Hyperon Matter in Neutron Star

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Introduction

The possible presence of hyperon matter in β-equilibrate neutron star matter is shown in ref. [1, 2] and many other works like ref. [3]. They start appearing in neutron stars at a density when the neutron chemical potential exceeds the bare mass of the hyperons. But the appearance of the hyperons depends on the choice of the coupling constant between mesons and hyperons which can be obtained using different techniques like using SU(6) symmetry theories [4] or from binding energies of different hyperons in nuclear matter [1, 2]. In ref. [1] the coupling constants are calculated by fixing binding energy of Λ hyperon only. But with the experimentally determination of binding energies of the other hyperons in nuclear matter [5], we have calculated the couplings between the individual hyperon with the mesons to study their effect on mass and radius of neutron stars. However, the variation of these couplings are constrained by various hypernuclear studies [6, 7]. Theoretically, inclusion of hyperons in the core of the neutron star reduces the mass of the neutron star.

Formalism

The effective Lagrangian in ref. [1, 2] deals with the interactions between the nucleons and the hyperons with the different mesons like the scalar σ-meson (580 MeV), the vector ω-meson (783 MeV), the isovector ρ-meson (770 MeV). There are five parameters in this model viz. $g_{\sigma_B}, g_{\omega_B}, g_{\rho_B}$, B and C. They are to be determined from the saturated nuclear matter. The charge neutrality and chemical equilibrium conditions are to be imposed essentially. The equations of state (EoS) viz. energy density and pressure are [1, 2]

$$\varepsilon = \frac{m_B^2}{8C_{\sigma_B}}(1-Y^2)^2 - \frac{m_B^2 B}{12C_{\omega_B}C_{\sigma_B}}(1-Y^2)^3 + \frac{Cm_B^2}{16C_{\omega_B}^2 C_{\sigma_B}}(1-Y^2)^4 + \frac{1}{2Y^2}C_{\omega_B}\rho_B^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 + \frac{2}{\pi^2}\int_0^{k_B} k^2\sqrt{(k^2+m_B^{*2})}dk + \frac{1}{\pi^2}\sum_{\lambda=e,\mu^-}\int_0^{k_\lambda} k^2\sqrt{(k^2+m_\lambda^{*2})}dk$$

$$P = \frac{m_B^2}{8C_{\sigma_B}}(1-Y^2)^2 - \frac{m_B^2 B}{12C_{\omega_B}C_{\sigma_B}}(1-Y^2)^3 + \frac{Cm_B^2}{16C_{\omega_B}^2 C_{\sigma_B}}(1-Y^2)^4 + \frac{1}{2Y^2}C_{\omega_B}\rho_B^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 + \frac{2}{3\pi^2}\int_0^{k_B}\frac{k^4}{\sqrt{(k^2+m_B^{*2})}}dk + \frac{1}{3\pi^2}\sum_{\lambda=e,\mu^-}\int_0^{k_\lambda}\frac{k^4}{\sqrt{(k^2+m_\lambda^{*2})}}dk$$

We calculate the coupling constants $x_{\sigma H} = \frac{g_{\sigma H}}{g_{\sigma N}}$ and $x_{\omega H} = \frac{g_{\omega H}}{g_{\omega N}}$ reproducing the binding energy using the relation $(B/A)_H = x_{\omega H} g_{\omega H}\omega_0 + x_{\sigma H}(m_H{}^* - m_H)$ where, the binding energies $(B/A)_H$ = -30 MeV for Λ, +30 MeV for Σ and -18 MeV for Ξ [5]. We solve the EoS for these coupling constants and check the relative population of different baryons. Finally we obtain the mass and radius of the neutron star.

Results

The model parameters are $C_{\sigma_B} = 8.5 fm^2$, $C_{\omega_B} = 2.71 fm^2$, $C_{\rho_B} = 4.66 fm^2$, $B = -9.26 fm^2$, $C = -40.73 fm^4$, m*=0.80 & K=300 MeV. That this parameter agrees with the heavy-ion collision data [8] for symmetric nuclear matter, is shown in ref. [2]. This

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parameter set also satisfies all the other saturated matter properties like the energy per nucleon E_B =16.3 MeV at a saturation density of 0.153 fm^{-3}, incompressibility K=300 MeV, effective mass (m*=0.8-0.9) and asymmetry energy coefficient value of 32 MeV [3]. The choice of couplings are like Set I: $x_{\sigma H}$ =0.5, Set II: $x_{\sigma H} = 0.6$, Set III: $x_{\sigma H} = 0.7$. For all sets $x_{\rho H} = x_{\omega H}$

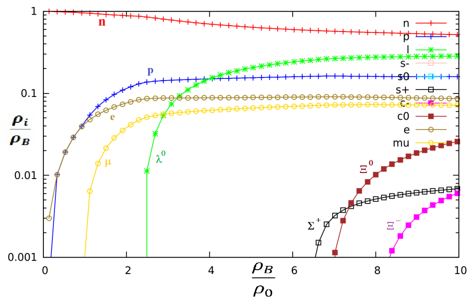

FIG. 1: Relative particle population for Set III.

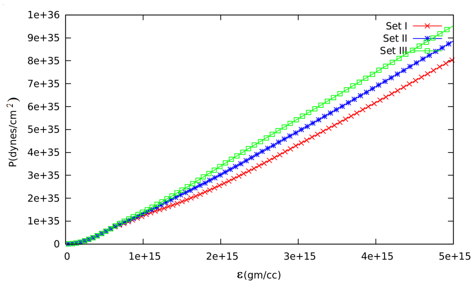

FIG. 2: The Equation of State for the three coupling sets.

Conclusion

The neutron concentration decreases with the formation of more and more baryons and leptons. For Set I, Λ^0 appears first at density about $2.1\rho_0$, followed by Ξ^- at $3.9\rho_0$. For Set II, Λ^0 appears at $2.3\rho_0$, Ξ^- at $4.8\rho_0$ and Ξ^0 at $8.0\rho_0$. For Set III, Λ^0 appears at $2.5\rho_0$, Σ^+ at $6.4\rho_0$, Ξ^- at $7.0\rho_0$ and Ξ^0 at $8.4\rho_0$. For no coupling constant Σ^- and Σ^0 have appeared (fig.1). The EoS for Set III is stiffest

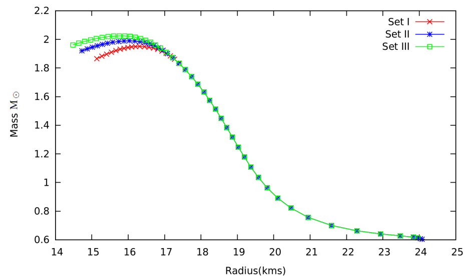

FIG. 3: The mass vs radius plot for the three coupling sets.

among all the sets (fig.2). For the three sets, the maximum masses are $1.95M_\odot$, $1.99M_\odot$ and $2.02M_\odot$ (fig.3) at central energy densities 1.04×10^{15}, 1.07×10^{15} and 1.18×10^{15} gm/cc, respectively and corresponding radii 16.31 km, 16.03 km and 15.75 km, respectively (fig.3). Set III yields the most massive neutron star for this model, satisfying the $2M_\odot$ criterion of neutron star mass [9]. We can conclude that the masses predicted by the three sets are well in accordance with both theoretical and observational values. The increase in the value of $x_{\sigma H}$ for a particular parameter set, makes the neutron star more massive and compact.

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