Probing dense matter equation of state in light of neutron star observable constraints

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Neutron stars (NSs), one of the end products of massive stars ($8 \leq M_{\rm star}/M_{\odot} \leq 20$), produced as remnants of supernova explosions, are among the fascinating objects of the universe in view of theoretical studies of matter in extreme conditions not yet possible to produce in terrestrial laboratories. NSs are highly compact stars with mass as high as that of the sun but with a radius of around 10 km. Consequently, its interior is the only laboratory to study matter at that much high density. Hence, astrophysical observations of NSs which are directly or indirectly related to the dense matter properties and composition come to aid of dense matter study. Recent observations of massive NSs ($\geq 2\ M_{\odot}$) [2] along with the mass-radii measurements by Neutron star Interior Composition ExplorER (NICER) space mission, gravitational-wave (GW) observables (tidal response) have put sturdy bounds on the equation of state (EoS) at high matter densities and provide vital information regarding the inclusion of exotic particle species into NS matter. The discovery of massive NSs opens up the possibility of exotic matter appearance in NS interiors.

In this study, we explore the novel aspects of new exotic degrees of freedom addition and its subsequent effects in dense matter EOS while satisfying the stringent constraints on NS astrophysical observables. From the recent observations mentioned above, we try to fix the shortcomings of exotic matter interaction. In order to do so, the particle interactions in the dense matter at high-density regimes, we implement the phenomenological relativistic mean field (RMF) model [1]. This work incorporates the non-linear (NL) and density-dependent (DD) coupling schemes within the framework of the RMF theory model.

In order to understand the dense matter behavior and properties, we investigated the meson (antikaon) condensations interior to NSs within the framework of phenomenological RMF model. We presented an EoS with phase transition from hadronic phase to antikaonic one as first order while satisfying the astrophysical constraints [3]. The viability of antikaons in dense matter is found to be allowed for a range of antikaon optical potentials ($-160 \leq U_{\bar{K}} \leq -120$ MeV). The functionals in the antikaonic sector are constrained by the experimental studies on K^- atomic, kaon-nucleon scattering data fits.

We further studied the effect of antikaon condensation on the properties of compact stars that develop hypernuclear cores with and without an admixture of Δ-resonances and the results are reported in Ref.-[4]. The meson-hyperon couplings are adjusted to the fits from Λ and Ξ^- hypernuclei data and for Δ-resonances sector, the couplings are tuned to the data obtained from heavy-ion collision experiments. We found that both the K^- and $\bar{K}^0$-condensations occur through a second-order phase transition, implying no mixed-phase formation. For large values of antikaon and Δ-resonance potentials in symmetric nuclear matter, we observe that condensation leads to the extinction of $\Xi^{-,0}$ hyperons. Moreover, the onset of Δ-baryons shifts hyperon thresholds to larger matter densities. Inclusion of heavier baryons and antikaons leads to further constrainment of antikaon optical potential range as well ($-150 \leq U_{\bar{K}} \leq -120$ MeV). In addition, due to the uncertainty of σ^*-meson role in dense matter behavior, we also investigated the influence of inclusion of this additional hidden-strangeness meson in RMF model. We found that it leads

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to a substantial softening of the EoS and delay in the onset of antikaons.

The nuclear matter properties and astrophysical constraints have strongly impacted ruling out of the coupling parametrization models. This was approached in Ref.-[5]. It was observed that allowing the inclusion of heavier strange and non-strange baryons along with the strict bounds from GWs and massive NS observations constrain the theoretical models of nuclear matter comportment at extensive density regimes. Considering non-nucleonic degrees of freedom in NS matter composition, most of the non-linear (NL) Walecka type coupling schemes do not support the bounds from astrophysical observations as well as terrestrial experiments, while most of the density-dependent (DD) coupling parametrizations satisfy these mentioned bounds. Astrophysical observations are well explained if heavier non-strange baryons are included as one fraction of the dense matter particle spectrum. We reported that for a 1.5 $M_\odot$ NS, the stringent limits on GW observable translates to an allowed radius range $11.89 \leq R_{1.5}/\mathrm{km} \leq 12.98$. And based on robust analysis of these EoS models, the lower bound on compactness parameter for a canonical 1.4 $M_\odot$ NS is inferred to be $C_{1.4} \geq 0.1608$.

Furthermore, the effects of nuclear symmetry energy on neutron star dense matter EoS considering exotic degrees of freedom and its impact on NS observables are reported in Ref.-[6]. The slope of symmetry energy parameter (L_{sym}) is adjusted following a density-dependence of isovector meson coupling to baryons. We found that smaller values of L_{sym} at saturation favour the early appearance of Δ-resonances in comparison to hyperons leading to the latter's threshold at higher matter densities. Thus, based on recent PREX-2 data implying $L_{\mathrm{sym}}(n_0)$ to be in the range $69-143$ MeV [7], the heavier non-nucleonic degrees of freedom incorporated in this work are comparatively shifted to higher matter density regimes. The dependence of L_{sym} on tidal deformability and compactness parameter of a canonical 1.4 $M_\odot$ NS for different EoSs were analysed, and similar converging behaviour for larger L_{sym} values was observed.

Additionally, we investigated the baryonic matter under an intense magnetic field within the framework of RMF theory [8]. We found that the EoS is perceived to stiffen with the magnetic field, which increases the maximum mass of NS compared to the non-magnetic case. Besides, the strangeness fraction is enhanced and several matter properties viz. Dirac effective mass, particle abundances show oscillatory behaviour similar to de Haas–van Alphen oscillations in the presence of strong magnetic fields.

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