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Hadronic Spectral Function and Charm Meson Production

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Abstract. At the chiral restoration/deconfinement transition, most hadrons undergo a Mott transition from being bound states in the confined phase to resonances in the deconfined phase. We investigate the consequences of this qualitative change in the hadron spectrum on final state interactions of charmonium in hot and dense matter, and show that the Mott effect for D-mesons leads to a critical enhancement of the J/ψ dissociation rate. Anomalous J/ψ suppression in the NA50 experiment is discussed as well as the role of the Mott effect for the heavy flavor kinetics in future experiments at the LHC. The status of our calculations of hadron-hadron cross sections using the quark interchange and chiral Lagrangian approaches is reviewed, and an Ansatz for a unification of these schemes is given.

Keywords: J/ψ suppression, Mott effect, Quark-Gluon Plasma, Charm Mesons
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1. Introduction

Charmonium states, in particular the J/ψ meson, play a key role in the experimental search for the quark-gluon plasma (QGP) in ultrarelativistic heavy-ion collisions. The anomalous suppression of J/ψ production found in 158 AGeV Pb-Pb collisions at the CERN SPS by the NA50 collaboration [1] seems to be the signal of QGP formation, as originally suggested by Matsui and Satz [2]. Since the first observation of J/ψ suppression in nucleus-nucleus collisions by the NA38 collaboration [3] a debate has been started whether this observation proves QGP formation or whether it can be understood in terms of more conventional hadronic absorption mechanisms on projectile/ target nucleons [4] and comoving hadrons formed in the collision [5,6]. So, there is a need for a refinement and extension of the experimental information as well as for a unifying theoretical approach which can consistently account for the complexity of the processes in high-energy hadronic collisions in a description based on quark and gluon substructure, including aspects of the QGP phase transition.

In the present contribution we will consider the characteristic energy dependence of the J/ψ dissociation cross section in collision with light hadrons in the constituent quark model, as well as considering their dissociation into $q\bar{q}$ resonances at the chiral/deconfinement phase transition (Mott effect).

2. Quark substructure effects in meson-meson scattering

In Fig. 1 we illustrate diagrammatically the relation between (a) the quark interchange model (QIM) and (d) the chiral Lagrangian model (CLM) of meson-meson scattering. Both approaches can be considered as limiting cases of a more general chiral quark model (CQM) approach (c). After the first calculation of J/ψ dissociation due to pion and rho-meson impact within the CLM [7], several improvements have been suggested, in particular the use of a global form factor in order to account for the finite size of the interaction vertex [8–10]. From the point of view of the unifying CQM [11], however, the contact terms and the meson exchange terms of the CLM should not have identical form factors since they are composed of a different number of corresponding meson-quark-antiquark vertices so that the relative importance of these subprocesses will depend on the actual parametrization [12,13]. It is unsatisfactory that these approaches depend strongly on the rather arbitrary definition of the form factor, see Fig. 2 for a comparison. The correspondence of CLM and QIM [14,15] results for the J/ψ dissociation cross section, Fig. 3 and Refs. [12, 13, 16], which can be considered as a heuristic constraint on the choice of the form factors, is yet accidental. Although the dependence of $\sigma(s; M_{D_1}, M_{D_2})$ on the D-meson masses in both approaches is qualitatively similar and will be important for our definition of the in-medium dissociation cross section, the dependence on the size parameters $\Lambda_h^{-1} \propto \sqrt{\langle r^2 \rangle_h}$ of the mesons predicted by the two approaches differ. Whereas the QIM cross section approximately reproduces [14] the phenomenological Povh-Hüfner law [17] $\sigma \propto \langle r^2 \rangle_{h_1} \langle r^2 \rangle_{h_2}$ for the processes considered here, the CLM cross section does not. This discrepancy may indicate the necessity of including

hadronic form factors in the CLM; this possibility is currently under investigation [18].

3. Spectral properties of mesonic states at finite T

Mesons are not elementary objects. In some models light mesons such as the ρ and the light "σ-meson" effect can be viewed either as quark-antiquark bound states or as resonances of the $\pi - \pi$ interaction in the corresponding channel. The total spectral width $\Gamma_\sigma(T)$ of the σ-meson, e.g., shows a minimum correlated with the chiral restoration phase transition in the phase diagram of strongly interacting matter [19] since the hadronic decay width $\Gamma_{\sigma\to 2\pi}$ is already negligible but the decay width $\Gamma_{\sigma\to q\bar{q}}$ is still small. The transition from a bound state with vanishing decay width (infinite lifetime) to a resonance in the continuum of unbound states is called the Mott transition [20] and can be described by the behaviour of the spectral function

$$A_h(s;T) = \frac{1}{N}\frac{\Gamma_h(T)\ M_h(T)}{[s - M_h^2(T)]^2 + \Gamma_h^2(T)\ M_h^2(T)}\ , \tag{1}$$

where $\Gamma_h(T)$ and $M_h(T)$ are the temperature dependent width and mass parameter of the hadron h. An introduction into critical phenomena related to the Mott transition for mesons at the chiral/ deconfinement transition within the NJL model for quark matter can be found in [21]. It has been found within this model that the Mott transition temperature for D mesons almost coincides with that for π and K mesons [22]. In order to obtain the parameters of the spectral function (1) for the light and charm mesons, we use a modified NJL model with infrared confinement (no unphysical quark production thresholds) [23], see Fig. 4, and compare to a fit with linear T-dependence of mass and width [24] above the Mott temperature. In the following, we investigate the consequences of the meson Mott effect for charmonium production.

4. Reaction rates for charmonium dissociation

The inverse lifetime of a charmonium state due to collisions with light hadrons $h = \pi, \rho$ is given by $\tau^{-1} = \tau_\pi^{-1} + \tau_\rho^{-1}$ with [24]

$$\begin{aligned} \tau_h^{-1}(T) &= \int \frac{d^3p}{(2\pi)^3} \int ds' A_h(s';T) f_h(p,s';T) j_h(p,s') \sigma_h^*(s;T) \\ &= \langle \sigma_h^* v \rangle n_h(T)\ , \end{aligned} \tag{2}$$

where $f_h(p,s';T)$ is the Bose distribution function with the energy argument $E(p,s') = \sqrt{p^2+s'}$, $j_h(p,s)$ is the flux factor for $(c\bar{c})$-h collisions, and $\sigma_h^*(s;T)$ is the in-medium dissociation cross section

$$\sigma_h^*(s;T) = \int\ ds_1\ ds_2\ A_{D_1}(s_1;T) A_{D_2}(s_2;T)\ \sigma_h(s;s_1,s_2)\ , \tag{3}$$

which is displayed in Fig. 5 for the spectral function fit of Ref. [24] as well as modified NJL model result of Fig. 4 (for $h = \pi$ we omit the subscript). In both cases the Mott effect for the D-meson final states entails a lowering of the threshold for the dissociation process. In Fig. 6 we show that the D-meson Mott effect leads to a strong enhancement in the thermal averaged dissociation cross section, i.e. in the inverse lifetime of the J/ψ, which is quite sensitive to the details of the temperature dependence of the D-meson spectral function. This effect could be a key to understanding the physical mechanism of anomalous J/ψ suppression [1] and fast chemical equilibration [25] in the CERN NA50 experiment. The role of the Mott effect in the D-$\bar{D}$ recombination rate (D-$\bar{D}$ fusion) merits further investigation.

5. Discussion of other processes

In the QGP (and in the mixed phase), due to the presence of quasifree quarks and gluons, new channels for charmonium formation and dissociation exist which could drive chemical equilibration during the existence of the fireball formed in the heavy-ion collision. This possibility has been considered within the statistical hadronization approach [25, 26] and seems to give appreciable contributions to J/ψ production even under SPS conditions [27]. A satisfactory description of the ψ'/ψ ratio however requires an increase in the ψ' dissociation rate, perhaps due to medium modification of the D-meson threshold [27] as provided for example by the Mott-effect scenario in the present approach [24]. The role of partonic in-medium effects in charmonium kinetics in a QGP, which has previously been discussed in the string-flip model of quark matter in the form of a modified mass action law [28] and dissociation rate [29], should be reconsidered. We anticipate that rate coefficients for the ionization and recombination of charm mesons could be described using an approach similar to methods used previously to study Coulomb plasmas [20, 30].

6. Conclusions

A detailed description of quark substructure and $q\bar{q}$ wavefunctions is is essential for the understanding of the behaviour of meson-meson cross sections in the vacuum as well as modifications in dense matter. We have shown that due to the Mott effect for D-mesons at the QGP phase transition a reduction of the threshold for charmonium dissociation occurs, which leads to a strong enhancement in the dissociation rate and a drop in the J/ψ lifetime. Important features of this approach are the off-mass-shell behaviour of the charmonium dissociation cross section and the hadronic spectral function, which we calculate using a modified NJL model. The approximate agreement in scale we find between the CLM and QIM dissociation cross sections must be considered something of an accident, since the QIM model cross section varies roughly according to the Povh-Hüfner law for these processes, whereas the CLM does not. A unifying microscopic approach at the quark-gluon level can hopefully be developed which will lead to additional insight into the use of charm

(and bottom) production in heavy ion collisions as a diagnostic tool for hot and dense matter.

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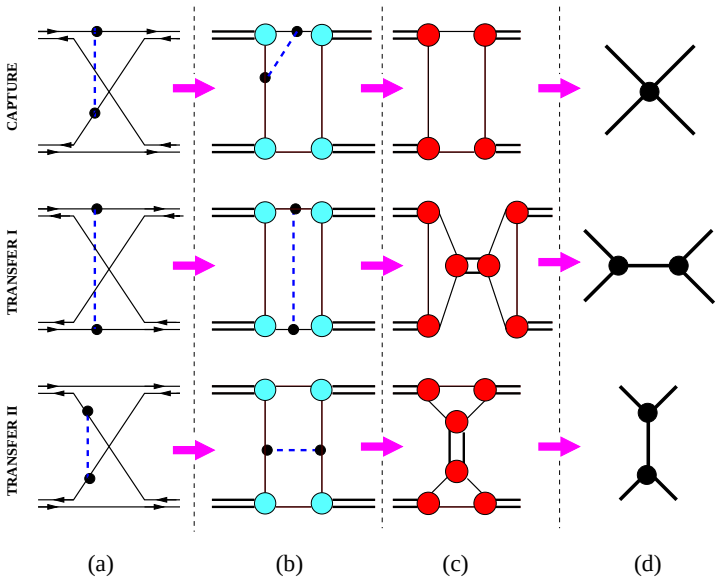

Fig. 1. Diagrammatic scheme of the relation between the quark interchange model (a) and the chiral Lagrangian approach (d) of meson-meson scattering. Both approaches can be viewed as limits of a more general chiral quark model approach (c). The transition (c) $\rightarrow$ (d) is a local limit in which the meson-quark-antiquark vertices are replaced by coupling constants and the momentum dependence of the quark propagators is dropped. The transition (c) $\rightarrow$ (a) is for the two lower lines (transfer diagrams) a replacement of the meson propagator by a single interaction (1st Born approximation) and for the first line (capture diagram) a first iteration of the meson-quark-antiquark vertex function using the Bethe-Salpeter equation.

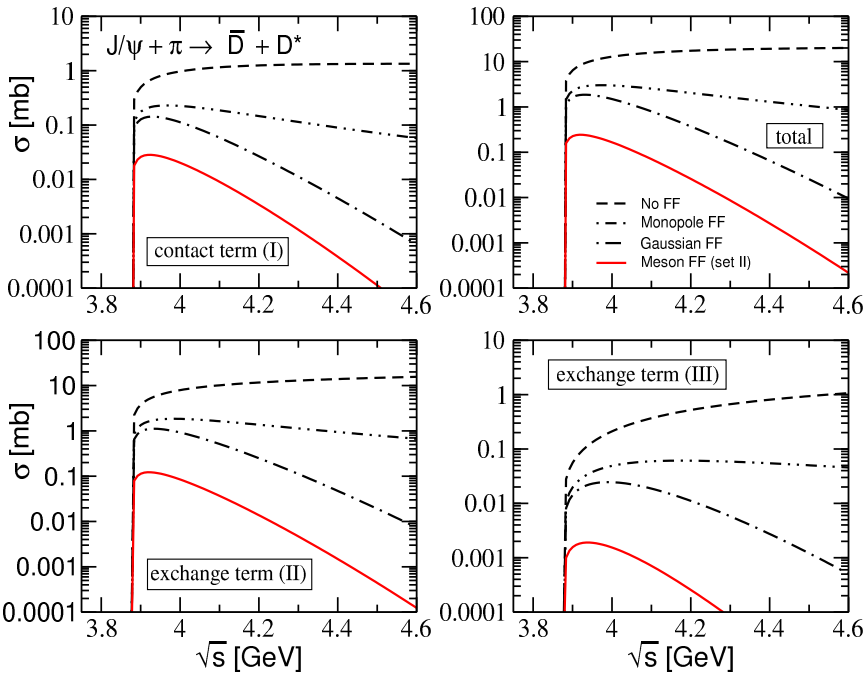

Fig. 2. Cross section for charmonium dissociation in the chiral Lagrangian approch with mesonic form factors [12] compared to the global form factors of Refs. [8, 9].

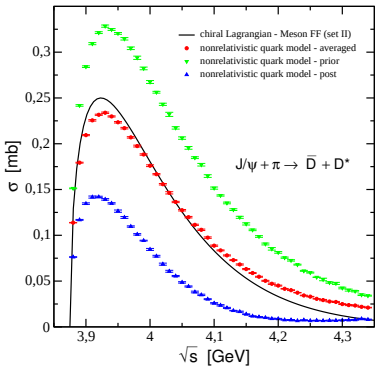

Fig. 3. Comparison of cross sections for chiral Lagrangian model with mesonic form factors [12] and quark interchange model [15].

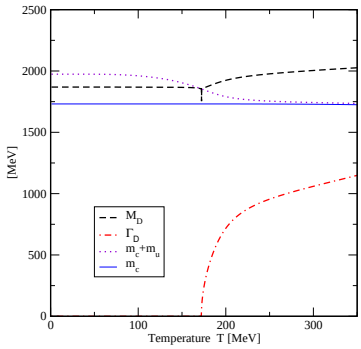

Fig. 4. D-meson mass and width at finite temperature from the NJL model with infrared cutoff of Ref. [23].

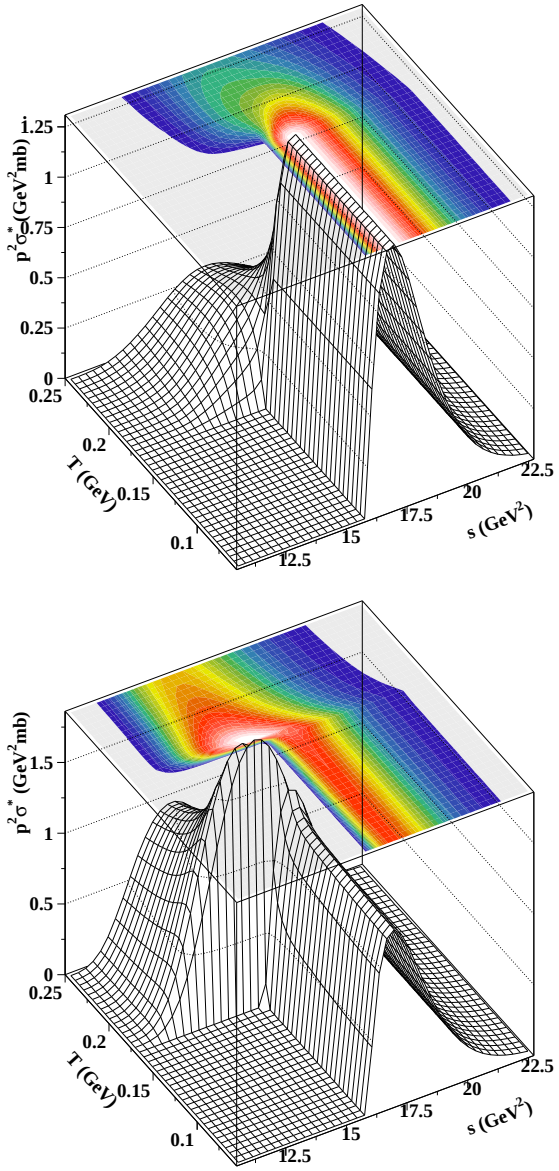

Fig. 5. In-medium cross section for $J/\psi + \pi \to D + \bar{D}^{*}$ with the spectral function from [24] (upper plot) and from [23] (lower plot).

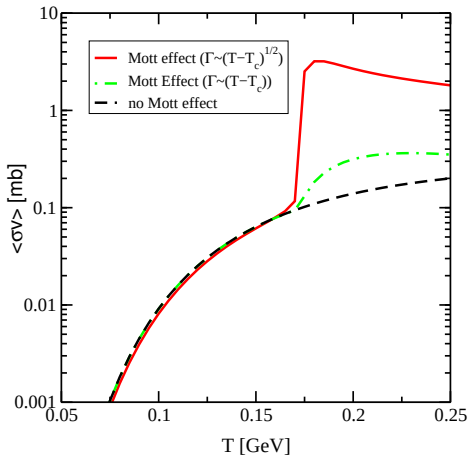

Fig. 6. Thermal average of the J/ψ dissociation cross section without Mott effect for the D- mesons (dashed line), with Mott effect and spectral function of Ref. [24] (dash-dotted line), and of Ref. [23] (solid line).