Equation of state for hybrid star using Maxwell Construction

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Introduction

Neutron stars (NSs) are a natural laboratory to explore dense and cold matter. In recent years, various astrophysics observations of NS have brought attention to the compact star structure which helps us to constrain the theoretical view of NS. The structure of NS is still a mystery to physicists. As we know, the density of matter inside the star increases due to gravity, and new particles such as hyperon, kaon, pion, and deconfined quark matter are formed. Therefore, compact stars are classified on the basis of their compositions as neutron stars, quark stars, and hybrid stars. The possibility of an NS consisting of a quark matter core, a nuclear matter core, and a crust is known as a hybrid star. Generally, there are two methods, the Maxwell construction (MC) and the Gibbs construction (GC), to derive the hadron-quark phase transition depending on the value of the surface tension at the transition boundary [1]. The equation of state (EoS) is key to the study of the structure of hybrid stars of strongly interacting matter. To create the hybrid star EoS, we used two different methods: the chiral SU(3) model for nuclear matter [2] and the Nambu-Jona-Lasinio (NJL) model for quark matter. [3]. Furthermore, we used Maxwell constructions to obtain mixed-phase EOS where a mixture of hadron and deconfined quark matter is observed. The phase transition in a hybrid star is determined by the crossing of the nuclear and quark matter curves in the P-μ_B plane. The EoS of hadronic and quark phases have been linked through mixed phase EoS.

Methodology

For neutron star matter which contains the mixture of baryons and leptons satisfies the β-equilibrium conditions without trapped neutrinos. These equations are

$$\mu_p = \mu_{\Sigma^+} = \mu_n - \mu_e, \tag{1}$$
$$\mu_\Lambda = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_n, \tag{2}$$
$$\mu_{\Sigma^-} = \mu_{\Sigma^-} = \mu_n + \mu_e \tag{3}$$
$$\mu_e = \mu_\mu \tag{4}$$

This matter also follows the charge neutrality condition which is expressed as

$$\rho_p + \rho_{\Sigma^+} - \rho_e - \rho_\mu - \rho_{\Sigma^-} - \rho_{\Xi^-} = 0 \tag{5}$$

Baryon density is defined as, $\rho_B^{HP} = \rho_p + \rho_n + \rho_{\Sigma^+} + \rho_{\Sigma^-} + \rho_{\Sigma^0} + \rho_{\Xi^-} + \rho_{\Xi^0}$. Using thermodynamical potential, Ω, we can calculate other thermodynamical quantities such as energy density and pressure using relations

$$P^{HP}_{\text{chiral}} = -\Omega, \qquad \epsilon^{HP}_{\text{chiral}} = \Omega + \sum_{i=N,H,l} \mu_i \rho_i, \tag{6}$$

respectively. The charge neutrality and β-equilibrium for the quark matter results in the conditions [4]:

$$2\rho_u = \rho_d + \rho_s + 3(\rho_e + \rho_\mu), \tag{7}$$
$$\mu_d = \mu_s = \mu_u + \mu_e, \quad \mu_e = \mu_\mu. \tag{8}$$

The total baryon density of quark is defined as ρ_B^{QP}=$(\rho_u + \rho_d + \rho_s)/3$.

The phase transition are determined by the simultaneous fulfillment of conditions of mechanical and chemical equilibrium:

$$P^{HP}_{\text{chiral}} = P^{QP}_{\text{NJL}} = P^{MP}, \tag{9}$$
$$\mu_B^{HP} = \mu_B^{QP} = \mu_B^{MP}, \tag{10}$$

where μ_B^{HP}=μ_n, and μ_B^{QP}=$\mu_u + \mu_d + \mu_s$ are the baryon chemical potential of hadronic and quark phases, respectively.

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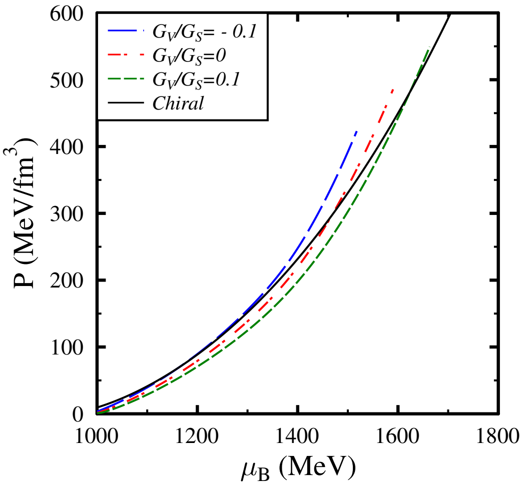

FIG. 1: Pressure as a function of baryonic chemical potential for nuclear and quark matter.

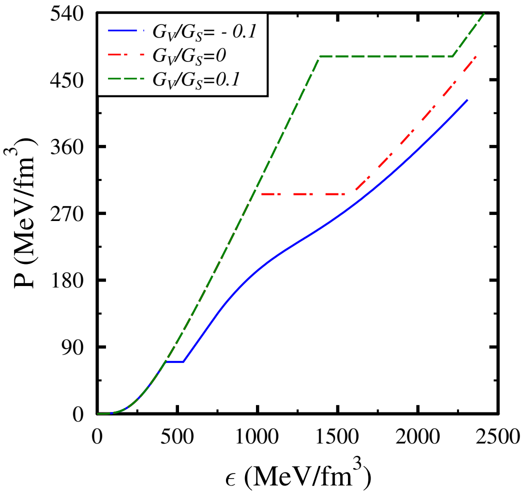

FIG. 2: (Color online) The equation of state (EoS) of hybrid star matter for different values of G_V/G_S.

Results and Discussion

In this section, we have explored the EoS of hybrid star using Chiral SU(3) model for nuclear matter and NJL model for quark matter at different ratio of scalar and vector coupling, G_S/G_V. The various parameters used in the present calculation for quark matter and nuclear matter are listed in Ref. [3] and Ref. [5], respectively.

Fig. 1 depicts the pressure as a function of baryonic chemical potential, μ_B, for both the nuclear matter within the chiral SU(3) model and the quark matter using the NJL model. The phase transition in the MC is identified by the points where the nuclear and quark matter curves are crossing in the P-μ_B plane as shown in Fig. 1.The phase transition pressure, P_0, increases with increase in G_V/G_S, for example, the values of P_0 are 69.89, 295.8 and 481.4 MeV at G_V/G_S=−0.1, 0 and 0.1, respectively. In Fig. 2, we plot the EoS of hybrid star matter with sharp quark-hadron phase transition at G_V/G_S=−0.1, 0, and 0.1. As we increases the vector coupling constant, G_V, the stiffness of the quark matter EoS increases, and the area of mixed-phase lies between nuclear and quark matter is become larger. The effect of vector interaction on phase transition from hadronic matter to quark matter and hybrid EoS has also been studied in Ref. [6] and observed that the stiffness of EoS for quark matter is increases with the increase in vector coupling. In the future, the observed EoS will use to explore the mass-radius of hybrid stars and other important properties.

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References

[1] S. Han *et al.*, Phys. Rev. D **100**, 103022 (2019)

[2] P. Papazoglou *et al.*, Phys. Rev. C **59**, 411 (1999).

[3] R. C. Pereira, P. Costa and C. Provideñcia, Phys. Rev. D **94**, 094001 (2016).

[4] M. Kumari and A. Kumar, Eur. Phys. J. C, **81**, 791 (2021).

[5] M. Kumari and A. Kumar, Int. J. Mod. Phys. E **31**, 2250050 (2022).

[6] G. Alaverdan, Symmetry **13**, 124 (2021).