# Effects of strangeness on the Mass-Radius of neutron stars in MQMC

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With the increase of baryon density towards centers of neutron stars, chemical potentials of neutrons become high so that neutrons at Fermi surfaces are changed to hyperons via strangeness non-conserving weak interactions overcoming rest masses of hyperons. This hyperon mixing to neutron star matter give rise to the hyperon puzzle. The neutron star mass constraints set by the pulsars PSR J0348+0432 and the recent space mission NICER (Neutron Star Interior Composition Explorer)[1] has brought about a resurgence of interest to develop models predicting low radii for massive netron stars. Our attempt in the present modified quark meson coupling model (MQMC) is to overcome the hyperon puzzle to get a high mass and predict a low radius. In our earlier attempt we studied hyperon stars in the MQMC model we realized the baryon-baryon interaction through $\sigma$, $\omega$, and $\rho$ mesons exchanges. We considered the strange quarks as spectators. In the present attempt [2] we incorporate an additional pair of hidden strange mesons $\sigma^*$ and $\phi$ which couple only to the strange quark and the hyperons of the nuclear matter.

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 $g^q_\sigma$, $g^q_{\sigma^*}$, $g^q_\omega$, $g^q_\phi$ and $g^q_\rho$ are the quark coupling constants with the $\sigma$, $\sigma^*$, $\omega$, $\phi$ and $\rho$ 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, $\sigma_0$, $\sigma^*_0$, $\omega_0$, $\phi_0$ and $\rho_{03}$ are the meson fields while $\tau_z$ 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 corrections, which is given as,

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

where $\epsilon_{cm}$ 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 $\delta M^\pi_B$ is the pionic self energy of the baryon due to pion coupling of the non-strange quarks.

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

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

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The total energy density and pressure including leptons in the mean field approximation for nuclear matter is given Eq 2 and Eq 3. Here $\gamma$ is the spin degeneracy factor for nuclear matter, with $\gamma = 2$ for the baryon octet, $B = N, \Lambda, \Sigma^{\pm}, \Sigma^0, \Xi^-, \Xi^0$, $l = e, \mu$. Here $\Lambda_v$ is a nonlinear $\omega$-$\rho$ coupling.

For compact stars with strongly interacting baryons, the composition is determined by the requirements of charge neutrality and $\beta$-equilibrium conditions under weak processes. 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. We fit the quark-meson coupling constants $g_\sigma^q$, $g_\omega = 3g_\omega^q$ and $g_\rho^q = g_\rho$ for the nucleons to obtain the correct saturation properties of nuclear matter. The couplings to the strange mesons are $2g_{\sigma^*\Lambda}=2g_{\sigma^*\Sigma}=g_{\sigma^*\Xi}=2\sqrt{2}g_\sigma/3$ and $2g_{\phi\Lambda}=2g_{\phi\Sigma}=g_{\phi\Xi}=2\sqrt{2}g_\omega/3$.

For quark mass $m_{u,d} = 300$ MeV, $m_s = 450$ MeV and $\Lambda_v = 0.15$ the couplings are $g_\sigma^q = 4.07$, $g_\omega = 9.09$ and $g_\rho = 8.51$ fixed at symmetry energy 32.5 MeV.

The hyperon-meson couplings are fixed by setting the hyperon-nucleon interaction potential at saturation density for the $\Lambda$, $\Sigma$ and $\Xi$ hyperons to $U_\Lambda = -28$ MeV, $U_\Sigma = 30$ MeV and $U_\Xi = -18$ MeV respectively. 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 $x_{\sigma B}=x_{\rho B}=1$, and $x_{\omega B}$ is fixed from $U_B = -(M_B^* - M_B) + x_{\omega B} g_\omega \omega_0$ with $U_B$ fixed at the above values.

The EoS is plotted in Fig 1. The shaded region shows the empirical EOS obtained by Steiner et al. from a heterogeneous set of seven neutron stars. The mass-radius relation of the hyperon star is plotted in Fig 2. We find that the maximum mass and corresponding radius are 2.36 $M_\odot$ and 13.7 km respectively. Without the strange mesons the maximum mass and radius are 2.51 $M_\odot$ and 15.5 km respectively. We observe that in the present model with the inclusion of the strange interactions through $\sigma^*$ and $\phi$ and the nonlinear coupling $\Lambda_v$, our radius decreases and the mass-radius relation comes out within a reasonable limit.

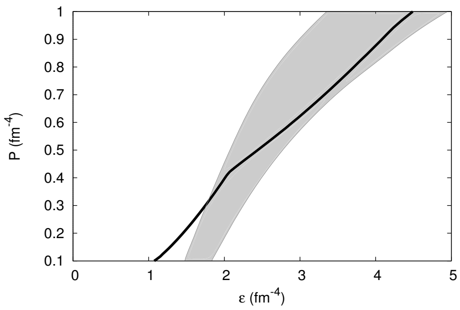


FIG. 1: Pressure for $\beta$-equilibrated hyperon matter as a function of the energy density.

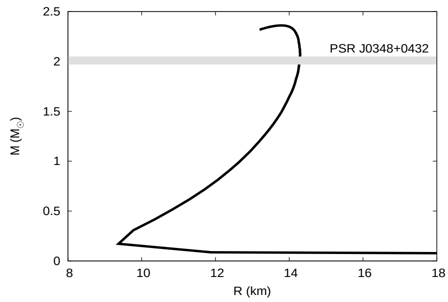


FIG. 2: Gravitational mass as function of radius of the neutron star.

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