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In-medium effects in ϕ-meson production in heavy ion collisions from subthreshold to relativistic energies

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Summary. — We investigate the hidden strange ϕ meson production in heavy-ion collisions from subthreshold ($E_{kin} \sim 1$ A GeV) to relativistic ($E_{kin} \sim 21$ A TeV) energies as well as its coupling to the open strange mesons (kaons, antikaons) and their productions. Our study is based on the off-shell microscopic Parton-Hadron-String Dynamics (PHSD) transport approach. 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. 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.

1. – Introduction

Understanding strangeness production in heavy-ion collisions has been a challenging subject in heavy-ion physics for several decades. Strangeness, being a newly generated flavor, emerges because the colliding nuclei initially consist of only "up" and "down" quarks. Given the initial system's strangeness neutrality, the production of s and $\bar{s}$

quarks occur in pairs, eventually manifesting in (anti-)strange mesons and baryons, or combining in mesons containing "hidden" strangeness, like the ϕ meson.

The comparison of experimental data of KaoS, FOPI, HADES collaborations for A+A collisions at beam energies of 1-2 A GeV for different observables (as multiplicities, rapidity and p_T-spectra as well as directed (v_1) and elliptic flow (v_2)) with theoretical transport calculations [1, 2]) showed the traces of in-medium modifications of the properties of (anti-)kaons as well as a sensitivity to the equation-of-state (EoS) of nuclear matter [1].

The HADES collaboration recently disclosed that ϕ mesons are produced in notable quantities in Au+Au collisions at subthreshold energies, with the ratio of hidden strangeness to open strangeness reaching approximately 0.5 [3]. This finding aligns with earlier observations from the FOPI collaboration [4, 5], which noted an enhanced ϕ production in Ni+Ni and Al+Al collisions at 1.93 A GeV. The ratio of hidden strangeness to open strangeness decreases to 0.2 with increasing beam energy, as measured by the STAR collaboration [6]. Furthermore, at high energies, the dependence of this ratio on collision energy is relatively mild, as indicated by studies from various collaborations including NA49 and E917 [7-11].

In this contribution we briefly recall the main findings from our recent study [12] which aims to demonstrate that the observed 'enhanced' multiplicity of ϕ mesons and the ϕ/K^- ratio near the threshold can be elucidated by incorporating a collisional broadening effect into the spectral function of the ϕ meson. Additionally, the investigation takes into consideration additional multi-step reactions involving meson-baryon and meson-hyperon interactions for the production of ϕ mesons, as predicted by the SU(6) extension of the meson-baryon chiral Lagrangian. This is accomplished within a unitary coupled channel T-matrix framework.

2. – Off-shell PHSD approach

Our study is based on the Parton-Hadron-String Dynamics (PHSD) [13-15] which is a microscopic covariant transport approach for the dynamical description of strongly interacting hadronic and partonic matter created in heavy-ion collisions. It is based on a solution of the Cassing-Juchem generalised off-shell transport equations for test particles [16] derived from the first-order gradient expansion of Kadanoff-Baym equations - cf. [17]. The PHSD differs from the semi-classical BUU model, since it propagates Green's functions (in phase-space representation) which contain information not only on the occupation probability (in terms of the phase-space distribution functions), but also on the properties of hadronic and partonic degrees-of-freedom via their spectral functions.

PHSD offers a comprehensive description of relativistic heavy-ion collisions, starting from the initial hard nucleon-nucleon interactions with subsequent string formation and decay, leading to the formation of a strongly interacting quark-gluon plasma (QGP), followed by hadronization and interactions within the expanding hadronic phase. This extends the earlier Hadron-String-Dynamics (HSD) transport approach [18] by incorporating in-medium effects such as collisional broadening of vector meson spectral functions and modifications of strange degrees of freedom, consistent with G-matrix calculations [19, 26]. Furthermore, PHSD implements detailed balance for $2 \leftrightarrow 3$ reactions, particularly in the primary channels of strangeness production/absorption involving baryons ($B = N, \Delta, Y$) and pions [26], as well as for multi-meson fusion reactions $2 \leftrightarrow n$ leading to the formation of $B + \bar{B}$ pairs.

3. – 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

$$\Gamma_\phi(M) \simeq \Gamma^{exp}_{\phi\to\rho\pi(3\pi)} \frac{\Gamma_{\phi\to\rho\pi(3\pi)}(M)}{\Gamma_{\phi\to\rho\pi(3\pi)}(M_0)} + \Gamma^{exp}_{\phi\to K\bar{K}} \left(\frac{M_0}{M}\right)^2 \left(\frac{q}{q_0}\right)^3 \theta(M-2m_K), \tag{2}$$

where M_0 is the vacuum pole mass of the vector meson spectral function and Γ^{exp}_i is the experimental decay width of channel i. q and q_0 are respectively the momenta of (anti)kaon for M and M_0 of ϕ mass in ϕ rest frame. Here $\Gamma_{\phi\to\rho\pi(3\pi)}(M)$ is the decay width of $\phi \to \rho\pi(3\pi)$, calculated in the effective chiral lagrangian with parity anomalous terms [21]. Γ_{coll} the collisional width approximated as

$$\Gamma_{coll}(M,|\vec{p}|,\rho) = \gamma\ \rho < v\ \sigma^{tot}_{VN} > \approx\ \alpha_{coll}\ \frac{\rho}{\rho_0}. \tag{3}$$

Here v is the velocity of the ϕ meson in the rest frame of the nucleon current, $\gamma^2 = 1/(1-v^2)$, ρ the nuclear density, $\rho_0 = 0.168$ 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 [20] with a coefficient α_{coll} which is taken to be 25 MeV [12].

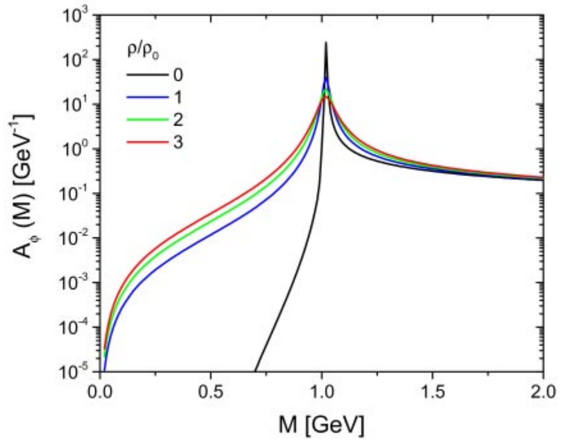

Fig. 1. – The spectral functions of ϕ mesons in the 'collisional broadening' scenario for nuclear densities of 0,1,2,3×ρ_0

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For the spectral function of a vector meson of mass M at baryon density ρ we take a Breit-Wigner form:

$$A_V(M,\rho) = C_1 \cdot \frac{2}{\pi} \, \frac{M^2\Gamma_V^*(M,\rho)}{(M^2 - M_0^{*2}(\rho))^2 + (M\Gamma_V^*(M,\rho))^2}\,, \tag{4}$$

where C_1 is fixed by the normalization condition for arbitrary ρ:

$$\int_{M_{min}}^{M_{lim}} A_V(M,\rho)dM = 1, \tag{5}$$

with $M_{lim} = 2$ GeV being chosen as an upper limit for the numerical integration. The lower limit for the vacuum spectral function is given by the two-pion decay, $M_{min} = 2m_\pi$ for a ρ meson and the three-pion decay, $M_{min} = 3m_\pi$ for a ϕ meson decay, whereas for the in-medium collisional broadening case by $M_{min} = 2m_e \to 0$ with m_e denoting the electron mass. M_0^* is the pole mass of the vector meson spectral function with $M_0^*(\rho = 0) = M_0$ in vacuum. The resulting spectral function of ϕ mesons is displayed in fig. 1 for the case of the 'collisional broadening' scenario for densities of 0,1,2, and 3 times ρ_0. Note that the hadronic width of ϕ mesons vanishes below the three-pion mass in vacuum. With increasing nuclear density the elastic and inelastic interactions of the vector mesons shift strength towards low invariant masses.

4. – 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 [22],

$$V_{ij}^{SIJ} = \varepsilon_{ij}^{SIJ} \frac{2\sqrt{s} - M_i - M_j}{4f_i f_j} \sqrt{\frac{E_i + M_i}{2M_i}} \sqrt{\frac{E_j + M_j}{2M_j}}, \tag{6}$$

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_{ij}^{SIJ} the degeneracy coefficient, corresponding to the scattering channel with $S, I,$ and J being total strangeness, isospin and angular momentum of the collision, respectively [23, 24]. The T-matrix approach can be formulated on the basis of the Born scattering amplitude V_{ik}^{SIJ},

$$T_{ij}^{SIJ} = V_{ij}^{SIJ} + V_{ik}^{SIJ} G_{kk}^{SIJ} T_{kj}^{SIJ}, \tag{7}$$

where k is the intermediate meson-baryon state and the sum is performed over all possible states. G_{kk}^{SIJ} is the product of the meson and baryon propagators of the state k [25], which is renormalized such that $G_{kk}^{SIJ}(s = m_N^2 + m_\pi^2) = 0$ with m_N and m_π being nucleon and pion masses, respectively. The channels considered in this study for ϕ meson production are $\eta N,\ K\Lambda,\ K\Sigma,\ \rho N,\ K\Sigma^*,\ \rho\Delta,\ K^*\Lambda,\ K^*\Sigma,\ K^*\Sigma^* \to \phi N$ for $I = 1/2$ and $K\Sigma,\ \rho N,\ \eta\Delta,\ K\Sigma^*,\ \rho\Delta,\ K^*\Sigma,\ K^*\Sigma^* \to \phi\Delta$ for $I = 3/2$, including their inverse reactions by detailed balance.

Figure 2 depicts the ϕ production cross sections of the mB channels for ϕN (left) and $\phi\Delta$ (right), computed within the T-matrix approach. For simplicity, all resonances

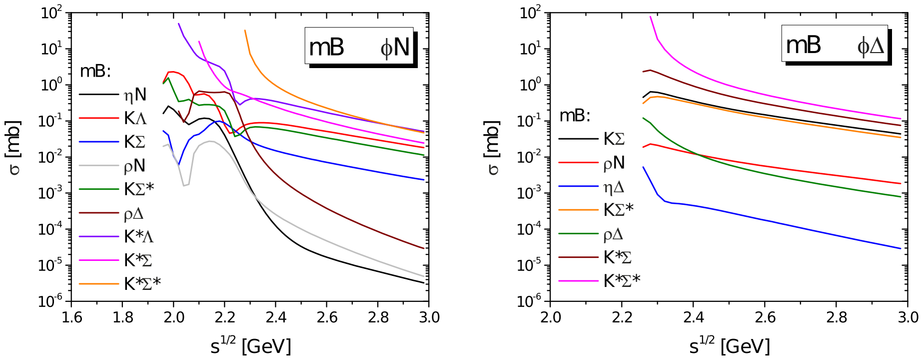

Fig. 2. – Cross sections of the mB channels for ϕN production (left) and for $\phi\Delta$ production (right), calculated in the T-matrix approach. All resonances here are taken with their pole mass.

are considered with their pole mass. It's evident that these cross sections exhibit a pronounced flavor dependence. Channels involving initial strange mesons and hyperons dominate due to the OZI-rule. However, in heavy-ion collisions, the relative contribution of different mB channels is dictated by the abundances of secondary hadrons participating in ϕ production. Since η mesons are more abundant than K^*, their scattering with nucleons is more probable than K^* scattering with strange baryons $\Lambda, \Sigma, \Sigma^*$, even if the ηN cross section is smaller than that for K^*Y.

5. – ϕ meson production in heavy-ion collisions

The in-medium effects on open strange mesons, including a repulsive potential for kaons and density- and temperature-dependent complex self-energies for antikaons derived from the G-matrix approach, result in significant modifications to the yield and spectra of (anti-)kaons, as previously explored in our research [26]. These effects also influence the final observables of ϕ mesons. Specifically, they lead to a reduction in the reconstructed ϕ mesons due to a decrease in the number of K^+ and an increase in the rescattering of K^- induced by the in-medium effects.

Figure 3 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 [26]. The dashed red lines indicate the ϕ rapidity distributions 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 $Br(\phi \to K^+K^-)$. 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 fig. 4 for 4 rapidity bins the m_T spectra of reconstructed ϕ mesons in 0-10 % (left) and 10-40 % (right) central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 3$ GeV in comparison with experimental data from the STAR collaboration [6]. The PHSD calculations approximately reproduce the slope of the m_T spectra of ϕ mesons. One can see again that the influence of in-medium effects for $K, \bar{K}$ mesons is relatively small as explained above.

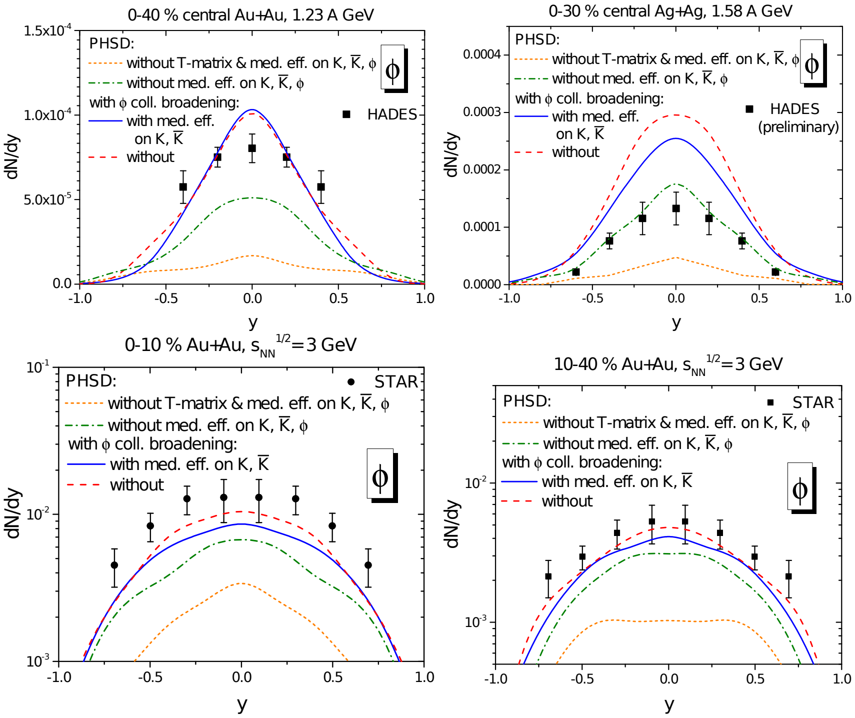

Fig. 3. – Rapidity distribution of reconstructed ϕ mesons in 0-40 % central Au+Au collisions at $E_{kin} = 1.23$ A GeV, in 0-30 % central Ag+Ag collisions at $E_{kin} = 1.58$ A GeV and 0-10 % and 10-40 % central Au+Au collisions at $\sqrt{s_{\rm NN}}$ =3 GeV, compared with experimental data from the HADES and STAR collaborations [3, 6]. Each colored line is explained in the text.

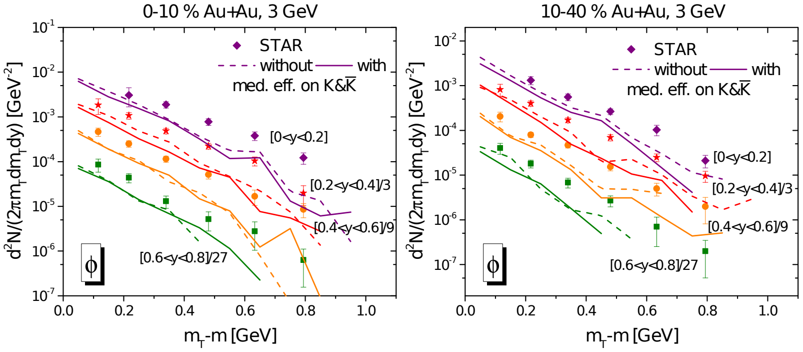

Fig. 4. – m_T spectra of reconstructed ϕ mesons in 0-10 % (left) and 10-40 % (right) central Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 3 GeV in comparison with experimental data from the STAR collaboration [6]. The number of ϕ mesons, reconstructed from K^+K^- pairs, is divided by the branching ratio $Br(\phi \to K^+K^-)$. The calculations are done with the collisional broadening of ϕ mesons and presented for 4 rapidity bins $0 \le y \le 0.2$, $0.2 \le y \le 0.4$ scaled by a factor 1/3 for better visualization, $0.4 \le y \le 0.6$ scaled by a factor 1/9 and $0.6 \le y \le 0.8$ scaled by a factor 1/27. The dashed lines show the results without in-medium effects for $K, \bar{K}$ mesons, while the solid lines that with in-medium modifications of $K, \bar{K}$ mesons.

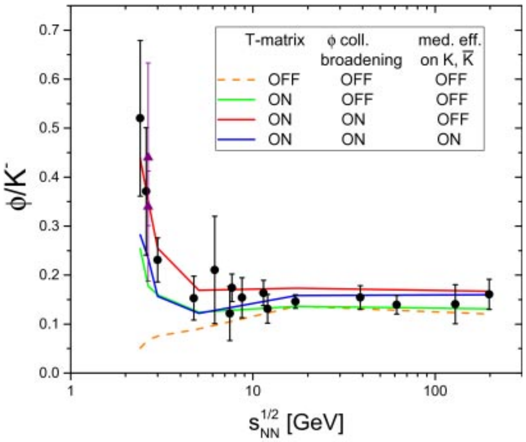

Fig. 5. – The PHSD results for the ratio ϕ/K^- at midrapidity ($|y| \leq 0.3$) as a function of the collision energy for four different scenarios: with and without novel mB channels for the ϕ meson production from the T-matrix approach and with and without the collisional broadening of the ϕ meson width and in-medium effects on (anti-)kaons (cf. the legend). The solid symbols show the compilation of the experimental data from refs. [5-11].

Figure 5 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. 3. An inclusion of the in-medium effects for $K, \bar{K}$ leads to a strong enhancement of the K^- yield [26] and, as a result, to a reduction of the ϕ/K^- ratio.

6. – Summary

In this study, we explored the production of hidden strangeness, focusing on the generation of ϕ mesons in heavy-ion collision from subthreshold to relativistic energies. We employ the microscopic off-shell PHSD transport approach, which is based on the off-shell Kadanoff-Baym equations, which allows for a consistent transport of the ϕ meson in the dense matter which is created in heavy ion reactions.

We observed that introducing a collisional broadening effect to the spectral function of ϕ mesons resulted in a notable increase in their production, particularly evident at subthreshold energies. Additionally, our investigation revealed that the incorporation of novel $mB \to \phi B$ channels, arising from the $SU(6)$ chiral Lagrangian within the T-matrix framework, significantly augmented the production of ϕ mesons in heavy-ion collisions.

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