Isoscalar-vector interaction and its influence on the hadron-quark phase transition (postprint)

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Full Text

Preamble

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Abstract

The hadron-quark phase transition is studied with the newly constructed Hadron–Poyakov-Nambu–Jona-Lasinio (PNJL) model. Particularly, in the description of quark matter, we include the isoscalar-vector interaction. With the constraints of neutron star observations, our calculation shows the isoscalar-vector interaction between quarks is indispensable if massive hybrid stars exist in the universe. Its strength determines the onset density of quark matter and the mass-radius relations of hybrid stars. Also, as a connection with heavy-ion-collision experiments, we discuss the strength of isoscalar-vector interaction and its effect on the signals of hadron-quark phase transition in heavy-ion collisions, such as NICA at JINR-Dubna and FAIR at GSI-Darmstadt.

Key words: Hadron-quark phase transition, Neutron star, Heavy-ion collisions

Introduction

The equation of state (EOS) of neutron star matter is closely associated with the particles that appear in neutron stars. Matter in the core of neutron stars may be compressed to several times nuclear saturation density, and strange particles may exist in the interior of these compact objects [1-7]. The appearance of such particles is crucial for determining the macroscopic features of neutron stars through the Tolman-Oppenheimer-Volkoff (TOV) equation [8]. Neutron star observations, particularly the accurate mass measurement of pulsar J1614-2230 at (1.97$±$0.04)M [9] and astrophysical observations of X-ray bursts and thermal emissions from quiescent low-mass X-ray binaries (LMXBs) in globular clusters [10,11], provide reliable limits on mass-radius relations that are tightly connected to the EOS of neutron star matter. Analysis of these astrophysical results shows that the radius of a 1.4 solar mass neutron star lies between 10.4 and 12.9 km, independent of assumptions about core composition [10,11]. The relatively small radius of 1.4 solar mass neutron stars indicates that the EOS near saturation density is soft, while the discovery of the massive neutron star J1614-2230 requires a stiff EOS at high densities. This combination of constraints rules out many EOSs from hadronic models. Additionally, experimental data from heavy-ion collisions [12,13] and lattice QCD simulations [14,15] provide further constraints on the EOSs of nuclear matter and quark matter.

Progress in astrophysical observation and nuclear physics experiments has stimulated research interest in the underlying physics. The hadron-quark phase transition represents a hot topic in this field, though it remains controversial whether quarks can appear in cold neutron stars [16,17]. This question is also important for heavy-ion collisions, and related experiments at medium and high densities will be performed in the near future at the upgraded facilities of NICA at JINR-Dubna and FAIR at GSI-Darmstadt.

Based on developments in theoretical modeling and neutron star observations, we investigate the hadron-quark phase transition using a newly constructed two-phase model. To describe nuclear matter, we employ the extended Walecka model with general meson-meson couplings recently calibrated by Steiner, Hempel, and Fischer [11], which better describes properties of nuclei and nuclear matter while supporting recent neutron star observations. For quark matter, we use the PNJL quark model [3], which shares global symmetries with QCD, exhibits chiral symmetry breaking, and implements effective confinement at finite densities and temperatures. In describing quark matter, we focus on the isoscalar-vector interaction and its influence on the hadron-quark phase transition in the interior of massive neutron stars. With constraints from neutron star observations, our calculations demonstrate that the isoscalar-vector channel interaction is required if massive hybrid stars exist in the universe, and its strength determines the onset density of quark matter and the mass-radius relation of hybrid stars.

As a connection to heavy-ion collision experiments, we also discuss the strength of the isoscalar-vector interaction and its influence on transition signals from asymmetric nuclear matter to quark matter in heavy-ion collision experiments such as NICA at JINR-Dubna and FAIR at GSI-Darmstadt.

2 Methods

In our two-phase model, the pure hadronic phase and quark phase are described by a nonlinear Walecka-type model and the PNJL model, respectively. For the coexisting phase between the pure hadronic and quark phases, the two phases are connected through Gibbs conditions ensuring thermal, chemical, and mechanical equilibrium, along with global charge neutrality [18].

2.1 The hadron model

For nuclear matter we use the new equation of state labeled SFHO [11], recently constructed based on the extended non-linear Walecka model in relativistic mean-field (RMF) theory and used to simulate core-collapse supernovae [19]. The obtained results satisfy the requirements of nuclear physics and match astrophysical observations well.

2.2 The quark model

For quark matter, we use the modified three-flavor PNJL model from Ref. [3] and additionally include the isoscalar-vector channel interaction. We focus on its influence on the hadron-quark phase transition in dense nuclear matter.

Although the strength of the isoscalar-vector coupling G_V is not yet well determined, different values can be obtained from Fierz transformation [20], Fock (exchange) terms [21], and fitting vector meson spectra [22]. We can therefore treat it as a free parameter and attempt to constrain its value using neutron star observations. For convenience in comparing it with the strength of the isoscalar-scalar interaction G_S and for later discussion, we define $R_V = G_V/G_S$.

2.3 The coexisted phase

The Gibbs criteria are typically implemented for phase equilibrium in complicated systems with more than one conserved charge. For the coexisting phase with hadron-quark phase transition in neutron star matter, the chemical potentials μ_α are usually chosen as μ_n and μ_e, and electric neutrality is fulfilled globally. However, for phase transitions in heavy-ion collisions, baryon chemical potential μ_B and isospin chemical potential μ_I are used, and the global asymmetry parameter α is determined by the heavy-ion source.

3 Results

3.1 Hadron-quark phase transition in neutron stars

Figure 1 [Figure 1: see original paper] shows the EOSs of neutron star matter with and without hadron-quark phase transition for different values of the isoscalar-vector interaction coupling R_V. For each R_V value, the two solid dots indicate the range of the coexisting phase, and the circle marks the maximum pressure reachable in the neutron star core by solving the TOV equation. Figure 1 demonstrates that the isoscalar-vector interaction of quark matter plays an important role in the hadron-quark phase transition, and the R_V value is crucial for the EOS of neutron star matter at high densities. It also shows that only the mixed phase can be reached inside massive neutron stars. For $R_V \geq 0.484$, our calculations indicate that quark matter does not appear in the neutron star core. Particularly, if R_V is sufficiently large, the onset density of quark matter exceeds the central density of the neutron star, meaning no quarks can appear in the core. This clearly demonstrates the crucial influence that the isoscalar-vector interaction exerts on the hadron-quark phase transition in massive neutron stars.

To examine how the isoscalar-vector interaction affects the threshold of the hadron-quark phase transition, we display in Figure 2 the relative fractions of different species as a function of baryon density for $R_V = 0$, 0.2, and 0.4. The results show that a stronger isoscalar-vector interaction postpones the onset density of quark matter, and the central density of the corresponding hybrid star shifts to higher values as well. A larger R_V means a smaller fraction of quark matter in the neutron star core.

Figure 3 [Figure 3: see original paper] presents the mass-radius relations of hybrid stars for different R_V values. The solid curve shows the result without quarks, while the dashed curves show results with hadron-quark phase transition for various R_V. The inner (outer) two contours show the 1σ and 2σ confidence ranges of the M-R relations from Ref. [10] (Ref. [11]), based on six (eight) neutron star observations of X-ray bursts and thermal emissions from quiescent LMXBs in globular clusters. Figure 3 demonstrates that the EOS of neutron star matter with the SFHO parameter set fulfills neutron star observations well.

Figure 3 also provides an explicit picture of how the strength of the isoscalar-vector interaction affects the macroscopic properties of massive hybrid stars. Radio timing observations of the binary millisecond pulsar J1614-2230 imply a pulsar mass of (1.97$±$0.04)M [9]. This accurate measurement of such a massive pulsar rules out many soft EOSs. If the isoscalar-vector interaction of quark matter is not included, the maximum mass of hybrid stars is 1.88M , less than the known maximum neutron star mass. However, with the inclusion of this channel, taking $R_V = 0.055$, the maximum mass of hybrid stars can reach the lower mass limit of pulsar J1614-2230. Therefore, $R_V \geq 0.055$ is required if massive hybrid stars exist in the universe, while no quarks appear for $R_V \geq 0.484$ as shown in Figure 1.

3.2 Hadron-quark phase transition in heavy-ion collisions

In this section we discuss the influence of isoscalar-vector interaction on the hadron-quark phase transition in heavy-ion collisions with neutron-rich sources. In our calculations we take the global asymmetry parameter $\alpha = 0.2$, with other parameters from Ref. [19].

Figure 4 [Figure 4: see original paper] shows the phase diagram of the hadron-quark phase transition for asymmetric matter with $\alpha = 0.2$. The lines on the left side corresponding to $\chi = 0$ represent the onset of the mixed phase, while dash-dot lines on the right side corresponding to $\chi = 1$ denote the beginning of the pure quark phase. With the inclusion of isoscalar-vector interaction, the phase transition is significantly shifted toward higher densities. This can be explained by the repulsive contribution of the isoscalar-vector channel to the quark energy and consequently to the chemical potential.

Figure 5 [Figure 5: see original paper] displays the asymmetry parameters of hadronic and quark matter in the mixed phase as a function of quark fraction χ for temperature $T = 100$ MeV. One observes a clear isospin distillation effect [10], where the asymmetry of quark matter is much larger than 0.2 at the beginning of the phase transition and decreases with increasing quark fraction, whereas the asymmetry of hadronic matter remains below 0.2 as a slowly decreasing function of χ. These features of local asymmetry may lead to observable effects during hadronization in the expansion phase of heavy-ion collisions, such as an inversion in the trend of emission of neutron-rich clusters, enhancement of yield ratios π^-/π^+ and K^0/K^+ in high-density regions, and enhanced production of isospin-rich resonances and their subsequent decays. The inclusion of isoscalar-vector interaction further enhances the asymmetry of u and d quarks. These signals may be probed at the newly planned facilities FAIR at GSI-Darmstadt and NICA at JINR-Dubna.

The results for the isoscalar-vector interaction of quark matter are discussed as follows. When including this channel interaction in the quark model, the value of R_V affects the location and emergence of critical points of chiral symmetry restoration [24]. It also influences the onset densities and phase transition signals from asymmetric nuclear matter to quark matter in the two-phase model relevant to heavy-ion collision experiments [21]. Although this coupling cannot yet be determined from experiments and LQCD simulations, there are hints regarding its existence: (1) compared with the hadronic Walecka model, the isoscalar-vector interaction of quark matter plays a role similar to the ω meson, which is important for nuclear matter properties in quantum hadrodynamics models; (2) this channel interaction can be derived from higher-order Fock (exchange) terms or Fierz transformations fitting vector meson spectra [20-22]; and (3) the requirement of massive hybrid stars as shown in this study.

4 Conclusion

We have studied the hadron-quark phase transition in dense nuclear matter with an improved two-phase model. Our calculations show that massive hybrid stars may exist in the universe, and the isoscalar-vector interaction between quarks is crucial for the hadron-quark phase transition. Its strength determines whether quarks can appear in the interior of neutron stars. In heavy-ion collision experiments, including this channel interaction postpones the onset density of quark matter to higher values, and the corresponding phase-transition signals from asymmetric nuclear matter to quark matter are strengthened.

Although the precise value of R_V remains unknown, neutron star observations can gradually provide constraints. Based on the phase transition features of asymmetric strongly interacting matter in heavy-ion collisions, we have also proposed suggestions for probing phase transition signals in relevant experiments at FAIR and NICA. Therefore, the combination of neutron star observations and energy scans of phase-transition signals at FAIR/NICA in the future may provide hints on the value of R_V, which will be helpful for understanding quark matter interactions and neutron star structure.

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Note: Figure translations are in progress. See original paper for figures.