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

Taesoo Song1,*, Joerg Aichelin2,3, and Elena Bratkovskaya1,4,5

1GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany
2SUBATECH UMR 6457 (IMT Atlantique, Université de Nantes, IN2P3/CNRS), 4 Rue Alfred Kastler, F-44307 Nantes, France
3Frankfurt Institute for Advanced Studies, Ruth-Moufang-Strasse 1, 60438 Frankfurt am Main, Germany
4Institute for Theoretical Physics, Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany
5Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center for Heavy Ion Physics, Campus Frankfurt, 60438 Frankfurt, Germany

Abstract. We study $\phi$ meson production in heavy-ion collisions from sub-threshold 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 $\phi$ mesons based on a coupled channel T-matrix approach are implemented along with the collisional broadening of the $\phi$ meson spectral width in medium. Since $\phi$ 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 $\phi$ 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 $\approx 0.5$ [1]. The same tendency of an enhanced $\phi$ 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’ $\phi$ multiplicity and $\phi/K^-$ ratio close to threshold can be understood by considering a collisional broadening of the $\phi$ meson spectral function and accounting for additional multi-step meson-baryon and meson-hyperon reactions for $\phi$ meson production as predicted by the SU(6) extension of the meson-baryon chiral Lagrangian within a unitary coupled channel T-matrix approach.

*e-mail: T.Song@gsi.de

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2 In-medium modification of $\phi$ meson properties

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

$$\Gamma_\phi(M, |\vec{p}|, \rho) = \Gamma_\phi(M) + \Gamma_{\text{coll}}(M, |\vec{p}|, \rho),$$

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

$$\Gamma_{\text{coll}}(M, |\vec{p}|, \rho) = \gamma \rho < v > \sigma_{\text{tot}}^{\text{VN}} \approx \alpha_{\text{coll}} \frac{\rho}{\rho_0},$$

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

3 $\phi$ 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],

$$V^{S_{ij}}_{ij} = \varepsilon^{S_{ij}}_{ij} \frac{2 \sqrt{s} - M_i - M_j}{4f_if_j} \sqrt{\frac{E_i + M_i}{2M_i}} \sqrt{\frac{E_j + M_j}{2M_j}},$$

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 $\varepsilon^{S_{ij}}_{ij}$ 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 $V^{S_{ij}}_{ik}$,

$$T^{S_{ij}}_{ij} = V^{S_{ij}}_{ij} + V^{S_{ij}}_{ik}G^{S_{ij}}_{kk}T^{S_{ij}}_{kj},$$

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

4 $\phi$ meson production in heavy-ion collisions

Fig. 1 shows the PHSD results for the rapidity distribution of reconstructed $\phi$ 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 $\phi$ and $K, \bar{K}$ mesons. The dash-dotted green lines show the results without in-medium modifications of $\phi$ and $K, \bar{K}$ mesons [17]. The dashed red lines indicate the $\phi$ rapidity distributions.
with $\phi$ collisional broadening, but without in-medium effects for $K, \bar{K}$ mesons. The solid blue lines show the results with collisional broadening for $\phi$ mesons and with in-medium modifications of $K, \bar{K}$ mesons. The number of $\phi$ mesons, reconstructed from $K^+ K^-$ pairs, is divided by the branching ratio $Br(\phi \to K^+ K^-)$. We note that the rescattering of the $K^+$ or $K^-$ in the medium reduces the reconstructed $\phi$ meson to 60-70% in Au+Au reactions at energies between $E_{kin} = 1.23$ A GeV and $\sqrt{s_{NN}} = 3$ GeV. In addition, $\phi$ yield rapidly increases from $E_{kin} = 1.23$ A GeV to $E_{kin} = 1.58$ A GeV, because both are sub-threshold energies for $\phi$ production.

Fig. 2 shows the $\phi/K^-$ ratio as a function of the collision energy from $E_{kin} = 1.23$ A GeV to $\sqrt{s_{NN}} = 200$ 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 $\phi/K^-$ ratio.

5 Summary

In this study we have investigated the hidden strangeness ($\phi$ 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 $\phi$ meson spectral function lead to an enhancement of $\phi$ meson production, especially at subthreshold energies.
and that the novel $mB \to \phi B$ channels from the SU(6) chiral Lagrangian in the T-matrix approach also enhance considerably the $\phi$ production in heavy-ion collisions.

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