Effects of the ϕ-meson on the hyperon production in the hyperon star.

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Introduction

Neutron star provides a platform to study the nuclear matter with high degrees of asymmetry and density. The neutron star is composed of mainly 80-90% of neutron and 10-20% of proton and small amount of electron and muon to maintain β-equilibrium. So it is worthy to study neutron star to reveal more about the nature of the asymmetry nuclear matter. The density of the neutron star is about 5-6 times the nuclear saturation density $(0.13 fm^{-3})$. This ultra dense environment favor the probability for the production of the exotic degrees of freedom like hyperon (Λ, Σ, Ξ). The main ingredient to study the global properties of the neutron star like maximum mass and radius, is the equation of state (EOS). Addition of the hyperon degrees of the freedom in the EOS, significantly reduces the EOS and produces a lower maximum allowed mass for the neutron star. The recent observation of the maximum mass of the neutron star, which is around 2 $M_{\odot}$[4] reopen the subject. This is quoted as the hyperon puzzle. It was reported by V. A. Ambartsumyan in 1960 [1, 2]. Lots of efforts have been going on in this direction to resolve the hyperon puzzle. There are basically three way to look deep into in this puzzle : (a) addition of repulsive strange vector ϕ-meson (b) addition of the repulsive hyperonic three-body force (c) possibility of phase transition to deconfinment quark matter. We will discuss more about the first method in this present manuscript.

1. Formalism

In this present manuscript, we have used the relativistic mean filed formalism to calculate the EOS of the neutron and hyperon star. We have included the strange vector ϕ-meson on the top of the G1-interaction. The mean filed Lagrangian density is given by the eq. 1. All the symbol carry their usual meaning. The nucleon-meson coupling constants are taken from the G1-parameter set[3] and for the the hyperon-meson coupling constants, we have followed the procedure described in [2].

$$\begin{aligned}
\mathcal{L} = {} & \sum_B \overline{\psi}_B \Big(i\gamma^\mu \partial_\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu \\
& -\frac{1}{2} g_{\rho B}\gamma_\mu \tau \rho^\mu - g_{\phi B}\gamma_\mu \phi^\mu \Big)\psi_B + \frac{1}{2}\partial_\mu \sigma \partial_\mu \sigma \\
& -m_\sigma^2 \sigma^2 \left(\frac{1}{2} + \frac{\kappa_3}{3!}\frac{g_\sigma \sigma}{m_B} + \frac{\kappa_4}{4!}\frac{g_\sigma^2 \sigma^2}{m_B^2} \right) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} \\
& +\frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu \left(1 + \eta_1 \frac{g_\sigma \sigma}{m_B} + \frac{\eta_2}{2}\frac{g_\sigma^2 \sigma^2}{m_B^2} \right) - \frac{1}{4} R_{\mu\nu} R^{\mu\nu} \\
& +\frac{1}{2} m_\rho^2 R_\mu R^\mu \left(1 + \eta_\rho \frac{g_\sigma \sigma}{m_B} \right) + \frac{1}{4!}\zeta_0 \left(g_\omega \omega_\mu \omega^\mu \right)^2 \\
& +\frac{1}{2} m_\phi{}^2 \phi_\mu \phi^\mu + \sum_l \overline{\psi}_l \left(i\gamma^\mu \partial_\mu - m_l \right)\psi_l \\
& +\Lambda_v R_\mu R^\mu (\omega_\mu \omega^\mu), \qquad (1)
\end{aligned}$$

The value of σ-hypeon $(x_{\sigma Y})$ interaction strength and ω-hyperon interaction strength $(x_{\omega Y})$ is adjusted to produced the different hyperon potential by the formula :

$$U_Y = m_n\left(\frac{m_n^*}{m_n} - 1\right)x_{\sigma Y} + \left(\frac{g_\omega}{m_\omega}\right)\rho_0 x_{\omega Y}. \quad (2)$$

The potential depth for the different hyperon are U_Λ=-30 MeV, U_Σ=+40 MeV and U_Ξ=-28 MeV. The ρ-hyperon interaction strength is fitted according to the SU(6) group symmetry.

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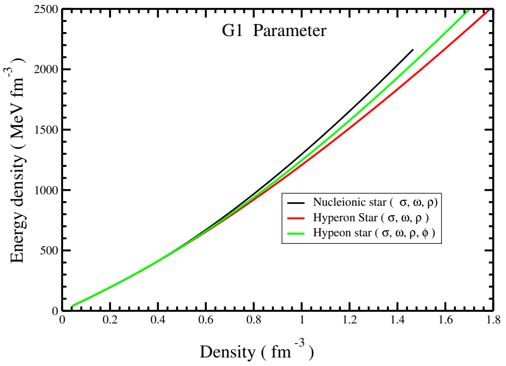

FIG. 1: Variation of the energy density with baryon density in different model.

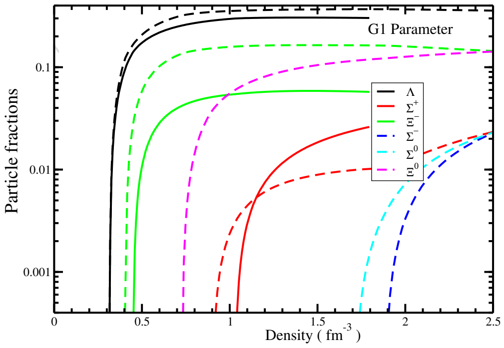

FIG. 2: Production of various hyperon at different density. the dotted line are without ϕ-meson and the solid line with ϕ-meson.

$x_{\rho\Lambda}$=0.0, $x_{\rho\Sigma}$=1.0 and $x_{\rho\Xi}$=2.0. The strength of interaction the ϕ with hyperon are given like

$$2g_{\phi\Lambda} = 2g_{\phi\Sigma} = g_{\phi\Xi} = \frac{-2\sqrt{2}}{3} g_{\omega N} \qquad (3)$$

Results and Discussions

We have added the ϕ-meson on the top of the G1 interaction to see the effects of the strange vector meson on the equation of state of the hyperon and neutron star. In Fig. 1, we have plotted the energy density with baryon density for three different models. The stiffest equation of the state is case where the nucleon degrees of freedom with interacting meson as σ,ω and ρ-meson. With the inclusion of the hyperon the equation of become softer than previous case. This is basically due to the reduction of the Fermi pressure with production of the hyperon. In third case with have added the ϕ-meson with hyperon degrees of freedom, the inclusion of the strange vector meson gives some extra repulsion, which gives slightly stiff equation of state than previous case. In Fig. 2, we have shown how the hyperon production affected by the inclusion of the ϕ-meson. The production of the hyperon governed by the equation

$$\begin{aligned} \mu_n - q_B\mu_e \geq g_\omega B\omega_0 + g_\rho B\rho_{03} \\ + M_B - g_{\sigma B}\sigma_0 + g_{\phi B}\phi. \end{aligned} \qquad (4)$$

The positive term in the right hand side due to the ϕ-meson shift the production of the hyperon to higher density. Except the Λ-hyperon all other hyperons are shifted significantly to higher density. Some of the hyperon like Ξ^0,Σ^- and Σ^0 are disappeared, when the ϕ-meson included with hyperon degrees of freedom.

Conclusion

With the inclusion of the strange vector ϕ-meson in the hyperon system, the equation of state become stiffer, which consequently gives slightly higher maximum allowed mass for the hyperon star. The stiff equation of state is due to the shifting of the threshold density of the hyperon production to higher density. This reduces the hyperon content in the hyperon star and makes the equation of the state stiff and increases the maximum allowed mass.

References

[1] V. A Ambartsumyan and G. S. Saakyan, Sov. Astron. **4**, 187 (1960).
[2] N. K. Glendenning, The Astrophysical Journal **293**, 470 (1985).
[3] R. J. Furnstahl, B. D. Serot and H. B. Tang, Nucl. Phys. A **615**, 441 (1997).
[4] J. Antoniadis et al., Science **340**, 6131 (2013).