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Open and hidden strangeness production in heavy-ion collisions

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Strangeness production in heavy-ion collisions reveals the modification of the properties of strange hadrons in hot and dense nuclear matter. Adopting in-medium properties of antikaons ($\bar{K} = K^-, \bar{K}^0$) described by the self-consistent coupled-channel unitarized scheme based on a SU(3) chiral effective Lagrangian (G-matrix), we study strangeness production in heavy-ion collisions within the off-shell Parton-Hadron-String Dynamics (PHSD) transport approach. The in-medium modification of kaons ($K = K^+, K^0$) are accounted for via the kaon-nuclear potential, which is proportional to the local baryon density. Our results are found consistent with the experimental data on (anti)kaon production from the KaoS, FOPI and HADES Collaborations. Moreover, we demonstrate the sensitivity of kaon observables to the equation-of-state of nuclear matter. We also study hidden strangeness production with in-medium effects realized by a collisional broadening of spectral function, which reflects the partial chiral symmetry restoration. Implementing novel meson-baryon and meson-hyperon production channels for ϕ mesons, calculated within a T-matrix coupled-channel approach based on the extended SU(6) chiral effective Lagrangian model, along with the collisional broadening of the ϕ meson in-medium spectral function, we find a substantial enhancement of ϕ meson production in heavy-ion collisions, especially at sub- and near-thresholds, as shown by the experimental data at the HADES collaboration. This allows to describe the experimentally observed strong enhancement of the ϕ/K^- ratio at low energies without including hypothetical decays of heavy baryonic resonances to ϕ as in alternative approaches. Our results support that the modifications of open and hidden strange hadrons in the nuclear medium are necessary to understand various experimental data.

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1. Introduction

For decades, the study of strangeness production in heavy-ion collisions has posed a key challenge in high energy physics. Strangeness represents a newly generated flavor, as the colliding nuclei initially consist solely of "up" and "down" quarks. The strangeness is produced in the form of hyperons or strange mesons which are 200-300 MeV heavier than the normal baryons and mesons composed of up and down flavors. However, in the deconfined phase like quark-gluon plasma (QGP) the strangeness will be produced in the form of strange quarks and antiquarks whose mass differ from up and down quarks by several tens MeV [1, 2]. Strangeness enhancement was considered as a signature for QGP formation in relativistic heavy-ion collisions. The strangeness is also important for the equation-of-state (EoS) of neutron stars. BY including strangeness, the EoS becomes too soft and the maximum mass of a neutron star gets smaller than observed, which is called hyperon puzzle [3]. For the study of strangeness in a hot and dense matter we employ the self-consistent coupled-channel unitarized G-matrix and apply it to relativistic heavy-ion collisions using the off-shell Parton-Hadron-String dynamics (PHSD) transport approach [4, 5] which describes the time evolution of heavy-ion collisions based on microscopic interactions of hadronic and partonic degrees-of-freedom.

PoS(QNP2024)130

2. Self-consistent coupled-channel unitarized G-matrix

The self-consistent coupled-channel unitarized G-matrix is based on a SU(3) chiral effective Lagrangian [6], where the leading scattering amplitudes are obtained. Then the scattering amplitudes are unitarized through

$$T_{i\to j} = V_{i\to j} + \sum_k V_{i\to k} G_k T_{k\to j}, \tag{1}$$

where i, j and k are, respectively, the initial, intermediate and final states of the baryon-meson system, $V_{i\to j}$ and $T_{i\to j}$ are respectively trivial and unitarized scattering amplitudes and G_k is the propagator of the baryon-meson which is modified at finite temperature and nuclear density. Since the intermediate state can be any state with the same quantum numbers, Eq. (1) is the linear equations where different $T_{i\to j}$ are coupled with each other.

From the unitarized scattering amplitude one can get the complex self-energy of a meson in the presence of baryons by connecting the external lines of the baryon:

$$\Sigma_{\bar{K}}(q_0, \vec{q}; T) = \int \frac{d^3p}{(2\pi)^3} n_N(\vec{p}; T) T_{N\bar{K}\to N\bar{K}}(P_0, \vec{P}; T), \tag{2}$$

where $n_N(\vec{p}; T)$ is the nucleon density including isospin and spin degeneracy, $P_0 = q_0 + E_N(\vec{p}; T)$ with nucleon energy E_N and $\vec{P} = \vec{q} + \vec{p}$. The complex self-energy provides the spectral function of an antikaon in the nuclear medium by

$$A_{\bar{K}}(q_0, \vec{q}; T) = \frac{-2\mathrm{Im}\Sigma_{\bar{K}}}{(q_0^2 - \vec{q}^2 - m_{\bar{K}}^2 - \mathrm{Re}\Sigma_{\bar{K}})^2 + (\mathrm{Im}\Sigma_{\bar{K}})^2}, \tag{3}$$

where $\Sigma_{\bar{K}} = \mathrm{Re}\Sigma_{\bar{K}} + i\mathrm{Im}\Sigma_{\bar{K}}$ and $m_{\bar{K}}$ is the antikaon mass in vacuum. Eq. (3) clearly shows that the real part of the self-energy determines the mass shift and the imaginary part - the width

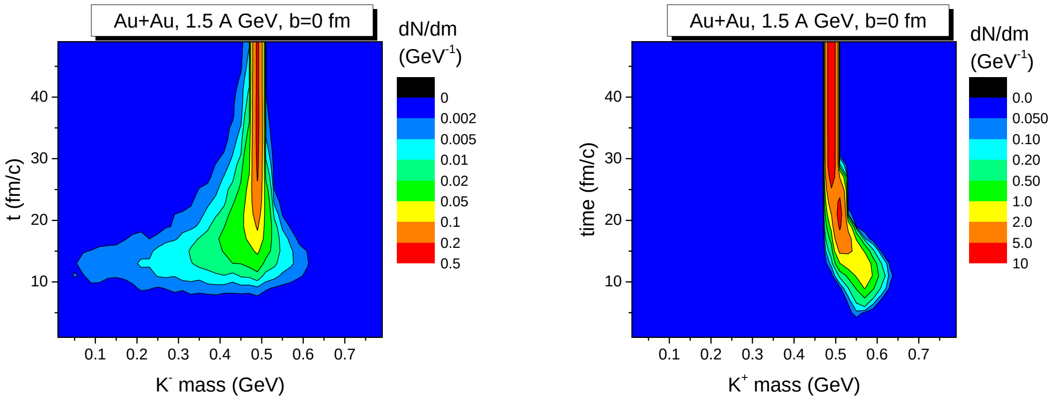

Figure 1: Mass distributions of k^- (left) and of K^+ (right) as a function of time in central Au+Au collisions at 1.5 A GeV.

broadening of the spectral function in the medium. According to Ref. [6] (Fig. 2) the real part of the self-energy decreases with nuclear density for small antikaon momenta but changes little for large momenta above 300 MeV$/c$. On the other hand, the negative imaginary self-energy, which corresponds to the spectral width, monotonously decreases with nuclear density regardless of antikaon momentum. For kaon we assume a repulsive potential energy which is proportional to nuclear density, $V_K = a(\rho/\rho_0)$ with a =25 MeV and ρ_0 being the saturation density.

Fig. 1 shows the mass distribution of (anti)kaon as a function of time in central Au+Au collisions at 1.5 A GeV. One can see that the K^- mass is widely spread at initial times due to the large nuclear density and then gradually shrinks to its pole mass according to the off-shell dynamics [7], because the nuclear density decreases with time. On the other hand, the K^+ mass is slightly larger than the vacuum mass, depending on the local nuclear density in heavy-ion collisions. But it also converges to the vacuum mass for large times.

3. Open strangeness in heavy-ion collisions

In order to compare with the experimental data, we simulate heavy-ion collisions by using the Parton-Hadron-String dynamics, which is a non-equilibrium microscopic transport approach for the description of the dynamics of strongly-interacting hadronic as well as partonic matter produced in heavy-ion collisions [4, 5]. The PHSD dynamics is based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory, which is beyond the semi-classical Boltzmann-Uehling-Uhlenbeck (BUU) transport approach.

Fig. 2 displays the p_T spectra of K^- (right) and of K^+ in Ni+Ni collisions at 1.93 A GeV. The dashed and solid lines, respectively, indicate the p_T spectrum without and with medium effects. One can see that the medium effects enhance K^- production and soften its spectrum, while they suppress K^+ production and harden the spectrum. As a result, the effective temperatures of K^- and K^+ are split with the former decreasing and the latter increasing as the mass number of the colliding nuclei increases [9]. We also note that the enhancement of K^- production and the suppression of K^+ production in the medium are consistent with the experimental data from the KaoS, FOPI and HADES Collaborations [8–14].

PoS(QNP2024)130

PoS(QNP2024)130

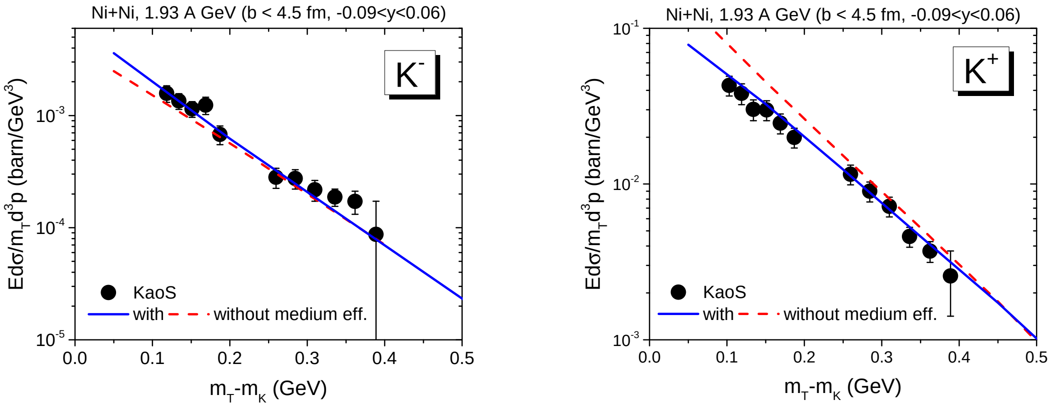

Figure 2: p_T spectra of K^- (right) and of K^+ in Ni+Ni collisions at 1.93 A GeV with and without medium effects. The results are compared with the experimental data from the KaoS Collaboration [8].

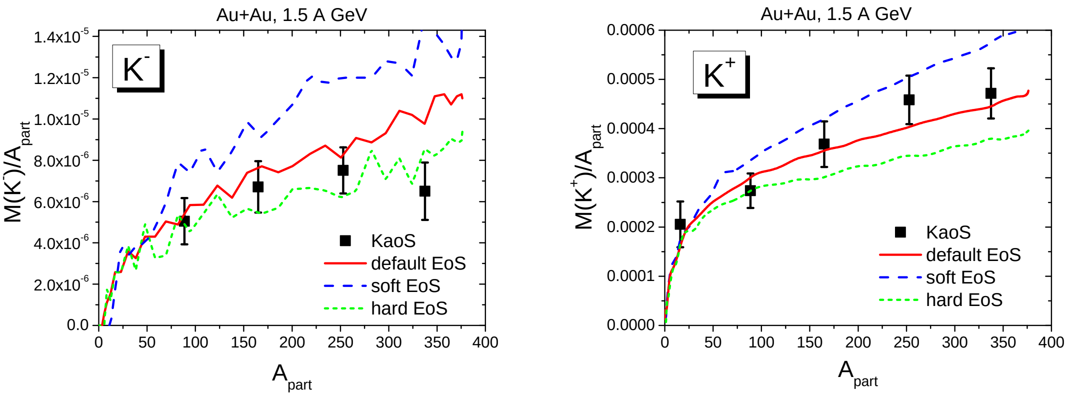

Figure 3: The number of produced K^- (left) and that of K^+ (right) per number of participants in Au+Au collisions at 1.5 A GeV for three different EoS of nuclear matter in comparison with the experimental data from the KaoS Collaboration [15].

One can also study the EoS of nuclear matter by (anti)kaon production in heavy-ion collisions. The EoS is characterized by the compression modulus (K) and a large compression modulus means that nuclear matter is hard to compress. In this case less nucleon-nucleon scatterings happen in heavy-ion collisions, because the maximum nuclear density is lower, and less (anti)kaons are produced. This is the case for hard EoS. The opposite holds true for a the soft EoS, which are characterized by K = 380 MeV and K = 210 MeV, respectively, in our study. We display in Fig. 3 the yields of K^- and K^+ per number of participants in Au+Au collisions at 1.5 A GeV. The red lines are from the default EoS of the PHSD, which corresponds to $K \simeq 300$ MeV, and best describes the experimental data from the KaoS Collaboration [15].

4. Hidden strangeness in heavy-ion collisions

For hidden strangeness or for ϕ meson production we use the same approach as in Sec. 2. But in-medium effects are introduced only by the spectral broadening such that the spectral width of ϕ

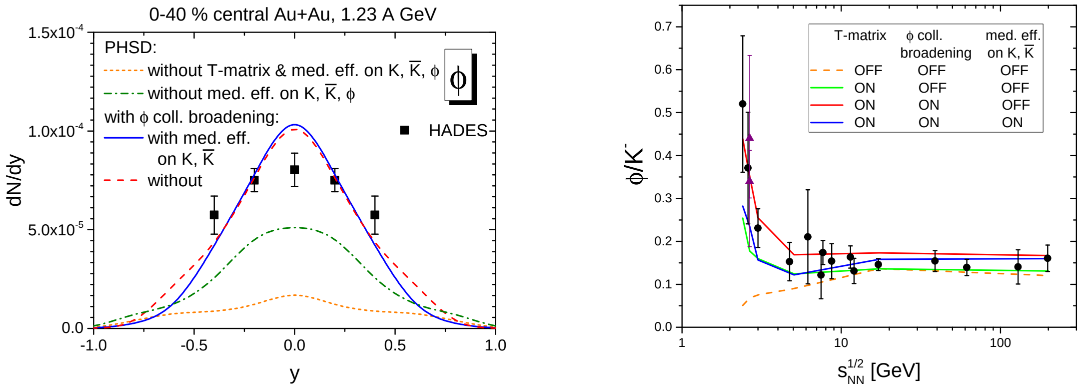

Figure 4: Left: the rapidity distribution of ϕ mesons in 0-40 % central Au+Au collisions at 1.23 A GeV, compared with the experimental data from the HADES Collaboration [13]. Right: the ratio of ϕ meson to K^- in heavy-ion collisions as a function of collision energy [16].

meson in medium (Γ^*) is the sum of the vacuum width (Γ_0) and collisional width ($\Gamma_{\rm coll}$), which is related to the chiral symmetry restoration:

$$\Gamma^*(M,p,\rho)=\Gamma_0(M,p)+\Gamma_{\rm coll}(\rho)\approx\Gamma_0(M,p)+\alpha_{\rm coll}(\rho/\rho_0), \tag{4}$$

where $\alpha_{\rm coll}$ is taken to be 25 MeV [16].

The left panel of Fig. 4 shows the rapidity distribution of ϕ mesons in 0-40 % central Au+Au collisions at 1.23 A GeV, incorporating the loss of ϕ mesons due to the interaction of K^+ or K^- after ϕ decay [16]. The difference between the orange dotted line and the green dot-dashed line is the contribution from meson-baryon scattering in the self-consistent coupled-channel unitarized scheme. The orange line includes only the elementary reactions such as $pp\to\phi X$ and $p\pi\to\phi X$ and the string fragmentation from the Lund string model. The red dashed line and the blue solid line include the in-medium effect (width broadening). The red dashed line does not include in-medium effects for (anti)kaon as described in Sec. 3 The right panel shows the ratio of ϕ to K^- in heavy-ion collisions as a function of collision energy for the same four different scenarios. Both figures show that in-medium effects are necessary to describe the experimental data.

5. Summary

We have studied the production of open and hidden strangeness in relativistic heavy-ion collisions by using the self-consistent coupled-channel unitarized G-matrix incorporated in the Parton-Hadron-String Dynamics microscopic off-shell transport approach. It has been found that in-medium effects enhance K^- production and soften its spectrum, while they suppress K^+ production and harden its spectrum, and that a compression modulus of around 300 MeV can explain the experimental data on (anti)kaon production in heavy-ion collisions. We have also studied ϕ production in heavy-ion collisions, introducing the collisional width broadening in nuclear matter, which originates from partial chiral symmetry restoration. This medium effect is necessary to reproduce the enhancement of ϕ production observed in heavy-ion collisions at low energies.

PoS(QNP2024)130

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PoS(QNP2024)130