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In-medium effects on hidden strangeness production in heavy-ion collisions

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Abstract. We study ϕ meson production in heavy-ion collisions from subthreshold energies of 1.23 A GeV up to RHIC energies within the microscopic Parton-Hadron-String Dynamics (PHSD) transport approach where novel production channels for ϕ mesons based on a coupled channel T-matrix approach are implemented along with the collisional broadening of the ϕ meson spectral width in medium. Since ϕ meson production is closely related to the production of kaons and antikaons, antikaon properties are described via the self-consistent coupled-channel unitarized scheme within a SU(3) chiral Lagrangian (G-matrix) which incorporates explicitly the s− and p− waves of the kaon-nucleon interaction, while the in-medium modifications of kaons are accounted for via a kaon-nuclear potential, which is assumed to be proportional to the local baryon density.

1 Introduction

Recently it has been reported by the HADES collaboration that ϕ mesons are produced in a relatively large quantity in Au+Au collisions at subthreshold energies and the ratio of hidden strangeness to open strangeness reaches values of ≈ 0.5 [1]. The same tendency of an enhanced ϕ production in Ni+Ni and Al+Al collisions at 1.93 A GeV has been reported earlier by the FOPI collaboration [2, 3]. With increasing beam energy this ratio decreases to 0.2 as has been measured recently by the STAR collaboration [4] and at high energies the dependence on the collision energy is mild [5–9].

The goal of this study is to show that the observed 'enhanced' ϕ multiplicity and ϕ/K^- ratio close to threshold can be understood by considering a collisional broadening of the ϕ meson spectral function and accounting for additional multi-step meson-baryon and meson-hyperon reactions for ϕ meson production as predicted by the SU(6) extension of the meson-baryon chiral Lagrangian within a unitary coupled channel T-matrix approach.

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2 In-medium modification of ϕ meson properties

In order to explore the influence of in-medium effects on the vector-meson spectral function we introduce the collisional broadening by

$$\Gamma^*_\phi(M,|\vec{p}|,\rho) = \Gamma_\phi(M) + \Gamma_{coll}(M,|\vec{p}|,\rho), \tag{1}$$

where M is the mass, $\Gamma_\phi(M)$ the total width of the vacuum spectral function of the ϕ meson, and Γ_{coll} the collisional width approximated as

$$\Gamma_{coll}(M,|\vec{p}|,\rho) = \gamma\, \rho < \upsilon\, \sigma^{tot}_{VN} > \approx \ \alpha_{coll}\ \frac{\rho}{\rho_0}. \tag{2}$$

Here υ is the velocity of the ϕ meson in the rest frame of the nucleon current, $\gamma^2 = 1/(1-\upsilon^2)$, ρ the nuclear density scaled by $\rho_0 = 0.168$ fm^{-3} (normal nuclear density) and σ^{tot}_{VN} the meson-nucleon total cross section in vacuum. In order to simplify the calculations of $\Gamma_{coll}(\rho)$ we use the linear density approximation [10] with a coefficient α_{coll} which is taken to be 25 MeV [11].

3 ϕ production/absorption within a SU(6) based T-matrix approach

The s-wave scattering amplitude of meson and baryon from the SU(6) chiral effective Lagrangian is written as [12],

$$V^{SIJ}_{ij} = \varepsilon^{SIJ}_{ij} \frac{2\sqrt{s} - M_i - M_j}{4 f_i f_j} \sqrt{\frac{E_i + M_i}{2M_i}} \sqrt{\frac{E_j + M_j}{2M_j}}, \tag{3}$$

where $i(j)$ indicates the initial (final) meson-baryon scattering states, $M_{i(j)}$ and $E_{i(j)}$ are, respectively, mass and center-of-mass energy of the baryon, $f_{i(j)}$ the decay constant of the meson in the $i(j)$ state, and ε^{SIJ}_{ij} the degeneracy coefficient, corresponding to the scattering channel with $S, I,$ and J being total strangeness, isospin and angular momentum of the collision, respectively [13, 14]. The T-matrix approach can be formulated on the basis of the Born scattering amplitude V^{SIJ}_{ik},

$$T^{SIJ}_{ij} = V^{SIJ}_{ij} + V^{SIJ}_{ik} G^{SIJ}_{kk} T^{SIJ}_{kj}, \tag{4}$$

where k is the intermediate meson-baryon state and the sum is performed over all possible states. G^{SIJ}_{kk} is the product of the meson and baryon propagators of the state k [15], which is renormalized such that $G^{SIJ}_{kk}(s = m_N^2 + m_\pi^2) = 0$ with m_N and m_π being nucleon and pion masses, respectively. The channels considered in this study for ϕ meson production are ηN, $K\Lambda$, $K\Sigma$, ρN, $K\Sigma^*$, $\rho\Delta$, $K^*\Lambda$, $K^*\Sigma$, $K^*\Sigma^* \rightarrow \phi N$ for $I = 1/2$ and $K\Sigma$, ρN, $\eta\Delta$, $K\Sigma^*$, $\rho\Delta$, $K^*\Sigma$, $K^*\Sigma^* \rightarrow \phi\Delta$ for $I = 3/2$, including their inverse reactions by detailed balance.

4 ϕ meson production in heavy-ion collisions

Fig. 1 shows the PHSD results for the rapidity distribution of reconstructed ϕ mesons from the decay into K^+K^- pairs, compared with the experimental data from the HADES and STAR collaborations. The short dashed orange lines show the PHSD results without including the novel mB channels from the T-matrix approach and without any in-medium modifications of ϕ and $K, \bar{K}$ mesons. The dash-dotted green lines show the results without in-medium modifications of ϕ and $K, \bar{K}$ mesons [17]. The dashed red lines indicate the ϕ rapidity distributions

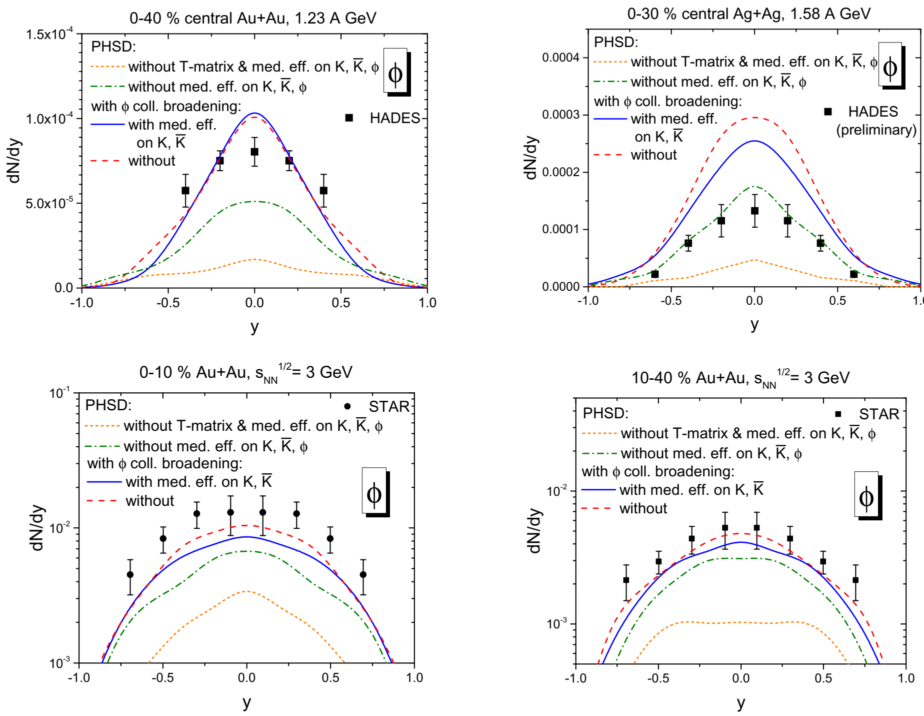

Figure 1. Rapidity distribution of reconstructed ϕ mesons in 0-40 % central Au+Au collisions at E_{kin} = 1.23 A GeV, in 0-30 % central Ag+Ag collisions at E_{kin} = 1.58 A GeV and 0-10 % and 10-40 % central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ =3 GeV, compared with experimental data from the HADES and STAR collaborations [1, 4, 16]. Each colored line is explained in the text.

with ϕ collisional broadening, but without in-medium effects for $K, \bar{K}$ mesons. The solid blue lines show the results with collisional broadening for ϕ mesons and with in-medium modifications of $K, \bar{K}$ mesons.The number of ϕ mesons, reconstructed from K^+K^- pairs, is divided by the branching ratio $Br(\phi \rightarrow K^+K^-)$. We note that the rescattering of the K^+ or K^- in the medium reduces the reconstructed ϕ meson to 60-70% in Au+Au reactions at energies between E_{kin} = 1.23 A GeV and $\sqrt{s_{\mathrm{NN}}}$ = 3 GeV. In addition, ϕ yield rapidly increases from E_{kin} = 1.23 A GeV to E_{kin} = 1.58 A GeV, because both are sub-threshold energies for ϕ production.

Fig. 2 shows the ϕ/K^- ratio as a function of the collision energy from E_{kin} = 1.23 A GeV to $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV. The PHSD results are presented for four different scenarios as in Fig. 1. An inclusion of the in-medium effects for $K, \bar{K}$, which leads to a strong enhancement of the K^- yield [17] and, as a result, to a reduction of the ϕ/K^- ratio.

5 Summary

In this study we have investigated the hidden strangeness (ϕ meson) production in heavy-ion collisions from subthreshold to relativistic energies within the microscopic off-shell PHSD transport approach. We have found that a collisional broadening of the ϕ meson spectral function lead to an enhancement of ϕ meson production, especially at subthreshold energies

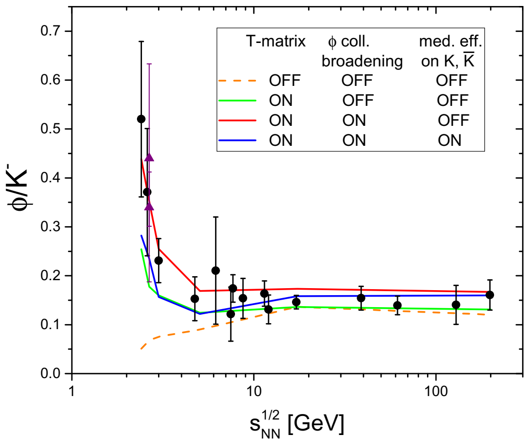

Figure 2. The PHSD results for the ratio ϕ/K^- at midrapidity ($|y| \leq 0.3$) as a function of the collision energy for four different scenarios: with and without novel mB channels for the ϕ meson production from the T-matrix approach and with and without the collisional broadening of the ϕ meson width and in-medium effects on (anti-)kaons (cf. the legend). The solid symbols show the compilation of the experimental data from Refs. [3–9].

and that the novel $mB \to \phi B$ channels from the SU(6) chiral Lagrangian in the T-matrix approach also enhance considerably the ϕ production in heavy-ion collisions.

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