Neutron Stars with Delta Isomers

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Introduction

In the interior of neutron star core Δ baryons (1232 MeV) may be present when the nucleons come very close to each other at very high density, forming Δ resonance states. In ref.[1], it is shown that by taking universal baryon-meson coupling, critical density of appearance of Δ's is about 9-10ρ_0. Moreover, they soften the EoS and reduces the mass of the neutron star than the $2M_\odot$ mass criterion (PSR J0348+0432)[3] by a good margin. However, recent studies [2] shows that by varying the coupling constants between the Δ's and the nucleons with the mesons not only lower the value of critical density of Δ's but also satisfy the mass criterion. We have used effective chiral model [4], which deals with the interactions between the nucleons and the Δ isomers ($\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$) with the different mesons like the scalar σ-meson, the vector ω-meson, the isovector ρ-meson.

Formalism

The effective Lagrangian in ref.[4] has five parameters in this model viz. $g_{\sigma_B}, g_{\omega_B}, g_{\rho_B}$ and B and C. Their values are evaluated exploiting the saturated properties of nuclear matter viz. the energy per nucleon E_B= -16.3 MeV at a saturation density of $0.153 fm^{-3}$, incompressibility K=300 MeV, asymmetry energy coefficient 32 MeV [1]. Since the different baryons have different charges, the charge neutrality and chemical equilibrium conditions are to be imposed [2]. The equation of state viz. energy density and pressure [4] are

$$\varepsilon = \frac{m_B^2}{8C_{\sigma_B}}(1-Y^2)^2 - \frac{m_B^2 B}{12C_{\omega_B}C_{\sigma_B}}(1-Y^2)^3 +$$

$$\frac{Cm_B^2}{16C_{\omega_B}^2 C_{\sigma_B}}(1-Y^2)^4 + \frac{1}{2Y^2}C_{\omega_B}\rho_B^2 + \frac{1}{2}m_\rho^2\rho_{03}^2$$

$$+\frac{2}{\pi^2}\int_0^{k_B} k^2\sqrt{(k^2+m_B^{*2})}dk$$

$$+\frac{1}{\pi^2}\sum_{\lambda=e,\mu^-}\int_0^{k_\lambda} k^2\sqrt{(k^2+m_\lambda^{*2})}dk$$

$$P = \frac{m_B^2}{8C_{\sigma_B}}(1-Y^2)^2 - \frac{m_B^2 B}{12C_{\omega_B}C_{\sigma_B}}(1-Y^2)^3$$

$$+\frac{Cm_B^2}{16C_{\omega_B}^2 C_{\sigma_B}}(1-Y^2)^4 + \frac{1}{2Y^2}C_{\omega_B}\rho_B^2 + \frac{1}{2}m_\rho^2\rho_{03}^2$$

$$+\frac{2}{3\pi^2}\int_0^{k_B}\frac{k^4}{\sqrt{(k^2+m_B^{*2})}}dk$$

$$+\frac{1}{3\pi^2}\sum_{\lambda=e,\mu^-}\int_0^{k_\lambda}\frac{k^4}{\sqrt{(k^2+m_\lambda^{*2})}}dk$$

We solve the equations of state for different coupling constants $a = \frac{g_{\sigma\Delta}}{g_{\sigma N}}, b = \frac{g_{\omega\Delta}}{g_{\omega N}}, c = \frac{g_{\rho\Delta}}{g_{\rho N}}$, to study the effect on relative population of different baryons and also on the EoS and calculate the mass and radius of the neutron star.

Results

The model parameters are $C_{\sigma_B} = 6.79 fm^2$, $C_{\omega_B} = 1.99 fm^2$, $C_{\rho_B} = 4.66 fm^2$, $B = -4.32 fm^2$, $C = 0.165 fm^4$, m*=0.85, K=300 MeV. For symmetric nuclear matter, the EoS obtained using this parameter set, passes through the heavy-ion collision data [5]. This is shown in ref. [6]. First we have observed the changes in the appearance of the Δ's and their effect on mass and radius of the neutron star by varying the $\Delta - \rho$ coupling for fixed values of a and b in table 1.
At c=1.2 there are no Δ particles. At c=1.0 Δ^- appears at density $5.4\rho_0$.

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Table 1

a	b	c	Appearance of Δs	M(M$\odot$)	R(kms)
2.0	0.6	1.2	no Δ	1.96	13.69
		1.0	Δ^-	1.96	13.69
		0.8	Δ^-, Δ^0	1.62	12.42
		0.6	Δ^-, Δ^0	1.40	10.58
		0.4	Δ^-, Δ^0,Δ^+	1.25	9.16
		0.2	Δ^-, Δ^0, Δ^+,Δ^{++}	1.22	8.66

At c=0.8 Δ^- appears at 2.5ρ_0 and Δ^0 at 6.8ρ_0. For c=0.6 Δ^- and Δ^0 appear at 2.3ρ_0 and 4.6ρ_0, respectively and Δ^+ at 8.4ρ_0. For c=0.4 Δ^-, Δ^0 and Δ^+ appear at 1.9ρ_0, 4.6ρ_0 and 7.6ρ_0, respectively. For c=0.2 Δ^-,Δ^0 and Δ^+ appear at 1.7ρ_0, 4.9ρ_0 and 7.0ρ_0 with Δ^{++} at 9.1ρ_0.

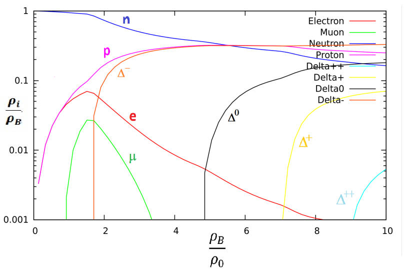

FIG. 1: Relative particle population for a=2.0, b=0.6 and c=0.2

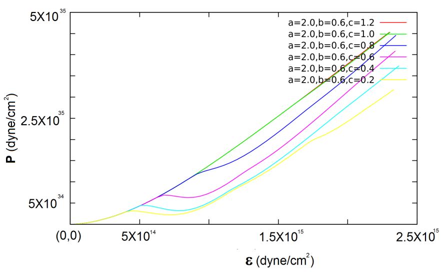

FIG. 2: Equation of State for a=2.0, b=0.6 with variation in c

Next we have varied a and b for a fixed moderate value of c=0.5, to study the effect on the appearance of Δ's, the corresponding EoS and the mass and radius of neutron star. The results are shown in table 2.

Table 2

a	b	c	Appearance of Δs	M(M$\odot$)	R(kms)
1.0	1.0	0.5	Δ^-	1.68	15.49
	0.8		Δ^-	1.64	15.70
	0.6		Δ^-, Δ^0	1.62	15.97
1.5	1.0	0.5	Δ^-	1.66	15.68
	0.8		Δ^-	1.62	16.01
	0.6		Δ^-, Δ^0	1.59	16.27

For c=1, b=1 Δ^- appears at density 2.3ρ_0, for b=0.8 Δ^- at 2.3ρ_0, for 0.6 Δ^- at 2.2ρ_0 and Δ^0 at 8.1ρ_0. For c=1.5,b=1 Δ^- appears at density 2.6ρ_0, for b=0.8 Δ^- at 2.6ρ_0, for 0.6 Δ^- at 2.2ρ_0 and Δ^0 at 6.5ρ_0.

Conclusion

The formation of the Δs depend on the choice of the coupling constants. But irrespective of the couplings, Δ^- is the first to appear, followed by Δ^0,Δ^+ and Δ^{++}. The formation of all the Δ's together is quite unfavourable in neutron star matter except for a certain coupling but Δ^- and Δ^0 may be present for a considerable fraction. The reduction of $\rho-\Delta$ coupling favours the formation more Δ's for fixed $\sigma-\Delta$ and $\omega-\Delta$ couplings but reduces both mass (1.22 - 1.96)$M_\odot$ and radius (8.66 - 13.69)kms. With this model, although we are not able explain the composition of $2M_\odot$ mass neutron star but we got the highest mass quite close (1.96$M_\odot$). For a fixed value of $\sigma-\Delta$ coupling and $\rho-\Delta$ coupling,the increase in $\omega-\Delta$ coupling makes the neutron star more massive upto 1.68$M_\odot$ with radius upto 15.49 kms.

References

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