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Delta Resonance Coupling with Walecka's Mesons: Implications to Stellar Matter EoS

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In this work we have obtained the equation of state to the highly asymmetric dense stellar matter, using the nonlinear Walecka model in the mean field approximation. We discussed the implication of changes in coupling constant of the delta baryonic resonance on the observable of the neutron star. A detailed analysis of the equation of state and of the baryonic effective mass in respect to changes in the delta coupling constants is carried out. We focus attention on a new aspect observed for pressure when varying the baryonic density of the medium; a first order phase transition like a liquid-gas phase transition was observed for an acceptable range of delta coupled constant values. We have explored the implication of this aspect for the neutron star structure and their maximum masses.

Keywords: Stars, Delta Resonances, Nonlinear Walecka Model, Equation of State.

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1. Introduction

The high production of delta-resonances in the dense phase ($\rho \geq 3\rho_0$) of relativistic heavy ion collisions [1,2], where ρ_0 is the normal nuclear matter density, leads to a great interest in the study on the delta matter effect to the neutron star structure. In this work we obtained the equation of state of baryons and leptons to the highly asymmetric dense stellar matter. We discussed the implication of changes in coupling constant of the delta baryonic resonance with Walecka's mesons to the formation of delta resonance matter in stellar medium. We adopt the nonlinear Walecka model in the mean field approximation [3,4], including the octet of baryons with spin 1/2 (n, p, Λ^0, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0), the baryonic resonances of spin 3/2 with isospin states (Δ^-, Δ^0, Δ^+, Δ^{++}) and Ω^- resonance in the baryonic sector [5,6]. In the leptonic sector we consider the electrons and muons.

2. The Lagrangian Density

The Lagrangian density of this hadronic and leptonic dense medium [3,4] is given by

$$\mathscr{L} = \mathscr{L}_{\rm F} + \mathscr{L}_{\rm I}, \tag{1}$$

where

$$\begin{aligned}\mathscr{L}_{\rm F} = &\sum_B \overline{\Psi}_B \left(i\gamma_\mu\partial^\mu - m_B\right)\Psi_B + \sum_{\zeta=\Delta,\,\omega} \overline{R}_{\zeta\nu}\left(i\gamma_\mu\partial^\mu - m_\zeta\right)R^\nu_\zeta \\ &+\frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{3}b\,m_N\left(g_{\sigma_N}\sigma\right)^3 - \frac{1}{4}c\left(g_{\sigma_N}\sigma\right)^4 - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} \\ &+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\rho^\mu + \sum_{\lambda=e^-,\,\mu^-}\overline{\Psi}_\lambda\left(i\gamma_\mu\partial^\mu - m_\lambda\right)\Psi_\lambda,\end{aligned} \tag{2}$$

is the Lagrangian density for free baryons, free leptons (e^-, μ^-), and the meson fields σ, ω_μ and ρ_μ. In addition, the interaction Lagrangian density is given by the following expression

$$\begin{aligned}\mathscr{L}_{\rm I} = &\sum_B \overline{\Psi}_B\left(g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - \frac{1}{2}g_{\rho B}\gamma_\mu\tau\rho^\mu\right)\Psi_B + \\ &\sum_{\zeta=\Delta,\,\Omega}\overline{R}_{\zeta\nu}\left(g_{\sigma\zeta}\sigma - g_{\omega\zeta}\gamma_\mu\omega^\mu - \frac{1}{2}g_{\rho\zeta}\gamma_\mu\tau\rho^\mu\right)R^\nu_\zeta.\end{aligned} \tag{3}$$

In the equations above the operator Ψ_B represents the Dirac spinor describing the 1/2-spin baryonic octet, with $B = n$, p, Λ^0, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0 and the operator R^ν_ζ is the Rarita-Schwinger spinor [7], with $\zeta = \Delta^-$, Δ^0, Δ^+, Δ^{++}, Ω^- describing the 3/2-spin baryonic resonances.

3. Results and Conclusions

In Figs. 1(a) and (b) we show the behaviour of the equation of state (pressure versus density) for different values of delta-mesons coupling constants. Notice in figure 1 (a), the presence of some intervals for which $dP/d\rho < 0$, that indicates the existence of a phase transition due to the production of delta-resonance in the medium. We note that the attractive nature of the delta resonance interaction with other baryons induces a first order phase transition like a liquid-gas phase transition. A Maxwell construction is thus implemented in order to connect both the phases. In Fig. 1(b) we show the behaviour of the pressure versus density after the Maxwell construction.

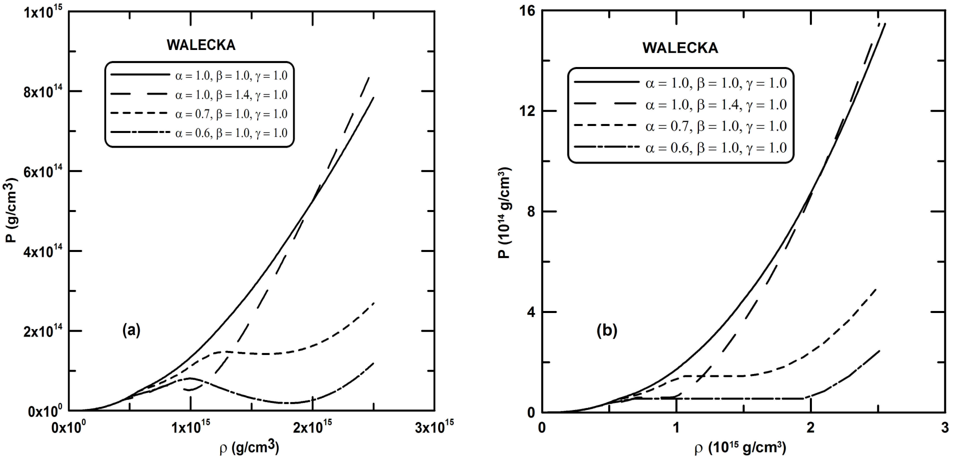

Fig. 1. Pressure as a function of density for different values of delta-mesons coupling constants, in (a), and the pressure as a function of density after the Maxwell construction, in (b).

In this work we have used the results of the finite density QCD Sum Rules (QCDSR) to determine the possible values of delta-meson coupling constants [8], where we have taken different values for the quantities $\alpha = g_{\omega\Delta}/g_{\omega N}$, $\beta = g_{\sigma\Delta}/g_{\sigma N}$ and $\gamma = g_{\rho\Delta}/g_{\rho N}$. For the nonlinear Walecka model we have used the set of coupling constants given in Ref. 9, namely $(g_{\sigma N}/m_\sigma)^2 = 9.927\ fm^2$, $(g_{\omega N}/m_\omega)^2 = 4.820\ fm^2$, $(g_{\rho N}/m_\rho)^2 = 4.791\ fm^2$, $b = 0.008659$ and $c = -0.002421$.

In figure 2 we show the behaviour of the effective mass for different values of delta-mesons coupling constants. We observe that the effective mass is reduced for the cases: ($\alpha = 1.0$, $\beta = 1.4$, $\gamma = 1.0$), ($\alpha = 0.7$, $\beta = 1.0$, $\gamma = 1.0$) and ($\alpha = 0.6$, $\beta = 1.0$, $\gamma = 1.0$), when compared to the case universal coupling ($\alpha = \beta = \gamma = 1.0$).

Using the equation of state obtained by the model, we have numerically solved the Tolman-Oppenheimer-Volkoff (TOV) structure equations [10,11] in order to obtain the mass-radius relationship of a neutron star. The figure 3 shows the mass-radius diagrams for the sets of parameters: ($\alpha = \beta = \gamma = 1.0$), ($\alpha = 1.0$, $\beta = 1.4$, $\gamma = 1.0$), ($\alpha = 0.7$, $\beta = 1.0$, $\gamma = 1.0$) and ($\alpha = 0.6$, $\beta = 1.0$, $\gamma = 1.0$).

4. Conclusion

In conclusion, we remark that the neutron star has a maximum mass when we use the parameter ($\alpha = \beta = \gamma = 1.0$). For this case, where the delta resonances appear near $\rho = 8\rho_0$, the equation of state is stiffer, and thus this explains why the neutron star can support more matter.

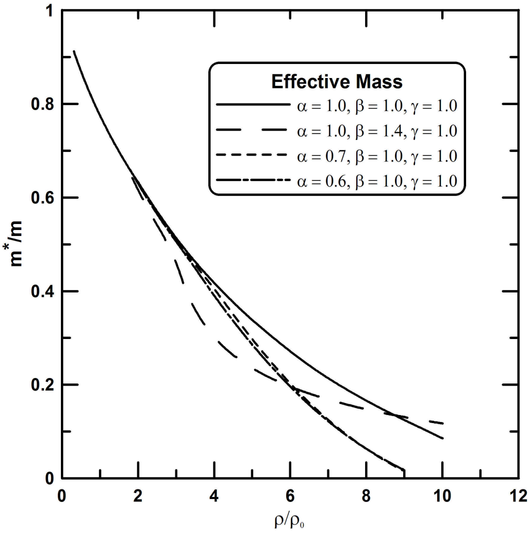

Fig. 2. Effective mass versus density for different values of delta-mesons coupling constants.

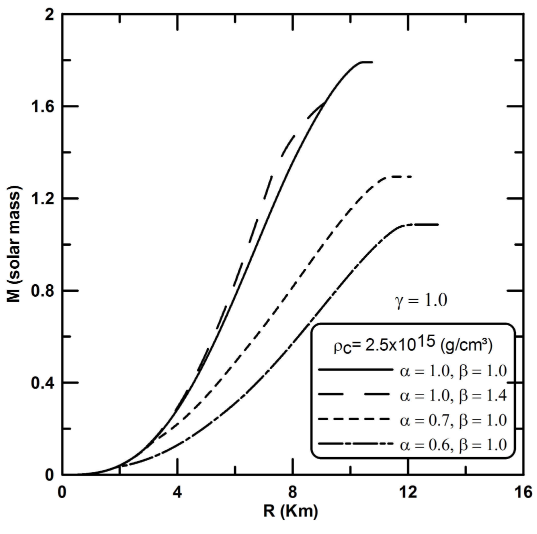

Fig. 3. Mass-radius diagrams for different values of delta-mesons coupling constants, with central density $\rho_c = 2.5 \times 10^{15}$ g/cm^3.

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