In-medium effects in strangeness production in heavy-ion collisions at (sub-) threshold energies

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Abstract. We study the in-medium effects in strangeness production in heavy-ion collisions at (sub-)threshold energies based on the microscopic Parton-Hadron-String Dynamics (PHSD) transport approach. The in-medium modifications of the antikaon properties are described via the self-consistent coupled-channel unitarized scheme based on a SU(3) chiral Lagrangian while the in-medium modification of kaons are accounted via the kaon-nuclear potential, which is assumed to be proportional to the local baryon density. We find that the modifications of (anti)kaon properties in nuclear matter are necessary to explain the experimental data in heavy-ion collisions.

1 Introduction

In this contribution we present the highlights of our recent study [1] of the in-medium effects in the strangeness production in heavy-ion collisions at (sub-)threshold energies employing the microscopic transport approach PHSD which incorporates the in-medium description of the antikaon-nucleon interactions based on 'state of the art' many-body theory realized by the G-matrix formalism [2]. This chiral unitary approach in coupled channels incorporates the *s*- and *p*-waves of the kaon-nucleon interaction, its modification in the hot and dense medium to account for Pauli blocking effects, mean-field binding for baryons, as well as pion and kaon self-energies. For the in-medium scenario of the kaon-nucleon interaction we adopt a

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repulsive potential linear in the baryon density. We then confront our theoretical results with available experimental data on (anti)kaon production at SIS energies (cf. Ref. [1] for details).

2 Chiral unitarized model for $\bar{K}N$ in hot nuclear matter

For low-energy scattering, the s-wave meson-baryon interaction from the lowest-order chiral Lagrangian which couples the octet of light pseudoscalar mesons to the octet of $1/2^+$ baryons can be written as [2]

$$V_{ij}^s \simeq -C_{ij} \frac{1}{4f^2}(k_i^0 + k_j^0), \tag{1}$$

where the coefficients C_{ij}, with i, j indicating the particular meson-baryon channel, can be found explicitly in Ref. [4], f is the meson weak decay constant, and $k_{i(j)}^0$ is energy of the meson in the $i(j)$ channel in the the center-of-mass (c.m.) frame. As for p-wave meson-baryon interaction $\tilde{V}_{ij}^p$, one can find the details in Refs. [2, 3]. The transition amplitudes can be obtained by means of a unitarization coupled-channel procedure based on solving the Bethe-Salpeter equation by using the tree level contributions to the s- and p-wave meson-baryon scattering as the kernel of the equation. Within the on-shell factorization [4, 5], the Bethe-Salpeter equation is given in matrix notation as

$$T = [1 - VG]^{-1}V, \tag{2}$$

where V is the kernel (potential), and the G is a diagonal matrix accounting for the loop function of a meson-baryon propagator. Nuclear matter effects at finite temperature are introduced through the modification of the meson-baryon propagators where all mesons and baryons in the intermediate loops interact with the nucleons of the Fermi sea, and their properties are modified with respect to those in vacuum in addition to the Pauli blocking, as described in Refs. [2, 6]. Once the transition amplitudes in free space and in matter are evaluated, the corresponding cross sections can be obtained by

$$\frac{d\sigma_{ij}}{d\Omega}(\sqrt{s}) = \frac{1}{16\pi^2} \frac{M_i M_j}{s} \frac{q_j}{q_i} \left\{ |T_{ij}^s + (2T_{ij+}^p + T_{ij-}^p)\cos\theta|^2 + |T_{ij+}^p - T_{ij-}^p|^2 \sin^2\theta \right\}, \tag{3}$$

where $M_i(M_j)$ is the incoming (outgoing) baryon mass, $q_i(q_j)$ is the modulus of the on-shell c.m. three-momentum of the incoming (outgoing) meson-baryon pair, and θ is the scattering angle in that frame. The self-energy of the antikaon in either s- or p-wave are obtained by convoluting the transition amplitudes with the nucleon Fermi distribution at a given temperature, for example,

$$\Sigma_{\bar{K}}^L(k; T) = 4 \int \frac{d^3p}{(2\pi)^3} n_N(\vec{p}, T) \bar{T}_{\bar{K}N \to \bar{K}N}^L(P; T), \tag{4}$$

where P is the total energy and momentum of the $\bar{K}N$ pair in the nuclear medium rest frame, k stands for the energy and momentum of the $\bar{K}$ meson also in this frame, and $\bar{T}^L$ indicates the spin and isospin averaged scattering amplitude for a given partial wave ($L = 0$ or $L = 1$). The spectral function can be then reconstructed as

$$A_{\bar{K}}(m^2) = \frac{-2\,\mathrm{Im}\Sigma_{\bar{K}}}{(m^2 - m_{\bar{K}}^2 - \mathrm{Re}\Sigma_{\bar{K}})^2 + (\mathrm{Im}\Sigma_{\bar{K}})^2}, \tag{5}$$

where $m_{\bar{K}}$ is $\bar{K}$ pole mass in vacuum.

3 $K/\bar{K}$ production in heavy-ion collisions

For the simulations of heavy-ion collisions we use the Parton–Hadron–String Dynamics transport approach [7–11], which is a microscopic off-shell transport approach for the description of strongly interacting hadronic and partonic matter in and out-of equilibrium. The antikaon production cross section in the medium is evaluated by folding the corresponding vacuum production cross section with the in-medium spectral function in Eq. (5):

$$\sigma_{\bar{K}}^*(\sqrt{s}) = \int_0^{(\sqrt{s}-m_4)^2} \frac{dm^2}{2\pi} A_{\bar{K}}(m^2)\, \sigma_{\bar{K}}(\sqrt{s} - \Delta m_{\bar{K}}), \tag{6}$$

where m_4 is the invariant mass of the final particles different from antikaons [1], m is the off-shell mass of the $\bar{K}$ meson in the medium defined by the spectral function $A(m^2)$ according to Eq. (5); $\Delta m_{\bar{K}} = m - m_{\bar{K}}$ describes the deviation from the vacuum mass. The equations of motion for the produced off-shell antikaon are given by the Cassing-Juchem off-shell transport equations for testparticles [12] used also for the propagation of antikaons in the early HSD study [13]. On the other hand, the in-medium kaon mass m_K^* is expressed in terms of the repulsive potential $V_K = 25$ MeV (ρ/ρ_0) with ρ_0 being the nuclear saturation density [1]:

$$m_K^* \simeq m_K\Big(1 + E_K V_K/m_K^2\Big). \tag{7}$$

The cross section for kaon production is then shifted by the mass difference:

$$\sigma_K(\sqrt{s}) \to \sigma_K(\sqrt{s} - \Delta m_K) \tag{8}$$

where $\Delta m_K = m_K^* - m_K$. Since Δm_K is positive, the mass shift suppresses K production in heavy-ion collisions.
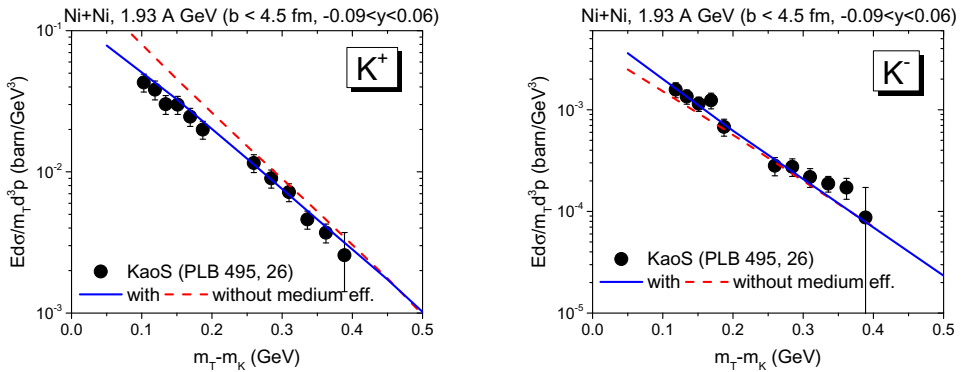
Figure 1. The PHSD results for the m_T-spectra of K^+ (left) and K^- (right) as a function of the transverse kinetic energy $m_T - m_K$ in central Ni+Ni collisions at 1.93 A GeV in comparison to the experimental data of the KaoS Collaboration [14]. The dashed lines indicate the results without medium effects for (anti)kaons, while the solid lines display the results with the medium effects. The figure is taken from Ref. [1].

Figure 1 shows the PHSD results for the m_T-spectra versus the transverse kinetic energy of K^+ and K^- at midrapidity in central Ni+Ni collisions at 1.93 A GeV in comparison to the experimental data of the KaoS Collaboration [14]. The kaon-nuclear potential suppresses the K^+ yield and pushes the K^+ spectrum to larger transverse momenta, while the antikaon potential enhances the K^- yield and pulls the p_T-spectrum toward smaller transverse momenta. The kaon potential is necessary to reproduce the experimental data on the p_T- spectra of K^+ and K^-.

4 Summary

We have investigated strangeness production in heavy ion collisions at (sub-)threshold energies within the microscopic Parton-Hadron-String Dynamics (PHSD 4.5) transport approach, extended for the incorporation of the in-medium effects for strangeness production in terms of the state-of-the-art coupled-channel G-matrix approach for the modification of antikaon properties in a dense and hot medium. We have found that the kaon-nuclear potential increases the threshold energy for the kaon production in a hot and dense medium. Consequently, the K^+ production in heavy-ion collisions is suppressed. On the other hand, the self-consistent coupled-channel unitarized scheme based on a SU(3) chiral Lagrangian leads to a broadening of the K^- spectral function without drastic changes of the pole mass due to the finite momentum. The K^- production in heavy-ion collisions is enhanced by the broad spectral width which leads to a reduction of the production threshold. Furthermore, the kaon-nuclear potential hardens the p_T-spectra of K^+ mesons while the in-medium effects in terms of self-energies within the G-matrix approach soften the K^- spectra.

Acknowledgements

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