Effects of Δ baryon in hyperon stars in a Modified Quark Meson Coupling Model

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Recent studies [1] on the appearance of the Δ (1232) isobars in neutron stars has ignited much debate on the possibility of its existence in neutron stars satisfying the observational limit of 2 $M_{\odot}$. Given the fact that the presence of the Δ tends to soften the equation of state (EoS) and reduce the maximum mass, theoretical and observational contradictions have given rise to the so called Δ puzzle, similiar to the hyperon puzzle. In the present work we develop the EoS for dense matter with the inclusion of the nucleons, hyperons and the Delta isobars and study the effects of such inclusion on stellar properties using a Modified Quark-Meson coupling model (MQMC)[2].

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 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 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 total energy density and pressure including leptons in the mean field approximation for nuclear matter is given as:

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

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

Here γ is the spin degeneracy factor for nuclear matter, with $\gamma = 2$ for the baryon octet and $\gamma = 4$ for the Δ isobars and $B = N, \Lambda, \Sigma^\pm, \Sigma^0, \Xi^-, \Xi^0, \Delta^{++}, \Delta^\pm, \Delta^0$, $l = e, \mu$. For compact stars with strongly interacting baryons, the composition is determined by the requirements of charge neutrality and β-equilibrium conditions under weak processes. After deleptonization the charge neutrality condition yields, $q_{tot} = \sum_B q_B \gamma k^3_B/(6\pi^2) + \sum_{l=e,\mu} q_l k^3_l/(3\pi^2) = 0$, where q_B and q_l are respectively the electric

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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^q_σ, $g_\omega = 3g^q_\omega$ and $g^q_\rho = g_\rho$ for the nucleons to obtain the correct saturation properties of nuclear matter. For quark mass $m_{u,d} = 150$ MeV and $m_s = 300$ MeV the couplings are $g^q_\sigma = 4.39$, $g_\omega = 6.74$ and $g_\rho = 8.79$. 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 150 MeV comes out to be 292 MeV.

The hyperon-meson couplings are fixed by setting the hyperon-nucleon interaction potential at saturation density for the Λ, Σ and Ξ 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. For the couplings between the Δs and mesons we fix, $x_{\sigma\Delta}$=$x_{\rho\Delta}$=1 and $x_{\omega\Delta} = 0.8$.

The particle populations are shown in Fig.1 where we plot the fraction of baryon species i, $Y_i = \rho_i/\rho_B$ as a function of total baryon density ρ_B. We observe that the Δs appear at densities relevant for neutron stars. In an earlier work [3] it was predicted that Δ resonances would appear at densities much higher than the typical densities of the core of neutron stars. Moreover, the appearance of the Δ^- at a density of 0.41 fm^{-3} delays the formation of hyperons.

The mass-radius relation of the hyperon star obtained with the inclusion of nucleons+hyperons+Delta baryons is plotted in Fig 2. We find that the maximum mass and corresponding radius are 2.15 M$_\odot$ and 15.4 km respectively. With nulceons+hyperons we obtain the same mass but a slightly higher radius of 15.6 km. For matter with only nucleons the star becomes more massive at 2.25 M$_\odot$. We conclude that within the present model, a neutron star with Δ isobars in its core is possible, with a mass slighty higher than the observed mass constraint of 2.01 ± 0.04 M$_\odot$ [4].

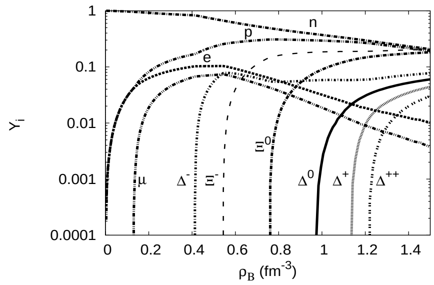

FIG. 1: Particle fraction in neutron star matter as a function of total baryon density.

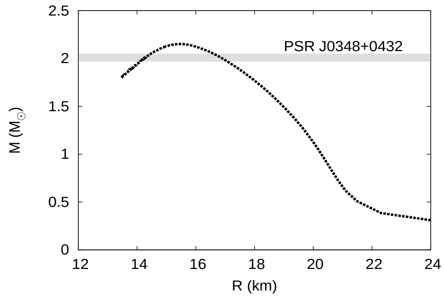

FIG. 2: Gravitational mass as function of radius of the neutron star.

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