, the general conditions of baryon and charge conservation are

$$n = n_n + n_p + \frac{n_d + n_u}{3} \qquad (2)$$

$$n_B Y_L = n_e + n_\mu = n_p + \frac{2n_u - n_d}{3} \qquad (3)$$

The minimum momenta for protons and neutrons in quarkyonic matter are obtained using the relation

$$k_{0(n,p)} = (k_{F(n,p)} - k_{t(n,p)}) \left[1 + \frac{\Lambda^2}{k_{F(n,p)} k_{t(n,p)}} \right]$$

The transition Fermi momenta $k_{t(n,p)}$ are obtained from beta equilibrium of the uniform n, p, e, μ system at the transition density (n_t).

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III. RESULTS AND DISCUSSION

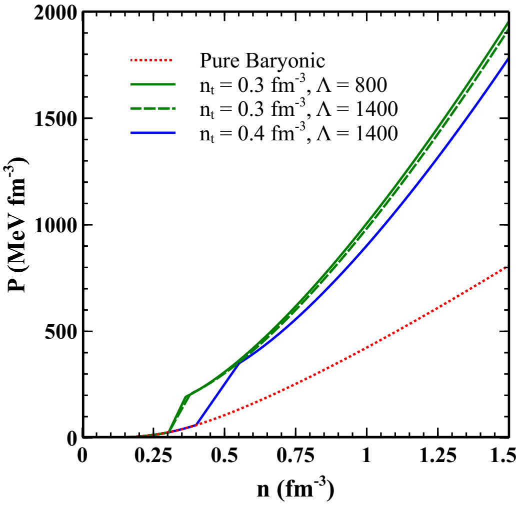

FIG. 1. Pressure as a function of baryon density of a quarkyonic neutron star. The curves are obtained for two different transition density 0.3 fm^{-3} and 0.4 fm^{-3} with allowable variations in the parameter Λ.

TABLE I. The maximum mass, corresponding radius and canonical star radius for the above stated EOSs of the IOPB-I parameter set.

	Max. Mass	R (Km)	$R_{1.4}$ (Km)
Pure Baryonic	2.15	11.76	12.78
$n_t = 0.3, \Lambda = 800$	2.43	11.92	12.84
$n_t = 0.3, \Lambda = 1400$	2.50	13.00	12.85
$n_t = 0.4, \Lambda = 1400$	2.17	11.81	12.78

The inclusion of quarks in the core of neutron star results in the increment of maximum mass of the star.

IV. SUMMARY

We consider quarkyonic matter description recently been employed by McLerran and Reddy for pure neutron matter, and reformulated it for a star matter to naturally explain the observational properties of neutron stars [2]. We propose a variation of quarkyonic matter along with relativistic mean-field formalism involving protons and leptons whose energy can be explicitly minimized to achieve both chemical and beta equilibrium, which cannot be done in the chargeless formulation (or pure neutron matter). The mass-radius profile of a quarkyonic matter neutron star is obtained using the IOPB-I parameter set.

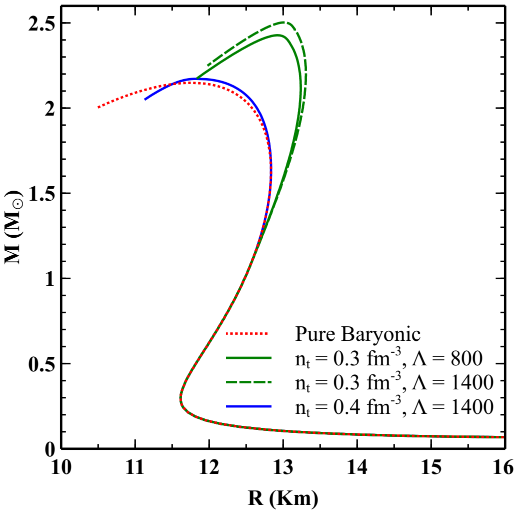

FIG. 2. Mass-radius profile obtained using the TOV equation for the same equation of states displayed in Fig. 1.

[1] Bharat Kumar, S. K. Patra, and B. K. Agrawal, Phys. Rev. C **97**, 045806, (2018).

[2] Larry McLerran, and Sanjay Reddy, Physical Review Letters, **122**, 122701 (2019).