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## 1 - 3 Probing the Incompressibility of Dense Hadronic Matter near the QCD Phase Transition in Relativistic Heavy-ion Collisions*

Wu Zhimin and Yong Gaochan

Based on the extended hadronic transport model, we investigate the incompressibility of dense hadronic matter formed in relativistic Au + Au heavy-ion collisions at $\sqrt{S_{\rm NN}} = 3$ GeV. By comparing various experimental observables, such as proton directed flow, production yields of strange hadrons $\phi$, $K^-$ as well as their ratio $\phi/K^-$ and proton high-order cumulants with our model calculations, we find that hadronic interactions play a dominant role in these collisions, consistent with experimental observations measure results. Our calculations also reveal that the incompressibility of hadronic matter exhibits variations across different density regions. Specifically, it appears to become stiffer from saturation density up to a certain baryon density, after which it turn to a softer regime before reaching the hadron-quark phase transition[1].

The slope of nucleon directed flow in semi-central heavy-ion collisions is a valuable measure of the stiffness of nuclear matter generated by the interactions of participant nucleons from the target and projectile nuclei. It serves as a significant probe for investigating the EoS and the QCD phase transition. The recent experimental observation of particle directed and elliptic flows in 10% ~ 40% centrality for Au + Au collisions at $\sqrt{S_{\rm NN}} = 3$ GeV at the Relativistic Heavy Ion Collider (RHIC) provides compelling evidence that predominantly hadronic matter is formed in these collisions and the QCD critical region.

Figure 1 depicts the proton directed flow $v_1$ as a function of rapidity, simulated using the AMPT-HC hadronic transport model with different incompressibilities in the mean-field option. The theoretical calculations are compared with experimental data[2], revealing that a higher incompressibility value is required to match the observed results. Consequently, the proton directed flow $v_1$ provides evidence for a large incompressibility of dense hadronic matter formed in Au + Au collisions at $\sqrt{S_{\rm NN}} = 3$ GeV at RHIC. Specifically, an incompressibility coefficient around $k \sim 300$ MeV appears to provide a satisfactory fit to the stiffness of the produced hadronic matter in these collisions. In contrast, the analysis of the nucleon directed flow with quark transport suggests that predominantly hadronic matter is indeed generated in such collisions.

Strange mesons are excellent probes of the dense nuclear matter created in heavy-ion collisions because they are hardly affected by final state interactions. In our study of Au + Au collisions at $\sqrt{S_{\rm NN}} = 3$ GeV, we used the AMPT-HC model with different incompressibilities in the mean-field option to calculate the production of $\phi$, $K^-$, and their ratio $\phi/K^-$. Our calculations were compared to experimental data[3]. The $\phi$ and $K^-$ mesons mainly produced through baryon-baryon and meson-baryon or meson-meson collisions during the highly compressed stage of the collision. As the compression of the colliding nuclei increases, more $\phi$ and $K^-$ mesons are produced. Comparing our results with experimental data, we find that a softer EoS or a smaller incompressibility coefficient ($75 < k < 150$ MeV) is favored. Our findings suggest that different observables yield different results for the incompressibility, indicating that the incompressibility of hadronic matter varies across different density regions(Fig. 2). Additionally, the incompressibility has a significant impact on the critical baryon density of the hadron-quark phase transition.

By analyzing the EoS of nuclear matter created in heavy-ion collisions and comparing it with experimental data, valuable insights can be gained regarding the stiffness of the EoS and the occurrence of the hadron-quark phase transition in nuclear matter. This information is crucial for mapping out the QCD phase diagram, which has significant implications for understanding the structure of neutron stars and the emission of gravitational waves, furthermore, studying QCD phase transition from Earth to space has crucial implications for understanding the early and present universe.

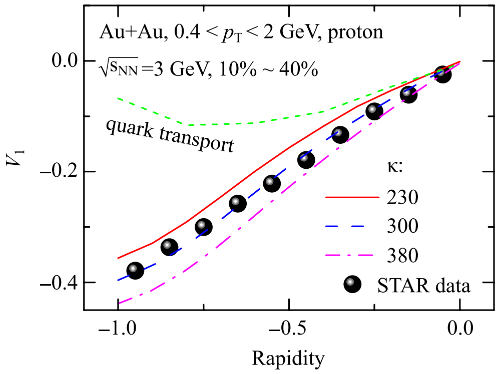


Fig. 1 (color online) Rapidity dependences of proton directed flow $v_1$ in 10% ~ 40% centrality for Au + Au collsions at $\sqrt{S_{NN}} = 3$ GeV given by the AMPT-HC mode with different EoSs and the quark transport AMPT-SM mode. The STAR data is taken from Ref. [2].

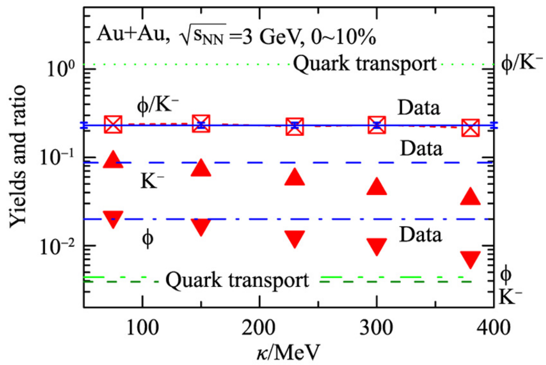


Fig. 2 (color online) Strange $\phi$ and $K^-$ productions and their ratios $\phi/K^-$ in 0 ~ 10% centrality for Au + Au collisions at $\sqrt{S_{NN}} = 3$ GeV given by the AMPT-HC mode with different EoSs and the quark transport AMPT-SM mode. The data is taken from Ref. [3].

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# 1 - 4 Probing the Symmetry Energy with Strangeness Production*

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The EoS of dense matter plays an important role in understanding the later evolution of the universe, the physics associated with compact stars. Therefore, constraints on the equation of state (EoS) of dense nuclear matter has been a longstanding and common goal of both nuclear physics and astrophysics. Nowadays one of the main goals of relativistic heavy-ion collision program is to understand the properties of dense nuclear matter, i.e., EoS of nuclear matter under conditions of extreme energy and baryon density[1]. While among all the potential observables used to probe the EoS of dense nuclear matter, strange mesons or baryons are different from the rest. They are rarely absorbed by surrounding matter, thus frequently used to probe the EoS of dense matter. A lot of studies on probing the nuclear symmetry energy have been carried out for many years. Constraints on the high-density behavior of the symmetry energy can be highly relevant to a series of properties of neutron stars. To constrain the high-density symmetry energy, many terrestrial experiments are being carried out (or planned) using a wide variety of advanced facilities.

Based on the updated AMPT-HC model with the momentum-dependent single particle potential, the effects of the symmetry energy on the $K_s^0/K^+$ ratio and the $\Sigma^-/\Sigma^+$ ratio in the Au+Au collisions at RHIC-STAR energies are studied[2]. From Fig. 1, one sees that the effects of the symmetry energy on the $K_s^0/K^+$ ratio are not more than 6%. At lower kinetic energies, the effects of the symmetry energy on the $\Sigma^-/\Sigma^+$ ratio can be as high as 20%, but disappear at high kinetic energies (energetic $\pi^{-,+}$'s experience many re-scatterings in compression matter, further cause the produced $\Sigma^{-,+}$'s mostly lose the information of the symmetry energy, one sees the $\Sigma^-/\Sigma^+$ ratio shows no effects of the symmetry energy).

Figure 2 shows the effects of the symmetry energy on the $\Xi^-/\Xi^0$ ratio in the Au+Au reactions at $\sqrt{s_{NN}} = 3$ GeV [2]. It is seen that both the kinetic energy and the transverse momentum distributions of the $\Xi^-/\Xi^0$ ratio are particularly sensitive to the symmetry energy. The value of the $\Xi^-/\Xi^0$ ratio with the soft symmetry energy is higher than that with the stiff symmetry energy and the effects reach about 30%.

Recent studies show in the central Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV, the dense matter formed in the collisions is most likely dense hadronic matter. The baryonic density reached may be approximatively maximum compression baryonic density in terrestrial laboratory, far close to the phase boundary and onset of quark deconfinement. It is thus interesting to see the behavior of the symmetry energy at such extreme high baryonic density. Our study