Compact stars in a modified quark meson coupling model

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The structure of neutron stars is chiefly determined by the equation of state (EOS) of the strongly interacting constituents. Several approaches involving non-relativistic and relativistic field theoretic models have been made to determine the EOS for dense nucleon matter. In the present work we attempt a study of the structure of neutron stars within a modified quark meson coupling (MQMC) model in which the bare nucleons are considered to be independently confined by a phenomenological equally mixed scalar and vector potential in harmonic form. In an earlier attempt [1, 2] we have successfully used this model in developing the nuclear EOS, analysed various other bulk properties of symmetric and asymmetric nuclear matter and studied the thermodynamic instabilities of the system.

In such a model the Dirac equation for individual quarks in the medium becomes

$$[\gamma^0\ (\epsilon_q - g^q_\omega\omega_0 - \frac{1}{2}g^q_\rho\tau_z\rho_{03}) - \vec{\gamma}.\vec{p} \\ -(m_q - g^q_\sigma\sigma_0) - U(r)]\psi_q(\vec{r}) = 0 \qquad (1)$$

where g^q_σ, g^q_ω and g^q_ρ are the quark coupling constants with the σ, ω and ρ mesons. In the above, $U(r) = \frac{1}{2}(1+\gamma^0)V(r)$, where $V(r) = (ar^2 + V_0)$ with $a > 0$. Here $(a,\ V_0)$ are the potential parameters which are determined through the baryon mass and proton charge radius, σ_0, ω_0 and ρ_{03} are the meson fields while τ_z is the third component of Pauli matrices. In the mean field approximation, the meson fields are treated by their expectation values. We realize the mass of the baryons in such a model after making appropriate centre of mass, pionic and gluonic corrections which is given as,

$$M^*_N = E^0_N - \epsilon_{cm} + \delta M^\pi_N + (\Delta E_B)^E_g + (\Delta E_B)^M_g$$

where ϵ_{cm} is the energy associated with the spurious center of mass correction, $(\Delta E_B)^E_g + (\Delta E_B)^M_g$ is the color electric and magnetic interaction energies arising out of the one-gluon exchange process and δM^π_B is the pionic self energy of the baryon due to pion coupling of the non-strange quarks.

The couplings are calculated using $g_{\sigma B} = x_{\sigma B}g_{\sigma N}$, $g_{\omega B} = x_{\omega B}g_{\omega N}$ and $g_{\rho B} = x_{\rho B}g_{\rho N}$ where $x_{\sigma B}$, $x_{\omega B}$ and $x_{\rho B}$ are equal to 1 for the nucleons and $\sqrt{2/3}$ for other baryons. The total energy density and pressure including leptons in the mean field approximation for nuclear matter is given as:

$$\begin{aligned}\varepsilon &= \frac{1}{2}m^2_\sigma\sigma^2_0 + \frac{1}{2}m^2_\omega\omega^2_0 + \frac{1}{2}m^2_\rho\rho^2_{03} \\ &+ \frac{\gamma}{(2\pi)^3}\sum_B\int_0^{k_B} d^3k\sqrt{k^2 + {M^*_B}^2} \\ &- g^2_\omega g^2_\rho\Lambda_v\rho^2_{03}\omega^2_0 \\ &+ \sum_l\frac{1}{\pi^2}\int_0^{k_l} k^2dk[k^2 + m^2_l]^{1/2} \qquad (2)\end{aligned}$$

$$\begin{aligned}P &= -\frac{1}{2}m^2_\sigma\sigma^2_0 + \frac{1}{2}m^2_\omega\omega^2_0 + \frac{1}{2}m^2_\rho\rho^2_{03} \\ &+ \frac{\gamma}{3(2\pi)^3}\sum_B\int_0^{k_B}\frac{k^2\ d^3k}{\sqrt{k^2 + {M^*_B}^2}} \\ &+ g^2_\omega g^2_\rho\Lambda_v\rho^2_{03}\omega^2_0 \\ &+ \frac{1}{3}\sum_l\frac{1}{\pi^2}\int_0^{k_l}\frac{k^4dk}{[k^2 + m^2_l]^{1/2}} \qquad (3)\end{aligned}$$

where $\gamma = 2$ is the spin degeneracy factor for nuclear matter and Λ_v is a nonlinear ω-ρ coupling. For compact stars with

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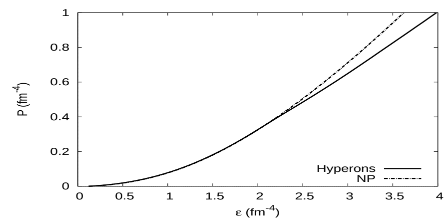

FIG. 1: Pressure for β-equilibrated np and np+hyperon matter as function of the energy density.

strongly interacting baryons, the composition is determined by the requirements of charge neutrality and β-equilibrium conditions under weak processes, $B_1 \rightarrow B_2 + l + \overline{\nu}_1$ and $B_2 + l \rightarrow B_1 + \nu_1$. After deleptonization the charge neutrality condition yields, $q_{tot} = \sum_B q_B \gamma k_B^3/(6\pi^2) + \sum_{l=e,\mu} q_l k_l^3/(3\pi^2) = 0$, where q_B and q_l are respectively the electric charge of the baryon and lepton species. The meson fields are determined through the respective meson field equations and the sigma field is fixed by $\frac{\partial \varepsilon}{\partial \sigma_0} = 0$.

We fit the quark-meson coupling constants g_σ^q, $g_\omega = 3g_\omega^q$ and $g_\rho^q = g_\rho$ for the nucleons to obtain the correct saturation properties of nuclear matter, $E_B = \varepsilon/\rho - M = -15.7$ MeV at $\rho = \rho_0 = 0.15 fm^{-3}$, $\epsilon_{sym} = 32.$ MeV. For quark mass $m_{u,d} = 200$ MeV and $m_s = 350$ MeV the couplings are $g_\sigma^q = 4.22$, $g_\omega = 7.63$ and $g_\rho = 8.70$. We take the standard values for the meson masses, namely $m_\sigma = 550$ MeV, $m_\omega = 783$ MeV, and $m_\rho = 770$ MeV. The compressibility at quark mass 200 MeV comes out to be 315 MeV.

The EOS, with the inclusion of the hyperons, is plotted in Fig 1. The particle populations are shown in Fig 2 where we plot the fraction of baryon species i, $Y_i = \rho_i/\rho_B$ as a function of total baryon density ρ_B. The first hyperon to appear is Σ^- at $\rho_B = 0.44 fm^{-3}$ followed by Λ at $\rho_B = 0.65 fm^{-3}$.

The mass-radius relation is plotted in Fig 3. It is found that the maximum mass of neutron star including hyperons is 2.25 $M_\odot$ which is quite near to the mass 2.01 ± 0.04 $M_\odot$ obtained by J. Antoniadis *et al* [3]. The radius

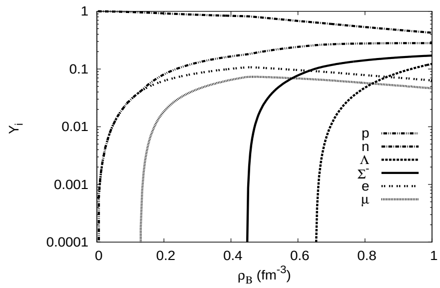

FIG. 2: Particle fraction in neutron star matter as a function of total baryon density.

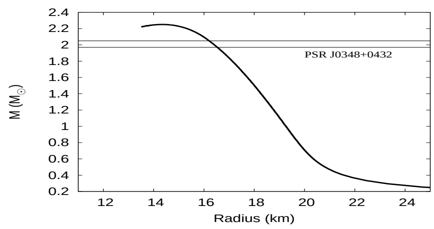

FIG. 3: Gravitational mass as function of radius.

corresponding to the mass 2.25 $M_\odot$ is found to be 14.34 km.

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