Mott dissociation of D-mesons at the chiral phase transition and anomalous $J/\psi$ suppression

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Abstract: We investigate the in-medium modification of the charmonium breakup processes due to the Mott-effect for D-mesons at the chiral phase transition. A model calculation for the process $J/\psi + \pi \rightarrow D + \bar{D}^* + h.c.$ is presented which demonstrates that threshold effects in the thermal averaged breakup cross section can be explained as a Mott transition where final state quark-antiquark bound states enter the continuum of resonant states at the QCD phase transition. Applications to heavy-ion collisions within a modified Glauber model scenario and the phenomenon of anomalous $J/\psi$ suppression in the CERN NA50 experiment are addressed.

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

1. Introduction

Recent results of the CERN NA50 collaboration on anomalous $J/\psi$ suppression 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 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 as e.g. dissociation by meson or quark impact is required to dissolve the $J/\psi$ signal.

In this paper, we suggest that at the chiral/deconfinement phase transition the charmonium breakup reaction cross sections are critically enhanced since the open charm 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 pion gas in order to demonstrate that the Mott dissociation of the D-mesons at the chiral phase transition leads to a threshold effect for the $J/\psi$ suppression ratio when applied to the case of Pb-Pb collisions at CERN within a modified Glauber model.

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 the selfenergy $	au^{-1}(p) = \Sigma(p) = \Sigma^>(p) \mp \Sigma^<(p)$. In the Born collision approximation for the dominant process in a hot pion gas, as shown in Fig. 1, we have

$$\Sigma^<(p, \omega) = \int_{p'} \int_{p_1} \int_{p_2} (2\pi)^4 \delta(p + p' - p_1 - p_2) \times |M|^2 G_{\pi}^>(p') G_{D_1}^>(p_1) G_{D_2}^>(p_2),$$

where the thermal Green functions $G_i^>(p) = [1 \pm f_i(p)|A_i(p)$ and $G_i^<(p) = f_i(p)A_i(p)$ are defined by the spectral function $A_i(p)$ and the distribution function $f_i(p)$ of the state $i$. In the low density approximation for the final
The quark exchange processes in meson-meson scattering can be calculated within the diagrammatic approach of Barnes and Swanson [8] which allows a generalization to finite temperatures in the thermodynamic Green function technique [9]. This technique has been applied to the calculation of \(J/\psi\) break-up cross sections by pion impact in [10], where also a fit formula has been given. The approach has been extended to excited charmonia states and consideration of rhomeson impact recently [11]. The generic form of the resulting cross section (given a band of uncertainty) can be fit to the form

\[
\sigma^{\text{vac}}(s; M_{D_1}^2, M_{D_2}^2) = \sigma_0 \ln(s/s_0) \exp(s/\lambda^2),
\]

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. An alternative fit is given in [10].

Recently, the charmonium dissociation processes have been calculated also in an effective Lagrangian approach [10, 11], but this method introduces new phenomenological parameters and ignores the quark substructure. The development of a unifying approach on the basis of a relativistic confining quark model is in progress [12]. Detailed numerical comparison cannot be made at present.

The major modification of the charmonium break-up process which we expect at finite temperatures in a hot meson gas comes from the Mott-effect for the light as well as the heavy 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 [13] for the light meson sector but can also be generalized to the case of heavy mesons [14]. Applying a confining quark model [12] we have obtained the critical temperatures

\[T_{D_M}^{\text{Mott}} = 110\text{ MeV},\]

\[T_{D}^{\text{Mott}} = 140\text{ MeV}.\]

In order to study the implications of the D-meson Mott effect for the charmonium breakup...
we adopt here a Breit-Wigner form for the spectral functions

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

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

$$\Gamma_D(T) = c(T - T_{Mott}^D)\Theta(T - T_{Mott}^D),$$

where the coefficient $c = 2.67$ is assumed to be universal for the pseudoscalar D-mesons and it is obtained from a fit to the pion width above the pion Mott temperature, see [15]. For the D-meson mass we have $M_D(T) = M_D^0 + 0.75\Gamma_D(T)$.

The result for the in-medium $J/\psi$ break-up cross section (2.2) is shown in Fig. 2.

With $M_D^\ast = 2.01$ 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 $D^\ast$ 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, the charmonium dissociation processes become "subthreshold" ones and their cross sections which are peaked at threshold rise and spread to lower onset with cms energy. This is expected to enhance the rate for the charmonium dissociation processes in a hot meson 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 pion gas according to Eq. (2.2),

$$\tau^{-1}(T) = \int \frac{d^3p}{(2\pi)^3} f_\pi(p) |p| E_\pi(p) \sigma^\ast(s) = <\sigma^\ast v_{rel}> n_\pi(T),$$

where we have assumed on-shell pions with the dispersion relation $E_\pi(p) = \sqrt{p^2 + M_\pi^2}$ obeying the thermal Bose distribution function $f_\pi(p) = 3[\exp((E_\pi(p) - \mu)/T) - 1]^{-1}$, $n_\pi(T)$ being the pion density. The cms energy of the pion impact on a $J/\psi$ at rest is $s(p) = M_D^2 + 2M_\psi E_\pi(p)$. The result for the temperature dependence of the thermal averaged $J/\psi$ breakup cross section $<\sigma^\ast v_{rel}>$ 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 [16]. It is remarkable that it is practically negligible below the D-meson Mott temperature $T_{Mott}^D = 110$ MeV but comparable to the nuclear absorption cross section above the chiral/deconfinement temperature of $T_{crit} \approx 150$ MeV. Therefore we expect the in-medium enhanced charmonium dissociation processes 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 [4].

**Figure 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: $T_{Mott}^{D^0} = 110$ MeV, $T_{Mott}^{D^\ast} = 140$ MeV.
5. Applications to Pb-Pb collisions at CERN

A more detailed comparison with the recent data from the NA50 collaboration requires a model for the heavy ion collision. In the following we will use a modified Glauber model [17, 18] which takes into account the formation of secondaries ("soft matter") during the collision and the propagation of the charmonium state through the debris of the collision. The suppression function is defined by

\[ S(E_T) = S_N(E_T) \exp \left[ - \int_{t_0}^{t_f} dt \tau^{-1}(n(t)) \right] \]

\[ = S_N(E_T) \exp \left[ \int_{n_0(E_T)}^{n_f} dn < \sigma^{*\tau_{rel}} > \right], \]

where we have assumed a nuclear absorption systematics \( S_N(E_T) = 18 + 36 \exp(-0.26 \sqrt{E_T}) \) and longitudinal expansion according to \( n(t) = n_0(E_T) t_0/t \). Within a Glauber model fit to the NA50 experiment [18] we obtain the \( n_0(E_T) \) as a parameter form depending on the impact parameter \( b \), where \( E_T(b) = 130 - b/\text{fm} \) and \( n_0(b) = 12.2 \sqrt{1 - (b/10.8\, \text{fm})^2} \).

In Fig. 3 we show the result for our model calculation in comparison with the data for Pb-Pb collision experiments of the NA50 collaboration [1]. The temperature (pion density) dependence of the J/\( \psi \) breakup cross section which exhibits a critical enhancement at the D-meson Mott temperature, see Fig. 3, leads to a threshold behaviour in the \( E_T \) dependence of the J/\( \psi \) suppression ratio. This is in qualitative agreement with the data and the mechanism for the occurrence of thresholds in this quantity can be considered as a possible explanation for the observed deviation from the ordinary nuclear absorption systematics (anomalous J/\( \psi \) suppression) in the NA50 experiment.

6. Summary and Outlook

In this contribution we have presented an approach to charmonium breakup 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 instead. 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 open charm mesons presented in this paper has demonstrated that heavy-flavor dissociation processes are critically enhanced at the QCD phase transition and could lead in the charmonium sector to the phenomenon of anomalous J/\( \psi \) suppression.
In subsequent work we will relax systematically approximations which have been made in the one presented here and improve inputs which have been used. In particular, we will investigate the off-shell behaviour of the charmonium breakup cross section in the vacuum [3.1] and calculate the spectral function (3.2) at finite temperature from a relativistic quark model. Dyson-Schwinger equations provide a nonperturbative, field-theoretical approach which has recently been applied also to heavy-meson observables [19] and have proven successful for finite-temperature generalization [20]. 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 $f_D(p) \approx 0$ has to be relaxed. In this case, not only the gain processes ($\bar{D}D$ annihilation [21, 22]) encoded in the $\Sigma^{<}$ has to be included but at the same time the Bose enhancement factors in the $G_i^n$ functions have to be considered.

We want to emphasize that this approach to the kinetics of open charm and charmonium states in a dense medium provides a framework for a systematic investigation of processes relevant to QCD plasma diagnostics in heavy-ion collisions using heavy quark bound states.

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