Static Properties of Hybrid Stars with Color-Flavor-Locked Quark Matter

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1. Introduction

The composition and equation of state (EoS) of dense neutron star (NS) cores are still quite inconclusive from experimental perspectives. However, observational constraints from massive pulsars like PSR J0740+6620, the gravitational wave events GW170817 and GW190425 and the NICER experiment help us to constrain the EoS to some extent. Theoretically, NS cores may support the formation of exotic matter and at further high density the hadronic matter (HM) may undergo phase transition (PT) to form quark matter (QM). Such QM can form Cooper pairs near the Fermi surface, the pairing strength being controlled by the gap parameter Δ. This leads to the formation of color-flavor locked (CFL) quark phase.

In this work, we invoke PT of β stable hadronic matter to CFL QM following Maxwell construction (MC) and obtain the hybrid EoS and the properties hybrid stars (HSs) with respect to the various constraints on them [1].

2. Formalism

The HM is described by the NL3$\omega\rho$6 model [2] in β stable condition. For the pure CFL QM, we consider the formalism depicted in [3]. The thermodynamic potential is given as

$$\begin{aligned}\Omega \;=\; & \frac{6}{\pi^2}\int_0^{\nu} k^2(k-\mu_q)dk \\ & + \frac{3}{\pi^2}\int_0^{\nu} k^2(\sqrt{k^2+m_s^2}-\mu_q)dk - \frac{3\Delta^2\mu_q^2}{\pi^2} \\ & + B \end{aligned} \quad (1)$$

where, μ_q is the quark chemical potential and B the bag pressure. The third term of eq. 1 depicts the CFL contribution via the pairing gap parameter Δ. Thus $\Delta = 0$ reduces to unpaired QM (UQM). The equal number density of the u, d and s quarks ensures the charge neutrality of the pure CFL QM. The EoS of the pure CFL phase can be calculated from eq. 1. With MC, we invoke PT and check for suitable values of B and Δ that yield reasonable HS configuration using the Tolman-Oppenheimer-Volkoff equations.

3. Results

For all (B, Δ) we notice large jump in energy density indicating rapid PT which justify the fact that there should be adequate difference in density between the pure hadronic and pure CFL phases as the latter occurs at high density. The higher values of B result in comparatively delayed PT. Figure 1 shows that the speed of sound (C_s) is quite high in the HM and the peak is noticed just before PT. For a particular B, C_s reduces with higher Δ. With PT, C_s reduces drastically to $\sim$0 and remains so till the onset of the CFL QM, beyond which C_s again rises drastically and then increases in the CFL phase. For all the cases the peaks lie above the conformal limit but below the causality limit.

Figure 2 shows that the $M-R$ solutions for all the chosen combinations of (B, Δ) satisfy the constraints from GW190425 and NICER experiment for PSR J0030+0451 while that on maximum mass is satisfied by all ($B^{1/4}$, Δ) except (185, 50). For fixed Δ, higher B yield more massive HS configurations with slightly greater radius. With fixed value of B, the scenario is just the opposite for higher Δ. As

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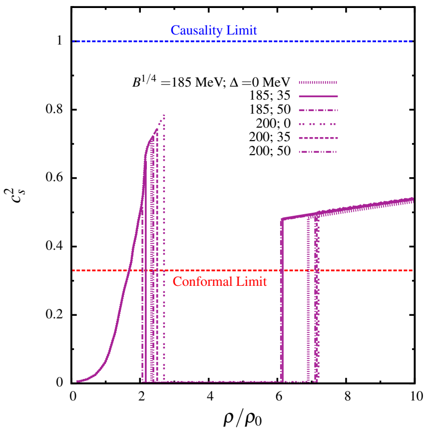

FIG. 1: Speed of sound for of the HS matter for different values of B and Δ.

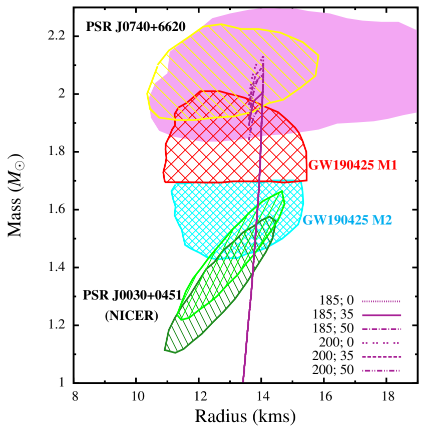

FIG. 2: Mass-radius relationship of HSs for different values of B and Δ.

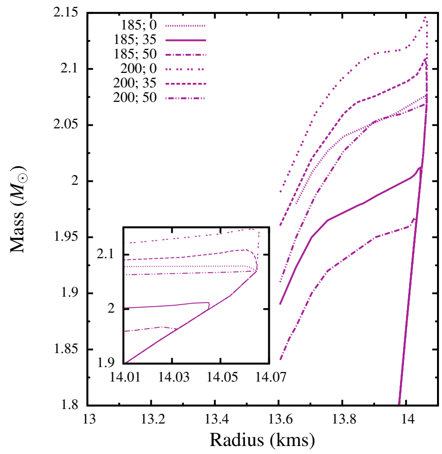

FIG. 3: Zoomed portion of transition of the mass-radius relationship of HSs.

PT occurs at quite high density (mass), the value of $R_{1.4}$(=13.75 km) is unaffected by PT and hence remain same for all (B, Δ) and also same as that fot the pure HM. Figure 3 shows that soon after PT, the $M-R$ configurations become unstable after a certain point i.e, the HSs remain stable within a very small window of the radius. This rapid unstable nature soon after PT is due to rapid and drastic PT and considerable high density jump, guided by MC. The inset shows that for ($B^{1/4}$, Δ)=(200, 50) the configuration is completely unstable.

4. Summary and Conclusion

Hadron-quark PT in HS cores is achieved with MC from β stable HM to CFL QM. Sharp PTs with large density jumps occurs for the chosen (B, Δ). We observe that just before PT, the speed of sound peaks high in between the conformal and causality limits and shows uphill-downhill behavior along the density profile of the HSs. The $M-R$ solutions of the HSs satisfy the recent astrophysical constraints on compact star properties. At particular density (radius) soon after PT, the HSs become unstable. For fixed B, both the maximum mass and the corresponding radius decrease with increasing Δ while the opposite trend in variation of M_{max} and R_{max} is noticed with respect to B for any particular Δ. This also ensures more massive HS configurations with UQM compared to that with CFL QM. We thus obtain stable HSs with CFL QM within a very restrictive choice of the values of B and Δ.

References

[1] D. Sen and G. Chaudhuri, J.Phys.G 49 (2022) 7, 075201.
[2] C. J. Horowitz et al., Phys.Rev.Lett. 86 (2001) 5647.
[3] M. Alford et al., Phys. Rev. D 67, 074024 (2003).