Potential effects of Δ–isobars on Neutron star bulk properties

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Introduction

In the vast cosmos, a neutron star is an extremely dense celestial object where all the four fundamental forces converge. Initially, it is believed that the core of a neutron star is mainly made up 90% of neutrons and 10% of protons. Advanced studies have revealed the possibility of formation of hyperons, the condensation of kaons, and the deconfinement of quarks within the core of a neutron star. In the early stages of research, the influence of Δ–isobars on neutron stars was mostly ignored, as they were thought to exist only at incredibly high densities. However, recent observations have changed this perspective. It has been discovered that by adjusting the Δ coupling constant to specific values, Δ–isobars can exist even at lower densities. The appearance of the Δ–isobars at lower density affect the threshold density of other hyperons and soften the equation of state (EOS). This leads to a decrease in the maximum mass, canonical radius and canonical tidal deformability of the neutron star.

In this work, we delve into the influence of the Δ–isobar on the bulk properties of neutron stars, including their mass, canonical radius, and tidal deformability. To achieve this, we utilize 22 distinct parameter sets within the framework of the Relativistic Mean-Field (RMF) model. Our study involves a meticulous comparison of our results with the constraints provided by the Neutron star Interior Composition Explorer (NICER) and the gravitational wave event GW170817 [1]. Through this comparative analysis, we aim to identify the parameter sets that exhibit the highest degree of consistency with these observational constraints. We also investigate how the bulk properties of the neutron star change with varying the coupling constants of Δ-isobars.

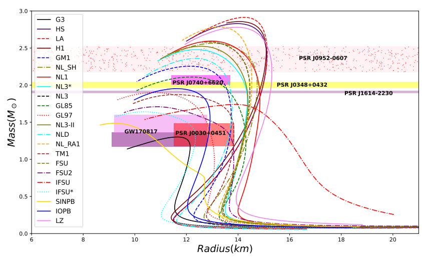

FIG. 1: Effect of the Δ-isobar on the mass-radius profile of the neutron and hyperon star.The boxes represent the NICER and GW170817 constraints.

Theoretical Formalism

The Relativistic Mean Field (RMF) theory serves as a successful theoretical framework for describing the properties of dense nuclear matter, with particular relevance in the study of neutron stars. This theory offers predictions for various neutron star properties, including mass-radius relations, equations of state, and stability criteria. Here, we use RMF theory to construct an EOS including Δ-isobar. The Lagrangian of RMF theory can be use to calculate the total energy $\mathcal{E}$ and pressure $\mathcal{P}$ from energy-momentum tensor $T^{\mu\nu}$ as

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$$
\begin{aligned}
\mathcal{E} &= \sum_B \frac{Y_B}{(2\pi)^3} \int_0^{k_F^B} d^3k \sqrt{k^2 + m_B{}^*} + \frac{1}{8}\zeta_0 g_\omega^2 \omega_0^4 \\
&+ m_\sigma^2 \sigma_0^2 \left(\frac{1}{2} + \frac{\kappa_3}{3!}\frac{g_\sigma \sigma_0}{m_B} + \frac{\kappa_4}{4!}\frac{g_\sigma^2 \sigma_0^2}{m_B^2} \right) \\
&+ \frac{1}{2} m_\omega^2 \omega_0^2 \left(1 + \eta_1 \frac{g_\sigma \sigma_0}{m_B} + \frac{\eta_2}{2}\frac{g_\sigma^2 \sigma_0^2}{m_B^2} \right) \\
&+ \frac{1}{2} m_\rho^2 \rho_{03}^2 \left(1 + \eta_\rho \frac{g_\sigma \sigma_0}{m_B} \right) + \frac{1}{2} {m_\phi}^2 \phi^2 \\
&+ \sum_l \int_0^{k_F^l} \sqrt{k^2 + {m_l}^2}\, k^2 dk + 3\Lambda_V \omega_0^2 R_0^2, \qquad (1)
\end{aligned}
$$

and

$$
\begin{aligned}
\mathcal{P} &= \sum_B \frac{Y_B}{3(2\pi)^3} \int_0^{k_F^B} \frac{k^2 d^3k}{\sqrt{k^2 + {m_B^*}^2}} + \frac{1}{24}\zeta_0 g_\omega^2 \omega_0^4 \\
&- m_\sigma^2 \sigma_0^2 \left(\frac{1}{2} + \frac{\kappa_3}{3!}\frac{g_\sigma \sigma_0}{m_B} + \frac{\kappa_4}{4!}\frac{g_\sigma^2 \sigma_0^2}{m_B^2} \right) \\
&+ \frac{1}{2} m_\omega^2 \omega_0^2 \left(1 + \eta_1 \frac{g_\sigma \sigma_0}{m_B} + \frac{\eta_2}{2}\frac{g_\sigma^2 \sigma_0^2}{m_B^2} \right) \\
&+ \frac{1}{2} m_\rho^2 \rho_{03}^2 \left(1 + \eta_\rho \frac{g_\sigma \sigma_0}{m_B} \right) + \Lambda_V R_0^2 \omega_0^2 \\
&+ \frac{1}{3\pi^2} \sum_l \int_0^{k_F^l} \frac{k^4 dk}{\sqrt{k^2 + m_l^2}}, \qquad (2)
\end{aligned}
$$

where l stands for the leptons (electrons and muons). The energy and pressure can be used in TOV equation [2–4] to calculate the mass and radius of a neutron star.

Result and conclusion

Our investigations reveal that the presence of the Δ-isobar softens the equation of state (EOS). This softening effect manifests itself through a reduction in both the maximum mass and the canonical radius of neutron stars, as illustrated in Fig.1. The comprehensive analysis shows none of the Relativistic Mean Field (RMF) parameter sets entirely conform to all observational constraints. Nevertheless, specific parameter sets such as NLD and GM1 adhere to the NICER constraints, while G3, SINPB, IFSU*, IOPB, and GL97 align with the GW170817 constraints.

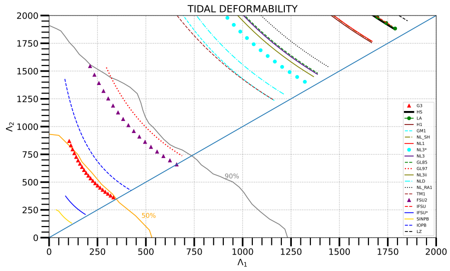

FIG. 2: The $\Lambda_1 - \Lambda_2$ plot of the neutron star for various parameter sets of RMF model with Δ-isobar.

We also explore the effect of Δ–isobar on the EOS, mass, canonical radius, and canonical tidal deformability ($\Lambda_{1.4}$) at different coupling constants of the Δ–isobar. We found that increasing the coupling constant $X_{\sigma\Delta}$ from 1 to 1.2 leads to the emergence of Δ-isobar at lower densities, resulting in a softening of the EOS, and a reduction of the maximum mass and canonical radius ($R_{1.4}$). Conversely, an increase in the coupling constant $X_{\rho\Delta}$ from 0 to 2 leads to populate Δ–isobar at higher densities, leading to a stiffening of the EOS and an increase in both the maximum mass and canonical radius ($R_{1.4}$).

Our study also reveals the inclusion of the Δ-isobar reduces the tidal deformability. Due to this, the parameter sets namely GL97, FSU2 , IOPB, G3, IFSU*, and SINPB lie within 90% credible limit (see Fig.2) satisfying the range of $\Lambda_{1.4}$=70-580 [1].

Acknowledgments

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References

[1] Abbott, B. P., et al. 2018, Phys. Rev. Lett., 121, 161101
[2] Tolman, R. C. 1939, Phys. Rev., 55, 364.
[3] Oppenheimer, J. R., and Volkoff, G. M. 1939, Phys. Rev., 55, 374.
[4] Glendenning, N. K. 1997, Compact Stars(Spinger - Verlag New York)