Mott effect at the chiral phase transition and anomalous $J/\psi$ suppression

Gerhard R.G. Burau, a David B. Blaschke, a 
and Yuri L. Kalinovsky b

a Fachbereich Physik, Universität Rostock, D-18051 Rostock, Germany 
b Laboratory of Information Technologies, JINR, 141980 Dubna, Russia

Abstract

We investigate the in-medium modification of the charmonium break-up process due to the Mott effect for light ($\pi$) and open-charm ($D, D^*$) mesons at the chiral/deconfinement phase transition. A model calculation for the process $J/\psi + \pi \rightarrow D + D^* + h.c.$ is presented which demonstrates that the Mott effect for the D-mesons leads to a threshold effect in the thermal averaged break-up cross section. This effect is suggested as an explanation of the phenomenon of anomalous $J/\psi$ suppression in the CERN NA50 experiment.

Key words: $J/\psi$ suppression, bound state dissociation, Mott effect

1 Introduction

Recent results of the CERN NA50 collaboration on anomalous $J/\psi$ suppression [1] in ultrarelativistic Pb-Pb collisions at 158 AGeV have renewed the quest for an explanation of the processes which may cause the rather sudden drop of the $J/\psi$ production cross section for transverse energies above $E_T \sim 40$ GeV in this experiment. An effect like this was predicted as a signal for quark gluon plasma formation [2] due to screening of the $c\bar{c}$ interaction. Soon after that it became clear that for temperatures and densities just above the deconfinement transition the Mott effect for the $J/\psi$ does not occur and that a kinetic process is required to dissolve the $J/\psi$ [3] in a break-up process by impact of thermal photons [4], quarks [5], gluons [6] or mesons [7,8].

In this paper, we suggest that at the chiral/deconfinement phase transition the charmonium break-up reaction cross sections are critically enhanced since
the light and open-charm mesonic states of the dissociation processes become unbound (Mott effect) so that the reaction thresholds are effectively lowered. We present a model calculation for the particular process $J/\psi + \pi \rightarrow D + \bar{D}^* + h.c.$ in a hot gas of resonant (unbound but correlated) quark-antiquark states in order to demonstrate that the Mott dissociation of the final states (D-mesons) at the chiral phase transition leads to a threshold effect for the in-medium $J/\psi$ break-up cross section and thus the survival probability.

2 In-medium modification of charmonium break-up cross sections

The inverse lifetime of a charmonium state in a hot and dense many-particle system is given by the imaginary part of its selfenergy

$$\tau^{-1}(p) = \Gamma(p) = \Sigma^>(p) - \Sigma^<(p) .$$  \hspace{1cm} (1)

$$\Sigma^>(p) = \int \int \int (2\pi)^4 \delta_{p,p',p_1,p_2} |M|^2 G^>(p') \ G^>_{D_1}(p_1) \ G^>_{D_2}(p_2) ,$$  \hspace{1cm} (2)

where the thermal Green functions $G^>(p) = [1 + f_i(p)]A_i(p)$ and $G^<(p) = f_i(p)A_i(p)$ are defined by the spectral function $A_i(p)$ and the distribution function $f_i(p)$ of the bosonic state $i$; with the notation $\int_p = \int \frac{d^4p}{(2\pi)^4}$, $\delta_{p,p',p_1,p_2} = \delta(p + p' - p_1 - p_2)$. 

Fig. 1. Diagrammatic representation of the complex selfenergy for the $J/\psi$ due to break-up in (off-shell) $D, \bar{D}^*$ pairs by impact of (off-shell) pions from a hot medium.
In the low density approximation for the final states \( f_D(p) \approx 0 \), one can safely neglect \( \Sigma^<(p) \) so that

\[
\tau^{-1}(p) = \int \int \int (2\pi)^4 \delta_{p,p';p_1,p_2} |M|^2 f_\pi(p') A_\pi(p') A_{D_1}(p_1) A_{D_2}(p_2). \quad (3)
\]

With the differential cross section

\[
\frac{d\sigma}{dt} = \frac{1}{16\pi} \frac{|M(s,t)|^2}{\lambda(s, M_{\psi}^2, s')}, \quad (4)
\]

using \( s = (p + p')^2 \), \( t = (p - p_1)^2 \), \( s' = p'^2 \) and \( \lambda(s, M_{\psi}^2, s') = [s - (M_\psi + \sqrt{s'})^2][s - (M_\psi - \sqrt{s'})^2] = 4 v_{\text{rel}}^2 [p^2 + M_{\psi}^2][p'^2 + s'] \) one can show that the \( J/\psi \) relaxation time in a hot pion as well as pionic resonance gas is given by

\[
\tau^{-1}(p) = \int \frac{d^3p'}{(2\pi)^3} \int ds' f_\pi(p', s') A_\pi(s') v_{\text{rel}} \sigma^*(s), \quad (5)
\]

where depending on the properties of the medium the pion spectral function describes either \( \bar{q}q \) bound states or resonant (off-shell) correlations. The in-medium break-up cross section is given by

\[
\sigma^*(s) = \int ds_1 ds_2 A_{D_1}(s_1) A_{D_2}(s_2) \sigma(s; s_1, s_2). \quad (6)
\]

Note that there are two kinds of medium effects due to (i) the spectral functions of the final states and (ii) the explicit medium dependence of the matrix element \( M \). In the following model calculation we will use the approximation \( \sigma(s; s_1, s_2) \approx \sigma^{\text{vac}}(s; s_1, s_2) \) justified by the locality of the transition matrix \( M \) which makes it rather inert against medium influence.

### 3 Model calculation

The quark exchange processes in meson-meson scattering can be calculated within the diagrammatic approach of Barnes and Swanson [10] which allows a generalization to finite temperatures in the thermodynamic Green function technique [11]. This technique has been applied to the calculation of \( J/\psi \) break-up cross sections by pion impact in [8]. The approach has been extended to excited charmonia states and consideration of rho-meson impact...
recently [12]. The generic form of the resulting cross section (given a band of uncertainty) can be fit to the form

$$\sigma^\text{vac}(s; M_{D_1}^2, M_{D_2}^2) = \sigma_0 \ln(s/s_0) \exp(-s/\lambda^2) , \quad s \geq s_0 , \quad (7)$$

where $s_0 = (M_{D_1} + M_{D_2})^2$ is the threshold for the process to occur, $\sigma_0 = 7.5 \cdot 10^9$ mb and $\lambda = 0.9$ GeV.

Recently, the charmonium dissociation processes have been calculated also in an effective Lagrangian approach [13,14], but the freedom of choice for the formfactors of meson-meson vertices makes predictions uncertain. The development of a unifying approach on the basis of a relativistic confining quark model is in progress [15] and will remove this uncertainty by providing a derivation of the appropriate formfactors from the underlying quark substructure.

The major modification of the charmonium break-up process which we expect at finite temperatures in a hot medium of strongly correlated quark-antiquark states comes from the Mott effect for the light as well as the open-charm mesons. At finite temperatures when the chiral symmetry in the light quark sector is restored, the continuum threshold for light-heavy quark pairs drops below the mass of the D-mesons so that they are no longer bound states constrained to their mass shell, but become rather broad resonant correlations in the continuum. This Mott effect has been discussed within relativistic quark models [16] for the light meson sector but can also be generalized to the case of heavy mesons [17]. Applying a confining quark model [18] we have obtained the critical temperatures $T_{D^*}^{\text{Mott}} = 110$ MeV, $T_D^{\text{Mott}} = 140$ MeV and $T_{\pi}^{\text{Mott}} = 150$ MeV [19].

In order to study the implications of the pion and $D$-meson Mott effect for the charmonium break-up we adopt here a Breit-Wigner form for the spectral functions

$$A_i(s) = \frac{1}{\pi} \frac{\Gamma_i(T) M_i(T)}{(s - M_i^2(T))^2 + \Gamma_i^2(T) M_i^2(T)} , \quad (8)$$

which in the limit of vanishing width $\Gamma_i(T) \to 0$ goes over into the delta function $\delta(s - M_i^2)$ for a bound state in the channel $i$. The width of the pions as well as the $D$-mesons shall be modeled by a microscopic approach. For our exploratory calculation, we adopt here

$$\Gamma_{\pi,D}(T) = c \left( T - T_{\pi,D}^{\text{Mott}} \right) \Theta(T - T_{\pi,D}^{\text{Mott}}) , \quad (9)$$

where the coefficient $c = 2.67$ is assumed to be universal for the pions and $D$-mesons and it is obtained from a fit to the pion width above the pion Mott
temperature, see [20]. For the meson masses we have $M_{\pi,D}(T) = M_{\pi,D} + 0.75 \Gamma_{\pi,D}(T)$. The result for the in-medium $J/\psi$ break-up cross section (6) is shown in Fig. 2.

Fig. 2. Energy- and temperature dependent in-medium $J/\psi$ break-up cross section for pion impact. Thresholds occur at the Mott temperatures for the open-charm mesons: $T_{D^*}^{\text{Mott}} = 110$ MeV, $T_{D}^{\text{Mott}} = 140$ MeV.

With $M_{D^*} = 2.01$ GeV and $M_D = 1.87$ GeV follows for the threshold $s_0 = 15.05$ GeV$^2$. At a temperature $T = 140$ MeV, where the D-meson can still be considered as a true bound state, the $D^*$-meson has already entered the continuum and is a resonance with a half width of about 80 MeV. Due to the Mott effect for the open-charm mesons (final states), the charmonium dissociation processes become "subthreshold" ones and their cross sections which are peaked at threshold rise and spread to lower onset with c.m.s energy. This is expected to enhance strongly the rate for the charmonium dissociation processes in a hot resonance gas.

4 $J/\psi$ dissociation in a hot “pion” gas

We calculate the inverse relaxation time for a $J/\psi$ at rest in a hot gas of pions (below $T_{\pi}^{\text{Mott}}$) and pion-like $q\bar{q}$ correlations (above $T_{\pi}^{\text{Mott}}$) by specifying Eq. (5) for this case.
\[
\tau^{-1}(T) = \int \frac{d^3p'}{(2\pi)^3} \int ds\pi A_\pi(s\pi)f_\pi(p',s\pi;T) \frac{|p'|}{E_\pi(p',s\pi)} \sigma^*(s)
\]
with the dispersion relation \(E_\pi(p',s\pi) = \sqrt{p'^2 + s\pi}\), the thermal Bose distribution function \(f_\pi(p',s\pi;T) = \frac{3}{\{\exp[E_\pi(p',s\pi)/T] - 1\}^{-1}}\) and the particle density \(n_\pi(T)\) for the “pions”. The cms energy of the “pion” impact on a \(J/\psi\) at rest is \(s(p';s\pi) = s\pi + M_\psi^2 + 2M_\psi E_\pi(p',s\pi)\).

The result for the temperature dependence of the thermal averaged \(J/\psi\) break-up cross section \(<\sigma^*v_{\text{rel}}>\) is shown in Fig. 3. This quantity has to be compared to the nuclear absorption cross section for the \(J/\psi\) of about 3 mb which has been extracted from charmonium suppression data in p-A collisions [21].

\[<\sigma^*v_{\text{rel}}> = n_\pi(T),\]

It is remarkable that it is practically negligible below the D-meson Mott temperature \(T_{D^*}^{\text{Mott}} = 110\) MeV but comparable to the nuclear absorption cross section above the chiral/deconfinement temperature of \(T_{\text{crit}} \approx 150\) MeV. It is obvious that the transition from D-meson bound states to unbound light-heavy quark correlations is responsible for the strong increase by one to two orders of magnitude. Note that in this calculation the Mott effect for the pion (initial state) above \(T_\pi^{\text{Mott}}\) has been included, but does not alter the result obtained previously [19] in a calculation neglecting this effect.

Therefore we expect the in-medium enhanced charmonium dissociation pro-
cess to be sufficiently effective to destroy the charmonium state on its way through the hot fireball of the heavy-ion collision and to provide an explanation of the observed anomalous $J/\psi$ suppression phenomenon [1]. A detailed comparison with the recent data from the NA50 collaboration requires a model for the heavy-ion collision. The effective in-medium break-up cross section for the $J/\psi$ derived in this work provides an input for all calculations which use this quantity, e.g. Glauber-type models [19,22–26], more detailed calculations based on a parton cascade model [27] or molecular dynamics [28].

5 Summary and Outlook

In this letter we have presented an approach to charmonium break-up in a hot and dense medium which is applicable in the vicinity of the chiral/deconfinement phase transition where mesonic bound states get dissolved in a Mott-type transition and should be described as resonant correlations in the quark plasma. This description can be achieved using the concept of the spectral function which can be obtained from relativistic quark models in a systematic way. The result of an exploratory calculation employing a temperature-dependent Breit-Wigner spectral function for light and open-charm mesons presented in this paper has demonstrated that heavy-flavor dissociation processes are critically enhanced at the QCD phase transition and could represent the physical mechanism behind the phenomenon of anomalous $J/\psi$ suppression.

In subsequent work we will relax systematically approximations which have been made in the present paper and improve inputs which have been used. In particular, we will investigate the off-shell behaviour of the charmonium break-up cross section in the vacuum (7) and calculate the spectral functions (8) at finite temperature within a relativistic quark model. Dyson-Schwinger equations provide a nonperturbative, field-theoretical approach which has recently been applied also to heavy-meson observables [29] and have proven successful for finite-temperature generalization [30,31]. Further intermediate open-charm states can be considered; the states in the dense environment should include rho mesons and nucleons besides of the pions which all can be treated as off-shell quark correlations at the QCD phase transition.

In future experiments at LHC the charm distribution in the created fireball may be not negligible so that the approximation $f_{D_i}(p) \approx 0$ has to be relaxed. In this case, one has to include the gain process ($\bar{D}D$ annihilation) encoded in the $\Sigma^{<}$ function. In comparison to previous investigations [32,33] the present quantum kinetic treatment contains Bose enhancement factors in the $G^>$ functions which modify the charm equilibration process.
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