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

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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 hybrids star 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

1 Introduction

The equation of state (EOS) of neutron star matter is closely associated with particles that appear in neutron stars. The matter in the core of neutron stars is possibly compressed to several times of the saturation nuclear density, and particles of strangeness may exist in the interior of the compact objects[1-7]. Appearance of the particles is crucial for macroscopic features of neutron stars by solving the Tolman-Oppenheimer-Volkoff (TOV) equation[8].

The neutron star observations, especially, the accurate measurement of the pulsar J1614-2230 with the mass $(1.97\pm0.04)M_{\odot}$[9], the astrophysical observations of X-ray bursts and thermal emissions from quiescent low-mass X-ray binaries (LMXBs) in the globular clusters[10,11], provide a reliable limit on the mass-radius relations which connect tightly to the EOS of neutron star matter. An analysis of the astrophysical observation 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 the composition of the core[10,11]. The relatively small radius of 1.4 solar mass neutron stars means the EOS near the saturation density is soft, but the discovery of massive neutron star J1614-2230 requires a stiff EOS of high densities. The combination of the constraints rules out many EOSs of hadron models. Besides, experimental data from heavy-ion collisions[12,13] and lattice QCD simulation[14,15] are also available to put some constraints on the EOSs of nuclear matter and quark matter.

Progresses in astrophysical observation and nuclear experiments promote research interest in exploring the relevant physics behind. The hadron-quark phase transition is a hot topic, but so far it is still controversial whether quarks can appear in cold neutron star[16,17]. It is also an important topic in heavy-ion collisions, and related experiments at medium and high densities will be performed in the

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near future on the updated facilities of NICA at JINR-Dubna and FAIR at GSI-Darmstadt.

Based on developments in theoretical model and neutron star observation, in this paper we will investigate the hadron-quark phase transition with a newly constructed two-phase model. To describe nuclear matter, we take the extended Walecka model with general meson-meson couplings recently calibrated by Steiner, Hempel and Fischer[11]. It better describes properties of nuclei and nuclear matter, and supports recent neutron star observations. For quark matter, we take the PNJL quark model[3] sharing global symmetries, phenomenon of chiral symmetry breaking with QCD and 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 the constraints of neutron star observations, our calculation shows the isoscalar vector channel interaction is needed 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 with heavy-ion collision experiments, discussions are carried out about the strength of isoscalar vector interaction and its influence on the phase transition signals from asymmetric matter to quark matter in heavy-ion collision experiments, such as NICA at JINR-Dubna and FAIR at GSI-Darmstadt.

2 Methods

In the two-phase model, the pure hadronic phase and quark phase are described by the nonlinear Walecka type model and the PNJL model, respectively. As for the coexisted phase between the pure hadronic phase and quark phase, the two phases are connected through the Gibbs conditions with the thermal, chemical and mechanical equilibriums, and the global electronic neutrality condition as well[18].

2.1 The hadron model

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

2.2 The quark model

For the quark matter, the modified three-flavor PNJL model in Ref.[3] is used. Besides, we include the isoscalar-vector channel interaction, $G_V(\bar{q}\gamma^{\mu}q)^2$, so as to reduce the quark chemical potential, $\tilde{\mu}=\mu-2G_V n_q$. We focus on its influence on the hadron-quark phase transition in dense nuclear matter. Although the strength of isoscalar-vector coupling G_V is not clear so far, different values can be obtained from the Fierz transformation[20], Fock (exchange) terms[21], and fitting vector meson spectrum[22]. Then, we can treat it as a free parameter and try to constrain its value with neutron star observations. For the convenience to compare it with the strength of isoscalar-scalar interaction G and later discussion, we define $R_V=G_V/G$.

2.3 The coexisted phase

The Gibbs criteria is usually implemented for the phase equilibrium of a complicated system with more than one conservation charge. The Gibbs conditions for the coexisted phase with a hadron-quark phase transition are $\mu_{\alpha}^{H}=\mu_{\alpha}^{Q},\ T^{H}=T^{Q},\ P^{H}=P^{Q}$. For neutron star matter, μ_α are usually chosen with μ_n and μ_e. And the electric neutrality is globally fulfilled. However, for the phase transition 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 using a heavy-ion source.

3 Results

3.1 Hadron-quark phase transition in neutron stars

Figure 1 shows the EOSs of neutron star matter without and with a hadron-quark phase transition for different value of the isoscalar-vector interaction R_V. For each value of R_V, the two solid dots indicate the range of the coexisted phase, and the cycle marks the largest pressure that can be reached in the core of neutron star by solving the TOV equation. Fig.1

demonstrates that the isoscalar-vector interaction of quark matter plays an important role on the hadron-quark phase transition. And the value of R_V is crucial for the EOS of neutron star matter at high densities. It also shows that only the mixed range can be reached inside massive neuron stars. For R_V of over 0.484, the calculation shows that quark matter does not appear in the neutron star core.

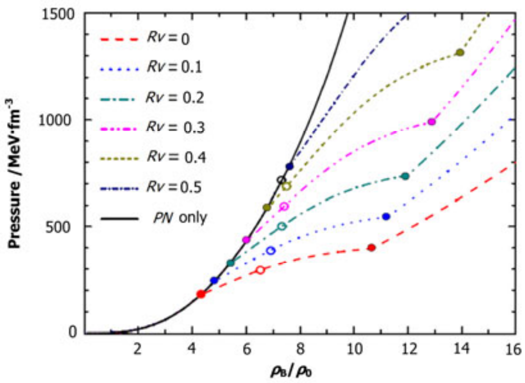

Fig.1 (Color online) EOSs of neutron star matter without and with a hadron-quark phase transition for different isoscalar-vector interaction coupling R_V. For each value of R_V, the two solid dots indicate the range of the mixed phase, and the cycle marks the largest pressure that can be reached in the core of neutron star.

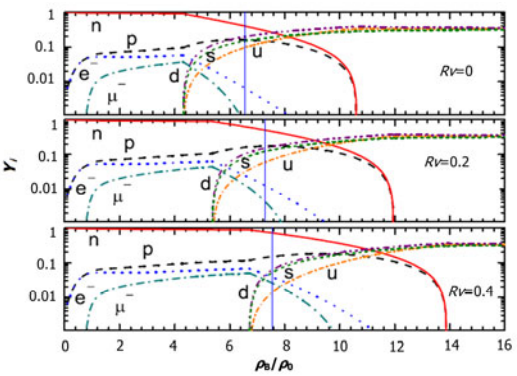

Fig.2 (Color online) Relative fractions of different species as a function of baryon density with R_V= 0, 0.2 and 0.4. The vertical lines mark the corresponding central densities of hybrid stars.

To see how the isoscalar-vector interaction affects the threshold of hadron-quark phase transition, we display in Fig.2 the relative fractions of different species as a function of baryon density for R_V=0, 0.2 and 0.4. It shows that a stronger isoscalar-vector interaction postpones the onset density of quark matter, and the central density of the corresponding hybrid star moves to a higher one, too. A larger R_V means a smaller fraction of quark matter in the core of neutron star. Particularly, if R_V is large enough, the onset density of quark matter shall be greater than the central density of the neutron star. In this case, no quarks can appear in the core of neutron stars. This clearly demonstrates the crucial role that the isoscalar-vector interaction plays on the hadron-quark phase transition in massive neutron stars.

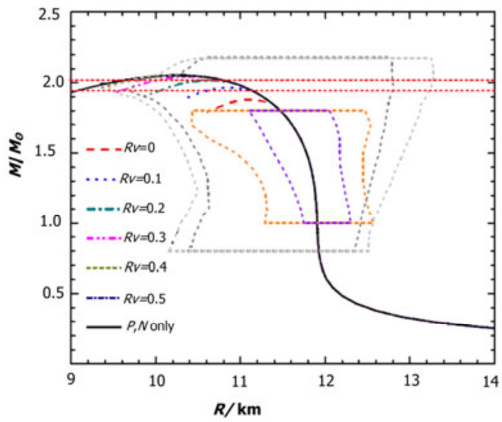

Fig.3 (Color online) Mass-radius relations of neutron stars. The solid curve is the result without quarks and the dash curves are the results with a hadron-quark phase transition for different R_V. The inner (outer) two contours show the 1σ and 2σ confidence ranges of the *M-R* relations given in Ref.[10] (Ref.[11]), based on six (eight) neutron star observations of the X-ray bursts and thermal emissions from quiescent LMXBs in the globular clusters.

In Fig.3 we plot the mass-radius relations of hybrid stars with different R_V. The inner (outer) two contours show the 1σ and 2σ confidence ranges of the $M-R$ relations given in Ref.[10] (Ref.[11]), based on six (eight) neutron star observations of the X-ray bursts and thermal emissions from quiescent low-mass X-ray binaries in the globular clusters. Fig.3 shows that the EOS of neutron star matter with the parameter set of SFHO well fulfills the neutron star observations. Fig.3 also gives us an explicit picture of how the strength of isoscalar-vector interaction affects the macroscopic properties of massive hybrid stars. The radio timing observations of the binary millisecond pulsar J1614-2230, implies that the pulsar mass is $(1.97\pm0.04)\,M_\odot$[9]. The accurate measurement of this 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 $1.88\,M_\odot$, less than the known maximum neutron star mass. However, with the inclusion of this channel interaction and taking R_V=0.055, the obtained maximum mass of hybrid star can reach the lower mass limit of the pulsar J1614-2230. Therefore, $R_V \geq 0.055$ is required if massive hybrid star exist in the universe, and no quarks appear for $R_V \geq 0.484$ as shown in Fig.1.

3.2 Hadron-quark phase transition in heavy-ion collisions

In this section we discuss the influence of isoscalar interaction on the hadron-quark phase transition in heavy-ion collisions with neutron-rich sources. In the calculation we take the global asymmetric parameter α=0.2. The other parameters are taken from Ref. [19].

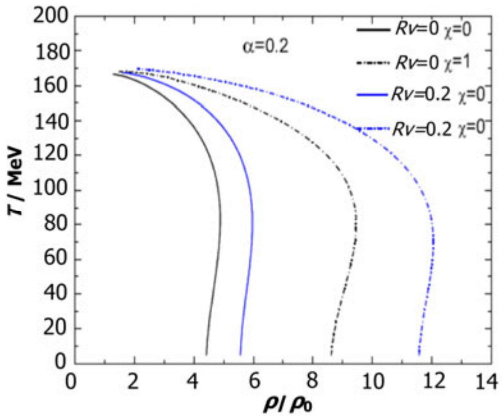

Fig.4 (Color online) Phase diagram of the hadron-quark phase transition for asymmetric matter with α=0.2. The lines in the left side corresponding to χ=0 represent the onset of the mixed phase, and dash-dot lines in the right side corresponding to χ=1 denote the beginning of the pure quark phase.

Figure 4 shows the phase diagram of the phase transition from the asymmetric nuclear matter to quark matter. With the consideration of isoscalar-vector interaction, the phase transition is significantly moved toward higher densities. This can be explained in terms of the repulsive contribution of the isoscalar-vector channel to the quark energy and, as a consequence, to the chemical potential.

Figure 5 displays the asymmetry parameters of hadronic and quark matter in the mixed phase as a function of the quark fraction χ, for the temperature T=100 MeV. One sees a clear isospin distillation effect[10], i.e., 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 the hadronic matter keeps below 0.2 as a slow-decreasing function of χ. These features of the local asymmetry possibly lead to some observable effects in the hadronization during the expansion phase of heavy-ion collisions, such as an inversion in the trend of emission of neutron rich clusters, an enhancement of yield ratios π^-/π^+, K^0/K^+ in high density regions, and an enhancement of the production of isospin-rich resonances and subsequent decays. The inclusion of isoscalar-vector interaction further enhances the asymmetry of u, d quarks. These signals are possible to be probed in the newly planned facilities, such as FAIR at GSID-armstadt and NICA at JINR-Dubna.

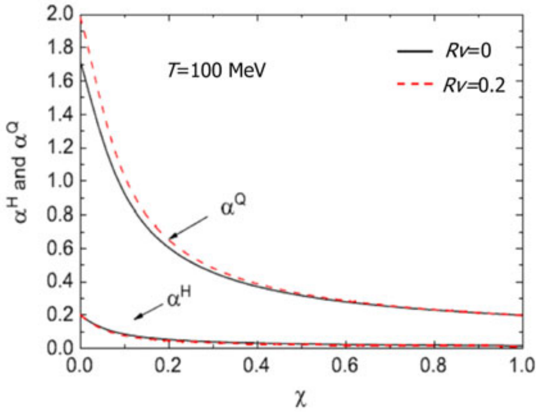

Fig.5 (Color online) Asymmetry of hadronic and quark matter in the mixed phase at T=100 MeV as a function of the quark concentration with and without the isoscalar-vector interaction channel.

The results of the isoscalar-vector interaction of quark matter are discussed as follows. When including this channel interaction in 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 the phase transition signals from asymmetric nuclear matter to quark matter in the two-phase model related to experiments in heavy-ion collisions[21]. Although this coupling cannot be determined by far from experiments and LQCD simulation, there are some hints on its existence, (1) compared with the hadron Walecka model, the isoscalar-vector interaction of quark matter plays a role similar to the ω meson important for the properties of nuclear matter in Quantum Hadron Dynamics model; (2) this channel interaction can be derived from higher order Fock (exchange) terms or Fierz translations or fitting vector meson spectrum[20-22]; and (3) the requirement of massive hybrid as shown in this study.

4 Conclusion

We have studied the hadron-quark phase transition in dense nuclear matter with the improved Two-Phase model. The calculations show massive hybrid stars possibly exist in the universe, and the isocalar-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, the inclusion of this channel interaction postpones the onset density of quark matter to a higher one, and the corresponding phase-transition signals from asymmetric nuclear matter to quark matter are strengthened.

Although the accurate value of R_V is still not known by far, neutron star observations can gradually provide some constraints on it. And based on the phase transition features of asymmetric strongly interacting matter in heavy-ion collisions, we also proposed some suggestions to probe the phase transition signals in the relevant experiments on FAIR and NICA. Therefore, the combination of neutron star observations and the energy scan of the phase-transition signals on FAIR/NICA in the future may provide us some hints on the value of R_V, which is helpful for the understanding of quark matter interactions and neutron star structure.

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