Hybrid Star Structure with Density Dependent Bag Model

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1. Introduction

The composition and equation of state (EoS) of neutron star (NS) cores (having density a few times nuclear density ρ_0) are still one of the most inconclusive aspects of nuclear physics since such conditions are extremely difficult to be attained from experimental perspectives. However, observational constraints from massive pulsars like PSR J0740+6620, the gravitational wave GW170817 detection and NICER experiment help us to constrain the EoS of NSs to some extent.

Theoretically, NS cores may support the formation of exotic matter like the hyperons and at further high density the hadronic matter (HM) may undergo phase transition (PT) to form quark matter (QM). Deconfined QM is often described by the MIT Bag model, characterized by the bag pressure B, which is the energy density difference between the perturbative vacuum and the true vacuum [1]. It is often taken as a free parameter but as the density increases, a PT from HM to QM implies that the difference between the two vacua and hence the bag pressure B should vanish. This justifies strongly that B should be density dependent, rather than being constant. A Gaussian dependence involves the values of $B(\rho)$ at asymptotic densities (B_{as}) and B_0 at vanishing density $\rho = 0$ [1].

In this work, the HM includes the nucleons and hyperons. By invoking PT to QM with different values of B_{as}, the hybrid EoS and hybrid stars (HS) properties are calculated and compared with the various constraints on them.

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2. Formalism

The hadronic phase is described by the effective chiral model [2]. It consists of nucleons and hyperons ($H = \Lambda, \Sigma^{-,0,+}, \Xi^{-,0}$) and scalar σ, vector ω and isovector ρ mesons. The same model parameter set is chosen as in [2]. The scalar hyperon couplings are chosen as x_{σ_H}=0.68 while the vector hyperon couplings x_{ω_H} are obtained using the potential depths of the individual hyperon species [3].

For the quark phase the MIT Bag model is considered without repulsive effects of the quarks. We consider density dependent bag pressure $B(\rho)$ given by a Gaussian distribution form [1]

$$B(\rho) = B_{as} + (B_0 - B_{as}) \exp\left[-\beta(\rho/\rho_0)^2\right]$$

where, β controls the decrease of $B(\rho)$ with the increase of density. We choose $B_0 = 400$ MeV fm^{-3} and $\beta = 0.17$ following [1]. The precise value of B_0 is not at all important since there cannot be any PT at this density but the asymptotic value (B_{as}) of $B(\rho)$ is of greater significance with relevance to HSs density [3].

With Maxwell construction, we invoke PT and check for a suitable value of B_{as} that yields reasonable HS configuration.

3. Results

In figure 1 we compare the two cases where the bag pressure is i) chosen constant as B=80 MeV fm^{-3} and ii) density dependent (variable) with value of B_{as}=80 MeV fm^{-3}. We find that the maximum gravitational mass M in the latter case is slightly more than the former one because in the second case PT is little delayed compared to the first case. Re-

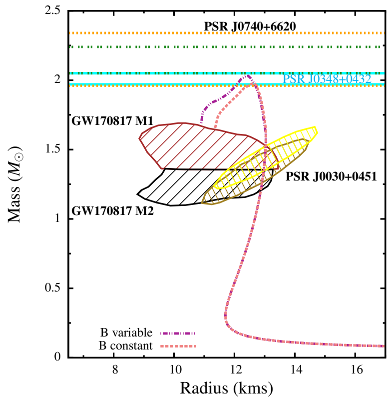

FIG. 1: The mass-radius dependence of the HSs for density dependent (variable) and independent (constant) bag pressure.

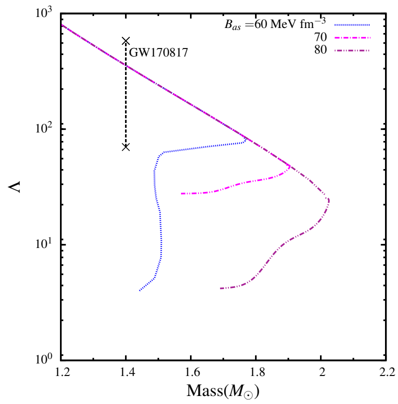

FIG. 2: Tidal deformability vs gravitational mass of HSs for different values B_{as}.

sults for both the cases satisfy the constraints on maximum mass from PSR J0348+0432 and PSR J0740+6620. The constraints from GW170817 and NICER experiment for PSR J0030+0451 are also well satisfied for both the cases. The PT is quite delayed due to the chosen high values of B_{as} and the maximum mass (M_{max}) is reached soon after the quarks start to nucleate (M_t) (reported in table I). In figure 2 we show the variation of dimensionless tidal deformability Λ with respect to M for three values of B_{as}. The values of $R_{1.4}$(=13.02 km) and $\Lambda_{1.4}$(=289.82) are consistent with the range prescribed by GW170817 observation. However, these values remain unaffected by the PT as the transitions are quite delayed. In table I we report the characteristics of the structural properties of HSs obtained for different values of B_{as}.

TABLE I: Mass of the HSs where quarks start to nucleate (M_t), maximum gravitational mass (M_{max}) and corresponding radius (R) for different values of B_{as}.

B_{as} (MeV fm^{-3})	M_t ($M_\odot$)	M_{max} ($M_\odot$)	R (km)
60	1.73	1.77	13.00
70	1.87	1.90	12.83
80	2.00	2.03	12.67
80 (const.)	1.94	1.98	12.51

4. Summary and Conclusion

Hadron-quark PT in HS cores is studied. The HM consists of nucleons and hyperons while QM is described by the MIT Bag model with density dependent bag pressure. B_{as}, which decides the density at which quarks attain asymptotic freedom, plays an important role in determining the HS properties especially the gravitational mass. Compared to the density independent scenario, there is 2.5% increase in M when density dependence is considered. For B_{as}=80 MeV fm^{-3} we have satisfied the constraints on maximum gravitational mass from PSR J0740+6620. Due to delayed PT, $R_{1.4}$ and $\Lambda_{1.4}$ are found same for all the chosen values of B_{as}. Nevertheless they are consistent with the range suggested by analysis of GW170817 data from binary NS merger. Moreover, our $M-R$ solutions are in good agreement with the NICER data obtained for PSR J0030+0451.

Acknowledgement

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