The Role of Produced Hadrons in $J/\psi$ Suppression

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Hadrons produced in high-energy heavy-ion collisions can suppress the production of $J/\psi$ and other charmonium states by charmonium spontaneous dissociation as the hot hadronic environment alters the interaction between the charm quark and charm antiquark. Furthermore, hadrons can thermalize a charmonium to excite it to higher charmonium states which subsequently dissociate spontaneously. They can also collide with a charmonium to lead to its prompt dissociation into an open charm pair.

1. Introduction

The suppression of heavy quarkonium production has been the subject of intense studies as it was proposed as a signature for the quark-gluon plasma \cite{1}. Recent experimental observations of an anomalous $J/\psi$ suppression in Pb+Pb collisions by the NA50 Collaboration \cite{2} have aroused a great deal of interest \cite{3}. There is, however, considerable uncertainty concerning the role of the produced hadrons on the suppression of $J/\psi$ production. In order to confirm that the suppression of $J/\psi$ comes from the presence of the quark-gluon plasma, it is necessary to understand how the produced hadrons may affect the suppression of $J/\psi$ production so that the desired signal from the quark-gluon plasma can be separated out.

We shall study three different mechanisms of $J/\psi$ and charmonium dissociation in a hadronic medium: spontaneous dissociation, dissociation by thermalization, and dissociation by collision. We shall briefly summarize these mechanisms in turn.

2. Interaction between the Charm Quark and Charm Antiquark

The interaction between the quark and the antiquark in a heavy quarkonium depends on the temperature of the medium \cite{4}. We can understand such a dependence as coming from the change of the quark and gluon fields between the heavy quark pair and the change of the QCD vacuum surrounding the quarkonium. The former arises from the disorientation of the quark and gauge fields between the heavy-quark pair as temperature increases, while
the latter arises from the change of the external pressure which tends to confine the quark with the antiquark. At the deconfinement phase transition temperature, the confining interaction is expected to vanish. Hadron matter at high temperature provides an altered environment which can lead to the spontaneous dissociation of a heavy quarkonium.

Using the $Q$-$\bar{Q}$ interaction as inferred from lattice gauge calculations of Karsch et al.\textsuperscript{[4]}, Digal, Petreczky, and Satz \textsuperscript{[5]} recently reported theoretical results on the dissociation temperatures of heavy quarkonia. Subsequent analysis using different parametrization of the interaction and selection rules was given in \textsuperscript{[6]} and will be described below.

To study the behavior of a heavy quarkonium at finite temperatures, we calculate the energy $\epsilon$ of the heavy quarkonium state $(Q\bar{Q})_{JLS}$ from the Schrödinger equation\textsuperscript{[6,7]}

\[
\left\{-\nabla \cdot \frac{\hbar^2}{2\mu_{12}} \nabla + V(r, T) + (m_Q + m_{\bar{Q}} - M_{Q\bar{q}} - M_{q\bar{Q}}) \theta(R-r)\right\} \psi_{JLS}(r) = \epsilon \psi_{JLS}(r),
\]

where the energy $\epsilon$ is measured relative to the pair of lowest-mass mesons at $r \to \infty$, $M_{Q\bar{q}}$ and $M_{q\bar{Q}}$ are the masses of the open heavy-quark mesons, and $R \sim 0.8$ fm. We represent the interaction $V(r, T)$, as inferred from lattice gauge calculations of Karsch et al.\textsuperscript{[4]}, by a Yukawa plus an exponential potential \textsuperscript{[8,7]}

\[
V(r, T) = -\frac{4\alpha_s}{3} e^{-\mu(T)r} - \frac{b(T)}{\mu(T)} e^{-\mu(T)r}
\]

where $b(T) = b_0 [1 - (T/T_c)^2] \theta(T_c - T)$, $b_0 = 0.35$ GeV$^2$, $\mu(T) = 0.28$ GeV, and $T_c$ is the deconfinement phase transition temperature. We use a running $\alpha_s$ and include spin-spin, spin-orbit, and tensor interactions \textsuperscript{[3]}. The eigenvalues of the Hamiltonian can be obtained by matrix diagonalization.

3. Spontaneous Dissociation

Figure 1 shows the charmonium state energy as a function of temperature \textsuperscript{[3]}. The solid circles indicate the locations of the dissociation temperatures after taking into account the selection rules. The dissociation temperatures are listed in Table I.

We confirm the general features of the results of Digal et al.\textsuperscript{[4]}, but there are also differences as the dissociation temperatures depend on the selection rules and the spin-orbit, spin-spin, and other details of the potential. Our results from Fig. 1 and Table I indicate that the dissociation temperatures of all charmonia, obtained by using the temperature-dependent potential of Eq. \textsuperscript{[3]}, are below $T_c$.

![Fig. 1. Charmonium states as a function of temperature.](image)

| Table I. Charmonium dissociation temperatures $T_d$ in units of $T_c$ |
|---|---|---|---|---|
| Charmonium | $\psi'$ | $\chi_{c2}$ | $\chi_{c1}$ | $J/\psi$ |
| $T_d/T_c$ | 0.50 | 0.91 | 0.90 | 0.99 |
| $T_d/T_c$ (Digal et al.) | 0.1-0.2 | 0.74 | 0.74 | 1.10 |
4. Dissociation by Thermalization

If a quarkonium is placed in a hadronic medium, there will be non-dissociative reactions between the quarkonium and medium particles which change a charmonium state into another charmonium state: \( h + (Q\bar{Q})_{JLS} \leftrightarrow h' + (Q\bar{Q})_{J'S'} \). These reactions lead to the thermalization of the charmonium system \([9,6]\). When the heavy quarkonium system is in thermal equilibrium with the medium, the occupation probabilities of the heavy quarkonium state \( \epsilon_i \) will be distributed according to the Bose-Einstein distribution

\[
n_i = \frac{1}{\exp\{ (\epsilon_i - \mu) / T \} - 1},
\]

where \( \mu \) is the chemical potential. The system at thermal equilibrium will lose the memory of the initial state. There is the probability \( f \) for the quarkonium to lie above the threshold for spontaneous dissociation leading to its subsequent dissociation into an open charm pair. We evaluate the survival probability \( S = 1 - f \) as a function of temperature for charmonium. The results are shown in Fig. 2. A state label along the curve denotes the onset of the occurrence when that state emerges above its dissociation threshold. As one observes, the survival probability \( S \) decreases with increasing temperature in a step-wise manner, and it becomes quite small as one approaches the transition temperature.

5. Dissociation by Collision with Hadrons

A heavy quarkonium can dissociate into an open charm pair by collision with hadrons through reactions of the type \((q\bar{q}) + (Q\bar{Q})_{JLS} \rightarrow (Q\bar{q}) + (q\bar{Q})\). As the temperature of the medium increases, the quarkonium state energy changes (Fig. 1) and the dissociation threshold energy decreases. As a consequence, the dissociation cross section will increase. We calculate the dissociation cross sections of \( J/\psi \) in collision with \( \pi \) as a function of the temperature using the Barnes and Swanson model \([10]\), as in Ref. \([11]\). We use the temperature-dependent Yukawa and exponential interaction in Eq. (2) with the usual color dependence for the interquark interaction \([6]\). The sum of dissociation cross sections for \( \pi + J/\psi \rightarrow D\bar{D}^*, D^*\bar{D}, D^*\bar{D}^* \) are shown in Fig. 3 for different temperatures \( T/T_c \) as a function of the kinetic energy \( E_{KE} \).

We observe in Fig. 3 that the maximum values of the dissociation cross sections increase and the positions of the maxima shift to lower kinetic energies as the temperature increases. Such an increase arises from the decrease of the threshold energies as the temperature increases. Over a large range of temperatures below the phase transition temperature, dissociation cross sections of \( J/\psi \) in collisions with \( \pi \) are large.

We can estimate the survival probability of a heavy quarkonium in a hot pion gas in the presence of this type of collisional dissociation. The degree of absorption by collision with pions depends on the initial absorption time \( \tau_0 \), the freeze-out pion density \( \rho_{\text{freeze}} \), and the initial temperature \( T_0 \). If \( T_0 \sim T_c \), \( \rho_{\text{freeze}} = 0.5 \text{ fm}^3 \), and \( \tau_0 = 3 \text{ fm}/c+R/\gamma \), then for the most central Pb-Pb collision at 158A GeV, the heavy quarkonium survival
probability is $S \sim 0.5$, and for the most central Au-Au collision RHIC at $\sqrt{s_{NN}} = 200$ GeV, the heavy quarkonium survival probability is $S \sim 0.1$. These estimates show that the absorption of $J/\psi$ by the hot pion gas is substantial.

6. Discussions and Conclusions

The temperature of the medium alters the interaction between a heavy quark and antiquark in the medium. We have calculated the quarkonium state energies using a potential inferred from lattice gauge calculations of Karsch et al.[4] and obtain the dissociation temperatures. We find that the dissociation temperatures of all charmonia are below $T_c$.

A quarkonium in a medium can collide with particles in the medium to reach thermal equilibrium. A heavy quarkonium in thermal equilibrium can dissociate by thermalization as there is a finite probability for the system to be in an excited state lying above its dissociation threshold. We find that the survival probability of a charmonium decreases with increasing temperatures in a step-wise manner.

Dissociation of a heavy quarkonium into open heavy-quark mesons can occur in collision with hadrons. As the temperature increases, the threshold energies for collisional dissociation decrease. As a consequence, the dissociation cross sections increase. We have estimated the absorption of $J/\psi$ in collision with pions in central Pb-Pb collisions at SPS and RHIC energies and found the absorption to be substantial. Further microscopic investigations of the dissociation of heavy quarkonium in collision with hadrons in high-energy heavy-ion collisions will be of great interest.

REFERENCES

1. T. Matsui and H. Satz, Phys. Lett. B178, 416 (1986).
2. M. Gonin, NA50 Collaboration, Nucl. Phys. A610, 404c (1996).
3. C. Y. Wong, Nucl. Phys. A610, 434c (1996); Nucl. Phys. A630, 487 (1998); C. Y. Wong, hep-ph/9809497; D. Kharzeev, Nucl. Phys. A610, 418c (1996); J.-P. Blazoit et al. Nucl. Phys. A610, 452c (1996); A. Capella et al., Phys. Lett. B393, 431 (1997); W. Cassing and C. M. Ko, Phys. Lett. B396, 39 (1997); M. Nardi and H. Satz, Phys. Lett. B442, 14 (1998).
4. F. Karsch, E. Laermann, and A. Peikert, Nucl. Phys. B605, 579 (2001).
5. S. Digal, D. Petreczky, and H. Satz, Phys. Lett. B514, 57 (2001) and Phys. Rev. D64, 094015 (2001).
6. C. Y. Wong, Phys. Rev. C65, 034902 (2002), and J. Phys. G28, 2349 (2002).
7. C. Y. Wong, Phys. Rev. D60, 114025 (1999).
8. F. Karsch, M. T. Mehr, and H. Satz, Z. Phys. C37, 617 (1988).
9. D. Kharzeev, L. McLerran, H. Satz, Phys. Lett. B356, 349 (1995).
10. T. Barnes and E. S. Swanson, Phys. Rev. D46, 131 (1992).
11. C. Y. Wong, E. S. Swanson, and T. Barnes, Phys. Rev. E62, 045201 (2000) and Phys. Rev. C65, 014903 (2002).