Apparent softening of the symmetry energy with the inclusion of non-nucleonic components in nuclear matter (postprint)

Authors: JIANG Weizhou

Date: 2023-06-18T00:00:00+00:00

Abstract

Apparent softening of the symmetry energy with the inclusion of hyperon and quark degrees of freedom is demonstrated by the fact that the phase transition causes the change of the interaction and the suppression of nucleon fractions. The demonstration is fulfilled in the relativistic mean-field model.

Full Text

Preamble

Nuclear Science and Techniques 24 (2013) 050507

Apparent Softening of the Symmetry Energy with the Inclusion of Non-Nucleonic Components in Nuclear Matter

JIANG Weizhou*

Department of Physics, Southeast University, Nanjing 211189, China

Abstract: The apparent softening of the symmetry energy with the inclusion of hyperon and quark degrees of freedom is demonstrated by the fact that the phase transition causes changes in the interaction and suppression of nucleon fractions. This demonstration is performed using the relativistic mean-field model.

Key words: Symmetry energy, Nuclear matter, Relativistic mean-field model

---

Introduction

The nuclear symmetry energy of isospin asymmetric nuclear matter is essential for understanding the structure of neutron- or proton-rich nuclei, the reaction dynamics of heavy-ion collisions [?], and many astrophysical issues [?]. Over the past four decades, the properties of symmetric matter have been constrained rather satisfactorily. Only in the past decade has appreciable progress been made in constraining the symmetry energy at saturation and subsaturation densities, either through extraction based on astrophysical observations or through terrestrial data [?]. However, the density dependence remains poorly known, especially at supra-normal densities [?, ?]. According to theoretical predictions, the density dependence of the symmetry energy is rather diverse–it may increase nonlinearly or linearly with density. Strikingly, some non-relativistic models even predict that the symmetry energy soon becomes negative at densities several times normal density, which could cause severe problems for stabilizing the structure of neutron stars. On the other hand, similarly diverse results for the symmetry energy were extracted by analyzing the FOPI/GSI data on the π^-/π^+ ratio in relativistic heavy-ion collisions with various transport models [?]. Recently, the required coincidence with data from the ALADIN-2000 collaboration, analyzed by Kumar et al. [?], suggested a soft symmetry energy that differs from the super-soft one obtained from the FOPI/GSI data analysis. Further discussions on the status quo of experimental extraction can be found in a recent work [?]. These extractions reflect the fact that the density dependence of the symmetry energy remains very uncertain, provided the equation of state of symmetric matter used in transport models is well constrained.

However, besides experimental extractions, the theoretical uncertainty of high-density symmetry energy is regarded to be associated with the tensor force that originates from exchange terms [?, ?]. In the ladder approximation, the exchange terms can be well treated in the relativistic or Brueckner non-relativistic mean-field approximation without exchange terms, which works more sophisticatedly in high-density matter. It is thus incomprehensible that the tensor force can completely explain the remarkable softening of the high-density symmetry energy. In this work, we do not adopt the strategy of using the tensor force to solve the symmetry energy divergence and instead explore the effect of non-nucleonic degrees of freedom on the symmetry energy. The calculations reported here are performed in the relativistic Hartree approximation.

3 Results

In this work, we consider non-nucleonic degrees of freedom that include hyperons and quarks. On the hadronic level, we make use of relativistic hadron mean-field (RMF) models. The original Lagrangian of the RMF model was first proposed by Walecka 40 years ago [?]. The Walecka model and its improved versions were characterized by the cancellation between the large attractive scalar field and the large repulsive vector field. The success of the RMF models is partially attributed to their dynamical description of the spin-orbit interaction. On the quark level, we adopt the MIT bag model [?] to portray the quark phase. The mixed phase is built on mechanical and chemical equilibrium according to Gibbs conditions.

In the parabolic approximation, the energy per nucleon in isospin asymmetric nuclear matter can be written as $E/A = e(\rho) + e_{\mathrm{sym}}(\rho)$, where $e(\rho)$ is the energy per nucleon in symmetric matter, $e_{\mathrm{sym}}(\rho)$ is the density dependence of the symmetry energy, and δ is the isospin asymmetry. The symmetry energy in the RMF models reads, where C_ρ is the ratio of the ρ coupling constant with the nucleon to the ρ meson effective mass, k_F and E_F the nucleon Fermi momentum and energy, respectively. In the presence of hyperons, it reads B_ρ and N_ρ are the baryon and nucleon density, respectively. As the quarks appear, the system is first in the mixed phase and then in pure quark phase at very high densities. The symmetry energy can be defined according to a parabolic approximation of the equation of state, similarly, where H and Q denote hadrons and quarks, respectively, and Y is the quark phase proportion.

For simplicity, we consider only the Λ hyperon, which typically constitutes the majority of hyperons in hyperonized matter. The symmetry energy for various Λ fractions is calculated in symmetric matter at $\delta = 0$. The effect of Λ hyperons on the nuclear symmetry energy with the RMF model NL3 [**?**] is illustrated in [Figure 1: see original paper]. It is shown in [Figure 1: see original paper] that the symmetry energy is clearly softened with increasing Λ fraction. Compared with Eqs.(2) and (3), we see that the softening is dominated by the suppression factor B_ρ/ρ. However, even without this suppression factor, the symmetry energy in hyperonized matter is still modified by the isoscalar Λ hyperons, provided there exists the isoscalar-isovector coupling Λ_v (for model details, see Ref. [**?**]). This is clearly seen in the inset of the lower panel of [Figure 1: see original paper], where the potential part of the symmetry energy is displayed. Similarly, if charged hyperons are included, the potential part of the symmetry energy can be modified even without the isoscalar-isovector coupling. This can be verified numerically, though it is beyond the scope of the present work. Nevertheless, we may infer that the symmetry energy may be significantly modified by taking hyperons into account.

With increasing density, the hadron-quark phase transition may occur. In this work, quark matter—regarded as a free fermion gas without interactions—is described by the MIT bag model [**?**]. The mixed phase consists of high-density quark matter and low-density nuclear matter, with the quark phase proportion Y obtained according to Gibbs conditions. The quark phase proportion Y depends on the isospin asymmetry. In this way, the symmetry energy in the mixed phase obtained in symmetric matter cannot simply be used to predict the properties of asymmetric matter because the quark phase proportion changes with isospin asymmetry. Nevertheless, the symmetry energy obtained in symmetric matter is instructive for exhibiting its variation in the mixed phase. Shown in [Figure 2: see original paper] is the nuclear symmetry energy as a function of baryon density using the RMF models SLC and SLCd [**?**] combined with the MIT bag model with bag constant $B = (160\ \mathrm{MeV})^4$ (upper panel) and $B = (180\ \mathrm{MeV})^4$ (lower panel). An apparent decrease of the symmetry energy can be observed after the hadron-quark phase transition occurs. With increasing density, the nucleon proportion decreases, causing an apparent reduction of the nuclear symmetry energy. As the nucleon proportion reduces to zero, the nuclear symmetry energy vanishes. Notably, the change of the symmetry energy is very sensitive to the bag constant. Moreover, in [Figure 2: see original paper] we compare two cases with and without hyperons. It is found that the inclusion of hyperons further softens the symmetry energy as the hadron-quark phase transition occurs. It is worth noting that the softening of the symmetry energy in the mixed phase is mostly apparent because once the quark phase proportion can be identified at given densities, the nuclear symmetry energy would be extracted appropriately by singling out the effect of suppression factor $(1-Y)$. However, the determination of Y is strongly model-dependent and far from experimental feasibility. Thus, the extraction of the high-density symmetry energy for pure nucleonic matter is not well grounded once the hadron-quark phase transition takes place. Most likely, the high-density symmetry energy extracted from heavy-ion collisions would be as soft as that presented in this work because of the absence of a reliable discrimination of dynamically evolved matter.

---

4 Conclusion

We have reported the effect of Λ hyperons and quarks on the nuclear symmetry energy at high densities using RMF models combined with the MIT bag model. The softening of the nuclear symmetry energy is observed in nuclear matter at given Λ fractions. In the presence of the hadron-quark phase transition, the nuclear symmetry energy obtained in the mixed phase reduces quickly with the rise of quark phase proportion. We argue that this softening is apparent but is most likely realistic within the capabilities of experimental detection.

References

[?] Li B A. Phys Rev Lett, 2000, 85: 4221-4224; ibid. 2002, 88: 192701.

[?] Jiang W Z and Zhao Y L. Phys Lett B, 2005, 617: 33-39.

[?] Lattimer J M and Prakash M. Phys Rep, 2000, 333: 121-146; ibid. 2007, 442: 109-165.

[?] Horowitz C J and Piekarewicz J. Phys Rev Lett, 2001, 86: 1998, 81: 1584-1587.

[?] Steiner A W, Lattimer J M, Brown E F. Astrophys J, 2010, 722: 33-54.

[?] Newton W, Gearheart M, Li B A. 2011, arXiv:1110.4043.

[?] Tsang M B, Stone J R, Camera F, et al. Phys Rev C, 2012, 86: 015803.

[?] Chen L W, Ko C M, Li B A, et al. Phys Rev C, 2010, 82: 024620.

[?] Xu C and Li B A. Phys Rev C, 2010, 81: 064612.

[?] Vidana I, Polls A, Providencia C. Phys Rev C, 2011, 84: 062801(R).

[?] Jiang W Z, Li B A, Chen L W. Phys Lett B, 2007, 653: 471-476.

[?] Xiao Z G, Li B A, Chen L W, et al. Phys Rev Lett, 2009, 102: 062502.

[?] Russotto P, Trautmann W, Li Q F, et al. Phys Lett B, 2011, 697: 471-476.

[?] Jiang W Z, Li B A, Chen L W. Astrophys J, 2012, 756: 56.

[?] Kumar S, Ma Y G, Zhang G Q, et al. Phys Rev C, 2012, 85: 024620.

[?] Brockmann R and Machleidt R. Phys Rev C, 2000, 42: 1965-1980.

[?] Song H Q, Baldo M, Giansiracusa G, et al. Phys Rev Lett, 1998, 81: 1584-1587.

[?] Walecka J D. Ann Phys (NY), 1974, 83: 491-501.

[?] Chodos A, Jaffe R L, Johnson K, et al. Phys Rev D, 1974, 9: 3471-3495.

[?] Lalazissis G A, König J, Ring P. Phys Rev C, 1997, 55: 540-543.

[?] Shen H, Toki H, Oyamatsu K, et al. Nucl Phys A, 1998, 637: 435-450.

[?] Shen H, Toki H, Oyamatsu K, et al. Prog Theor Phys, 1998, 100: 1013-1031.

[?] Jiang W Z, Li B A, Chen L W. Phys Lett B, 2007, 653: 184-190.

[?] Jiang W Z. Phys Rev C, 2008, 78: 057601.

[?] Jiang W Z. Phys Rev C, 2009, 79: 028801.

[?] Jiang W Z. Phys Rev C, 2010, 81: 044306.

- Corresponding author. E-mail address: wzjiang@seu.edu.cn

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