Role of Ξ potential in neutron star matter in MQMC

H. S. Sahoo[1],* R.N. Mishra[1], P.K. Panda[2], and N. Barik[2]
[1]Department of Physics, Ravenshaw University, Cuttack, Odisha-753003, INDIA and
[2]Deptartment of Physics, Utkal University, Bhubaneswar, Odisha, 751004, INDIA

Neutrons and protons in β-equilibrium form the basic constituents of neutron stars. However, with the increase in baryon density, the Fermi momentum and the Fermi energy increase and exceed the masses of heavier baryons such as the hyperons. This results in the onset of the new hyperon degrees of freedom in dense neutron star matter which consequently impacts the equation of state (EoS) and the mass-radius of neutron stars. This impact strongly depends on the coupling constant of the hyperons with the mesons. In particular, since hyperons are strange baryons made up of both strange and non-strange quarks, the influence of strange quarks needs to be taken in to account. This can be achieved by incorporating in addition to the σ, ω and ρ mesons, an extra pair of hidden strange mesons σ^* and ϕ which couple only to the strange quark and the hyperons of the nuclear matter.

In the present work we study the influence of the variation of the Ξ-potential on the mass and radius of the neutron stars in a relativistic quark model, alternatively called the modified quark meson coupling model (MQMC). We may note here that we consider only one hyperon (Ξ) as the presence of other strange particles would make this study strongly model and parameter dependent. In the MQMC model the Dirac equation for individual quarks in the medium becomes,

$$[\gamma^0\ (\epsilon_q - g^q_\omega\omega_0 - g^q_\phi\phi_0 - \frac{1}{2}g^q_\rho\tau_z\rho_{03}) - \vec{\gamma}.\vec{p} \\ -(m_q - g^q_\sigma\sigma_0 - g^q_{\sigma^*}\sigma^*_0) - U(r)]\psi_q(\vec{r}) = 0 \quad (1)$$

where g^q_σ, $g^q_{\sigma^*}$, g^q_ω, g^q_ϕ and g^q_ρ are the quark coupling constants with the σ, σ^*, ω, ϕ 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, σ^*_0, ω_0, ϕ_0 and ρ_{03} are the meson fields while τ_z is the third component of the isospin matrix. In the mean field approximation, the meson fields are treated by their expectation values. The mass of the baryons is realised after making appropriate corrections,

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

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.

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

$$\begin{aligned}P &= -\frac{1}{2}m^2_\sigma\sigma^2_0 - \frac{1}{2}m^2_{\sigma^*}\sigma^{*2}_0 + \frac{1}{2}m^2_\omega\omega^2_0 \\ &+ \frac{1}{2}m^2_\phi\phi^2_0 + \frac{1}{2}m^2_\rho\rho^2_{03} + g^2_\omega g^2_\rho\Lambda_v\rho^2_{03}\omega^2_0 \\ &+ \frac{\gamma}{6\pi^2}\sum_B\int_0^{k_B}\frac{k^4\ dk}{\sqrt{k^2 + {M^*_B}^2}} \\ &+ \frac{1}{3}\sum_l\frac{1}{\pi^2}\int_0^{k_l}\frac{k^4dk}{[k^2 + m^2_l]^{1/2}} \qquad (3)\end{aligned}$$

*Electronic address: h.sekhar.s@gmail.com

The total energy density and pressure including leptons in the mean field approximation for nuclear matter is given Eq 2 and Eq 3. Here γ is the spin degeneracy factor for nuclear matter, with $\gamma = 2$ for the baryons $B = N, \Xi^-, \Xi^0$, $l = e, \mu$. Here Λ_v is a nonlinear ω-ρ coupling. The composition of the matter is determined by the requirements of charge neutrality and β-equilibrium conditions under weak processes. The charge neutrality condition after deloptonization 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. 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. The ω-Ξ coupling strength ($x_{\omega\Xi}$) is adjusted to the hyperon-nucleon interaction potential at saturation density for the Ξ hyperons with $U_\Xi = -18$ MeV using the relation $U_B = -(M_B - M_B^*) + x_{\omega B} g_\omega \omega_0$. To study the effect of the ω-Ξ coupling strength on the star properties we vary the interaction potential to $U_\Xi = -10$ MeV to determine the corresponding $x_{\omega\Xi}$.

The couplings to the strange meson σ^* is fixed $g_{\sigma^*}^q = 2$ considering a weak hyperon-hyperon coupling. For the ϕ-coupling we follow the scheme given in [1] using the Nijmegen extended soft core model in an SU(3) symmetry. Under such a scheme, $g_{\phi N} = \frac{\sqrt{3}z - \tan\theta_\nu}{1+\sqrt{3}z\tan\theta_\nu} g_{\omega N}$ and $g_{\phi\Xi} = -\frac{\sqrt{3}z + \tan\theta_\nu}{1+\sqrt{3}z\tan\theta_\nu} g_{\omega N}$. Here $\theta_\nu = 37.50^o$ is the mixing angle and $z = 0.1949$. For quark mass $m_{u,d} = 200$ MeV, $m_s = 300$ MeV and $\Lambda_v = 0.05$ the couplings are $g_\sigma^q = 4.36$, $g_\omega = 7.40$ and $g_\rho = 9.39$ fixed at symmetry energy 32 MeV. The values of $x_{\omega\Xi}$ fixed for $U_\Xi = -18$ MeV and -10 MeV are determined respectively to be 0.43399 and 0.51158. The particle fraction showing the composition of the matter is plotted in Fig 1. We observe that the Ξ^- appears at a density of around 0.6 fm^{-3} while Ξ^0 appears at significantly higher density of 1.3 fm^{-3}. The mass-radius relation is plotted in Fig 2. We find that the maximum mass and corresponding radius are 1.91 $M_\odot$ and 11.64 km respectively for $U_\Xi = -18$ MeV. By increasing the U_Ξ to -10 MeV we obtain a maximum mass of 1.95 $M_\odot$ and the corresponding radius decreases to 11.55 km. We conclude that a variation in the hyperon potential impacts the mass and radius as well as the composition of the neutron stars.

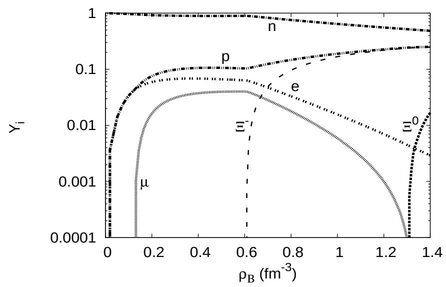

FIG. 1: Particle fraction in the β-equilibrated matter as a function of the density.

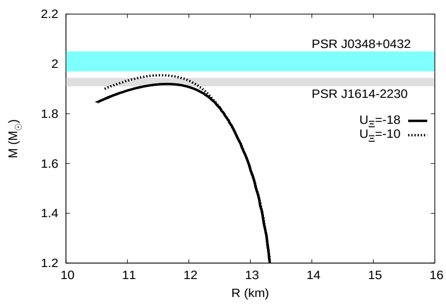

FIG. 2: Gravitational mass as function of radius of the neutron star for different U_Ξ.

Acknowledgment

The authors would like to acknowledge the financial assistance from DAE-BRNS for the project No. 2013/37P/66/BRNS.

References

[1] T. A. Rijken, M. M. Nagels, and Y. Yamamoto, Prog. Theor. Phys. Suppl. **185**, 14 (2010).

[2] R. N. Mishra, H. S. Sahoo, P. K. Panda, N. Barik and T. Frederico, Phys. Rev. C **94**, 035805 (2016).