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K* dynamics in heavy ion collisions

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Abstract. The dynamics of strange vector meson resonances (K^* and $\bar{K}^*$) is investigated within the Parton-Hadron-String Dynamics (PHSD) transport approach. We present the time evolution of the production of K^{*-} resonances from the QGP phase by quark fusion as well as from hadronic sources. We also give a brief overview of the modification of the K^* through $K\pi$ decay and K^*N interaction in a hot and dense nuclear medium.

1 Introduction

Strongly interacting matter at finite temperatures and densities has been a subject of great interest for a long time. There was especially a large focus on strange/anti-strange matter in the last few decades. Our goal is to investigate the in-medium resonance dynamics of the K^* (K^* refers to both the K^{*+} and K^{*-} meson and the neutral state ones, K^{*0} and $\bar{K}^{*0}$) vector resonance within the Parton-Hadron-String Dynamics (PHSD) approach. There are several reasons for the focus on the K^*. The K^* acts as a probe for the QGP production and freeze-out of the system. Furthermore, K^*s are modified in the medium to various degrees, e.g. a $\bar{K}^*$ is strongly modified in a dense nuclear medium [1] while a K^* in a hot nuclear medium is modified very little [2].

Experimentally it is not possible to measure the K^* directly. The K^* is a broad particle and therefore has a short lifetime, i.e. it decays before it reaches the detector. The primary decay channel of the K^* is the decay into a K and a π. Since these particles can be detected, the information on the K^* can be obtained indirectly through reconstruction via the $K^* \to K\pi$ channel. However, additional problems are posed by the rescattering of the $K(\bar{K})$ and π daughter particles. They can either scatter elastically or be reabsorbed. Furthermore the $K/\bar{K}$ and the π are also modified by the medium [3–6], which further distorts the signal from the initial decay reaction.

In this work we give an overview of the production of strangeness in PHSD [7] and present the time evolution of the various channels contributing to the production of the K^*. Furthermore, we characterise the mechanism responsible for the modification of the K^* in hot and dense nuclear media in terms of realistic K and $\bar{K}$ in-medium spectral functions and the K^*N interaction.

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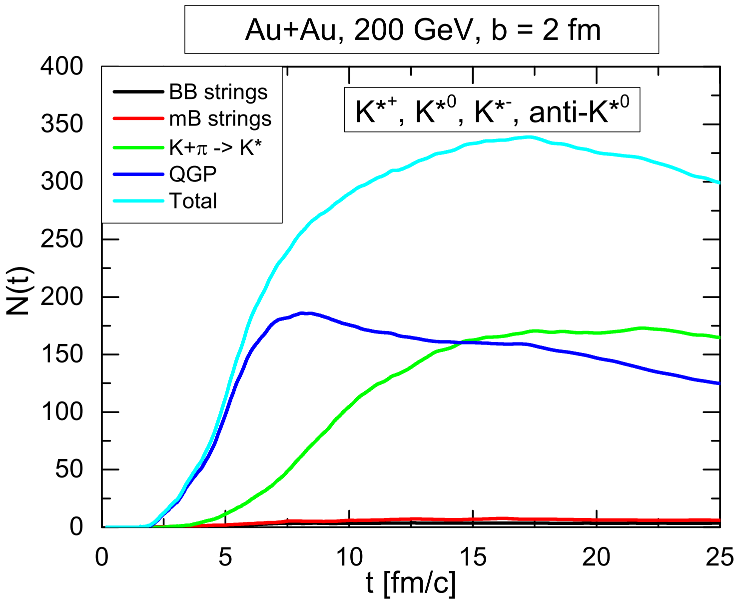

Figure 1. The number of all K^* mesons as a function of the time t for a central (impact parameter $b = 2$ fm) collision integrated over all y in a $Au + Au$ system at $E = 200$ GeV energy in the centre of mass system. The light blue solid line is the number of all mesons while the other lines show the channel decomposition of the K^*s. The red solid and the black solid lines show the number of K^*s coming from meson-baryon and baryon-baryon strings, respectively, the green solid line corresponds to the number of K^*s coming from $K + \pi$ collisions and the dark blue solid line is showing the number of K^*s coming directly from the QGP.

2 K^* production in PHSD

The production of the K^* in PHSD is accomplished through various mechanisms. Figure 1 shows the channel decomposition for the K^{*+}, K^{*0}, K^{*-} and $\bar{K}^{*0}$ production as a function of time for a central (impact parameter $b = 2$ fm) $Au + Au$ collision for all rapidities y at a centre of mass energy of $E = 200$ GeV.

There is a small fraction of K^* which come from primary baryon-baryon string excitations which occur in the peripheral region of the central reaction or from secondary energetic meson-baryon collisions. Most of the K^*s come directly from the QGP phase via quark fusion (i.e. $u + \bar{s} \to K^{*+}$, $d + \bar{s} \to K^{*0}$, $\bar{u} + s \to K^{*-}$, $\bar{d} + s \to \bar{K}^{*0}$) and from the scattering of kaons and pions through the $\bar{K}(K)\pi \to \bar{K}^*(K^*)$ channel until the $\bar{K}(K)\pi$ channel becomes dominant. A major part of all produced K^*s thus comes from $\pi + K(\bar{K})$ that suffer from absorption and elastic/inelastic rescattering effects.

The dynamics of strange mesons is strongly dependent on the in-medium effects in a dense or hot nuclear medium and to model properly the behaviour of K, K^* mesons in nuclear matter these effects need to be accounted for.

3 Modification of the K^* in a medium

The in-medium properties of the K^* are characterized by the K^* spectral function, which can be written in a relativistic Breit-Wigner form as

$$A_i(M,\rho_N) = C_1\,\frac{2}{\pi}\,\frac{M^2\,\Gamma_i^*(M,\rho_N)}{\left(M^2 - M_i^{*2}(\rho_N)\right)^2 + \left(M\,\Gamma_i^*(M,\rho_N)\right)^2}\,, \tag{1}$$

where C_1 is the normalisation constant which is determined in such a way that the spectral function fulfils the sum rule $\int_0^\infty A_i(M,\rho_N)\,dM = 1$, and $i = K/\bar{K}, K^*/\bar{K}^*$. Eq. (1) carries an explicit dependence on the nuclear density ρ_N of the medium for baryon rich systems, which should be replaced by a dependence on the temperature in the case of a hadronic gas. Medium effects are implemented by solving the strange meson (off-shell) dispersion relation, $E^2 - |\vec{p}\,|^2 - M_i^2 - \mathrm{Re}\Pi_i = 0$, where the width and the mass shift of the spectral function are related to the imaginary and the real part of the meson self-energy, respectively:

$$\mathrm{Re}\,\Pi_i(M_i,\rho_N) = (M_i^*)^2 - M_i^2\,, \quad \mathrm{Im}\,\Pi_i(M_i,\rho_N) = -M_i\,\Gamma_i^*(M_i,\rho_N)\,. \tag{2}$$

We shall distinguish between two different scenarios, namely dense nuclear matter ($\mu_B \neq 0$, $T \simeq 0$) and hot hadronic matter ($\mu_B \simeq 0$, $T \neq 0$).

For the $\bar{K}^*$ in a dense nuclear medium the major effects come both from the $\bar{K}\pi$ decay channel, where the $\bar{K}$ is largely modified [3–5], and from the highly inelastic $\bar{K}^*N$ interaction [1], leading to decay widths as large as 200 MeV at normal matter density ρ_0. The K^* interaction with the medium is much more moderate. The contribution of the $K\pi$ decay channel to the K^* width reads

$$\Gamma_{V,\mathrm{dec}}(\mu,\rho_N) = \Gamma_V^0\left(\frac{\mu_0}{\mu}\right)^2 \frac{\int_0^{\mu-m_\pi} q^3(\mu,M)\,A_j(M,\rho_N)\,dM}{\int_{M_{\mathrm{min}}}^{\mu_0-m_\pi} q^3(\mu_0,M)\,A_j(M,0)\,dM}\,, \tag{3}$$

$$q(\mu,M) = \frac{\sqrt{\lambda(\mu,M,m_\pi)}}{2\mu}\,, \quad q(\mu_0,M) = \frac{\sqrt{\lambda(\mu_0,M,m_\pi)}}{2\mu_0}\,,$$

with $\Gamma_V^0 = 42$ MeV ($V = K^*$ and $j = K$ here), μ (M) being the invariant mass of the K^* (K) and λ the Källen function. The scattering of the K^* with nucleons is elastic at low energies and has been evaluated recently in a chiral Lagrangian framework [2], extended to the octet of vector mesons in the Hidden Local Symmetry approach (see also [1] and references therein). The resulting K^* self-energy, calculated in a $t\rho$ approximation, leads to a mildly repulsive K^* mass shift of about 5% (30 MeV) at $\rho_N = \rho_0$.

Since the kaon becomes slightly heavier in the medium (at normal densities) as a result of the repulsive KN interaction, the width of the K^* nominally decreases when increasing the density. However, the repulsive self-energy from the K^*N interaction compensates this effort and the K^* spectral function only reflects a moderate shift in energy (and negligible changes in shape) from strangeness related mechanisms.

In a hot nuclear medium, which we identify with a pion gas, the dynamics does not distinguish between K and $\bar{K}$ mesons, and consequently the K^* and $\bar{K}^*$ experience identical effects. The vector-meson decay width is calculated from Eq. (3) by using the results in [6] for the $K/\bar{K}$ self-energy in a pion medium, evaluated in leading order chiral perturbation theory. We also estimate the real part of the K^* self-energy (i.e. the mass shift) from a dispersion relation over the imaginary part,

$$\mathrm{Re}\,\Pi_{K^*}(\mu,T) - \mathrm{Re}\,\Pi_{K^*}(\mu,0) = -\frac{2}{\pi}\int_{M_\pi}^{\infty}\frac{\mu'^2}{\mu'^2-\mu^2}\left[\Gamma^*_{K^*,\mathrm{dec}}(\mu',T) - \Gamma^{\mathrm{vac}}_{K^*}(\mu')\right]\,d\mu'\,, \tag{4}$$

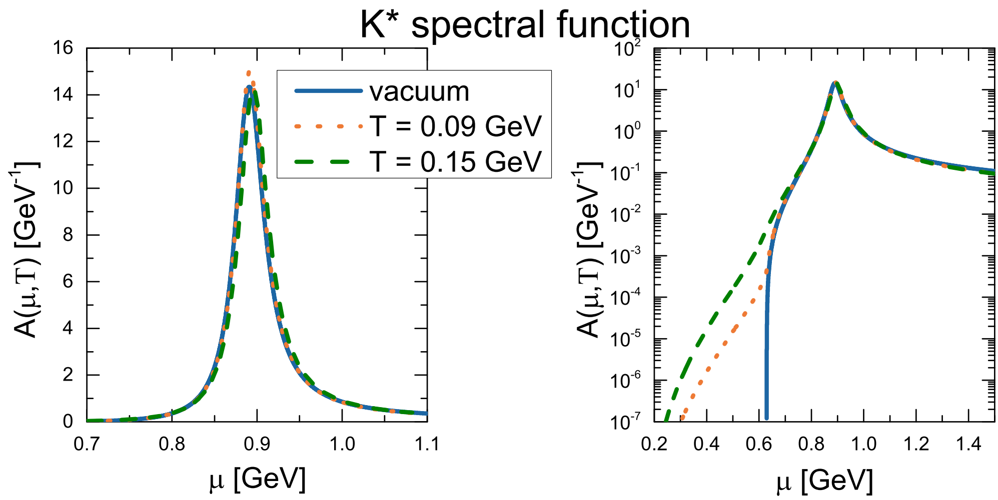

Figure 2. The K^* spectral function (left: linear scale; right: logarithmic scale) is plotted as a function of the invariant mass μ for different temperatures T for a hot, pionic medium. The blue solid line denotes the vacuum spectral function while the orange dotted line denotes a temperature of $T = 0.09$ GeV and the green dashed line denotes a temperature of $T = 0.15$ GeV.

regularized by subtraction of the vacuum part and a suitable hadronic form factor.

The resulting spectral function can be seen in Fig. 2. Within the temperature range explored here, the K^* in hot matter experiences only small medium effects and its spectral function differs little from the vacuum one at the peak of the resonance. However, one finds additional strength in the low mass region, particularly below the nominal $K\pi$ threshold, originating from broader and slightly lighter kaon modes.

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