heavy flavor probes of quark matter

R. L. Thews
Department of Physics, University of Arizona, Tucson, AZ 85721 USA

Abstract. A brief survey of the role of heavy flavors as a probe of the state of matter produced by high energy heavy ion collisions is presented. Specific examples include energy loss, initial state gluon saturation, thermalization and flow. The formation of quarkonium bound states from interactions in which multiple heavy quark-antiquark pairs are initially produced is examined in general. Results from statistical hadronization and kinetic models are summarized. New predictions from the kinetic model for $J/\psi$ at RHIC are presented.

1. Introduction

The references on the web which respond to the search for the term “heavy flavor” are predominantly physics-related. However, there are many from chemistry and food technology. One of particular interest cites experimental evidence that the molecular weight of inorganic salts determine the intensity, or equivalently the amount, of a specific flavor such as saltiness or bitterness. For the analogous statement applied to heavy quarks we must treat the amount of flavor in a discrete manner (charm, bottom, top) in order to retain the correlation of “amount” of flavor with the quark mass.

The property of heavy flavors which provides qualitatively different probes for heavy ion collisions is just that: heaviness. The relevant quantities are the current quark masses, generated by electroweak symmetry breaking. The distance scales corresponding to the inverse of the charm mass (1.5 GeV, 0.07 fm) and bottom mass (5.0 GeV, 0.02 fm) are small compared with the size of the interaction regions in heavy ion collisions and also the size of bound states in vacuum.

The following sections survey some characteristic features of heavy quark sensitivity to initial state properties in heavy ion collisions, possible interaction with light quarks and gluons in probing the spacetime development of a dense expanding region, and modification of final state hadrons containing heavy quarks due to interactions with a color deconfined medium. In addition, the utility of heavy quarkonium states as a signal of deconfinement is updated to include effects of multiple heavy quark pair production at collider energies.
Heavy flavor probes of quark matter

2. Initial production of heavy flavor and gluon saturation

Heavy flavor is not present (at least to any great extent) in the initial colliding nuclei, so it must be produced initially in the nuclear collision itself. Production of heavy flavor is one of the so-called "hard probes", since the mass scale $M_Q >> \Lambda_{QCD}$. This enables one to factor out all lower-scale effects and perform a perturbative expansion within QCD. The large mass also ensures that this production takes place at early times, allowing the heavy flavor to probe the subsequent medium during its entire history.

The primary production mechanism is through gluon-gluon interactions, so the total amount is a probe of the initial state gluon distribution. However, nuclear collisions bring in additional effects, such as shadowing in structure functions, initial state $k_t$ broadening, and perhaps saturation effects at low-x. The formation process is expected to scale with the number of binary nucleon-nucleon collisions $N_{coll}$. In terms of the number of nucleon participants, which is taken as a measure of the centrality of the collisions, the number of binary collisions is expected to grow as $N_{part}^{4/3}$.

Initial state gluon saturation is a consequence of very large gluon occupation numbers at low-x. It is characterized by yet another scale, the saturation energy scale $Q_s(x)$. In the color glass condensate picture, $Q_s$ is the scale below which the $k_t^{-2}$ behavior of the gluon transverse momentum spectra saturates. In nuclei, one expects an enhancement factor in $Q_s$, proportional to $A^{1/6}$. If the saturation scale becomes greater than the other scale in the problem, the heavy flavor mass, then one may expect collinear factorization to fail, since the relevant $k_t$ values will not be small compared with $M_Q$. One consequence is that the heavy quark production process would scale as $N_{part}$ rather than $N_{coll}$. However, there may be residual effects from the heavy quark mass scale even in the region where $N_{coll}$ scaling holds for the total rate. An example of this effect appears in a calculation of the hardening of the D meson spectrum predicted for central collisions at RHIC[1].

3. Thermal production

There may be subsequent production of heavy flavor from collisions of secondary partons in the medium, the amount of which is still subject to considerable theoretical uncertainty. However any thermal production will be very sensitive to the ratio $M_Q/T$, and hence may provide information on the temperature of an equilibrated medium.

4. Interaction with a hadronic or deconfined medium

The utility of heavy flavor as an independent probe of the dense medium relies on the mass dependence of energy loss/quenching. A first order effect is due to the dead cone, which sets the minimum angle of radiative gluon emission relative to the heavy quark direction at $M_Q/E$ [2]. In addition, there will be a change in the gluon formation time which reduces the coherence length in the medium and also the LPM effect[3]. Several
groups have recently calculated the resulting effect on the medium-induced radiation from a heavy quark. All conclude that some “filling in” of the dead cone will occur [4, 5, 6], but there will be a residual qualitative difference between energy loss of heavy relative to light flavors. This effect may be observable in the quenching of flavor-tagged jets in AA interactions. A study of the effects expected at LHC energy is underway[7]. The nuclear suppression ratios to be measured appear to be sensitive to flavor content under various assumptions of energy loss behavior.

5. Thermalization and flow

Finally there is the question of possible thermalization and flow of heavy flavor in the medium. This would require a large opacity of the medium, perhaps the sQGP fluid. One would then anticipate a reduced energy loss for the heavy quarks, since they would be effectively at rest with respect to the dense partonic medium. At present, one can only infer the production of heavy flavor hadrons in AA collisions at RHIC (in this case charm) by measuring the decay leptons at high $p_t$. However, it has been shown[8] that this lepton spectrum for $p_t$ less than about 2.5 GeV is essentially independent of the initial charm quark momentum distribution. Elliptic flow is, however, a more sensitive probe [9]. Recent measurements of elliptic flow for high-$p_t$ leptons provide a hint that the parent heavy quarks may be providing the underlying flow[10].

6. Quarkonium formation from uncorrelated heavy quarks

Quarkonium formation dynamics in heavy ion collisions originated the interest in heavy flavor, in particular the $J/\psi$, as a probe of color deconfinement. This of course was initiated by the seminal idea of Matsui and Satz[11], who noted that plasma screening of the color force would “melt” the $J/\psi$. During the period of deconfinement the $c$ and $\bar{c}$ quarks would generally diffuse apart. At hadronization they would have a much greater probability of combining with a light quark to form open charm mesons, hence the $J/\psi$ suppression, provided that no other source of charm quarks would be present.

An additional part of the scenario was added by Kharzeev and Satz[12], who noted that “ionization” of $J/\psi$ in medium would be readily accomplished by deconfined thermal gluons. The corresponding process using gluons confined within light flavor hadrons was shown not to produce any significant suppression, due to the different gluon momentum spectrum in bound states.

The NA50[13] experiment at the SPS have shown the existence of such a suppression, with respect to an “expected” baseline due to absorption by collisions with nucleons. Extrapolation of the suppression scenario to RHIC energy resulted in a variety of predictions. The initial $J/\psi$ data from PHENIX[14] did not have sufficient statistics to differentiate among these predictions[15], and the upcoming results from Run 4 are eagerly awaited.

The primary topic remaining is an investigation of the effects of high energy (RHIC
and above) nuclear collisions, in which one expects that multiple quark-antiquark pairs will be produced in an individual nucleus-nucleus collision. It is clear that this must happen at some point as energy increases, and there is some initial data on open charm production at RHIC with which to compare. The basic premise of work in this environment is that one can probe color deconfinement in a qualitatively different way, due to the presence of multiple pairs of heavy quarks. In this situation one avoids the Matsui-Satz condition of no additional heavy quarks with which to recombine. Then there should be a contribution to heavy quarkonium formation which utilizes combinations of initially uncorrelated quark and antiquark, leading to a \textit{quadratic} increase with the total number of heavy flavor quarks in the event. There are two specific models which implement this scenario.

\textbf{6.1. Kinetic formation model}

The kinetic model of quarkonium formation in a region of color deconfinement was first formulated\cite{16} to estimate a possible enhancement of the rate for $B_c$ production in heavy ion collisions relative to that in single nucleon-nucleon interactions. The subsequent application to $J/\psi$ formation\cite{17} found a more significant effect, due to the formation rate quadratic dependence on total charm quark numbers. The physical picture in this case is quite simple. The final $J/\psi$ population is determined by a competition between the rate of dissociation via gluon-initiated ionization, and the formation process which is simply the inverse of dissociation. Recent lattice calculations of spectral functions\cite{18, 19} which indicate that $J/\psi$ states survive in a medium substantially above the deconfinement temperature support this dynamical picture. The centrality and time dependence of the deconfinement region was modeled according to an isentropic expansion with initial temperature as a parameter, and a spatial dependence determined by a Glauber model of participant density in the transverse plane. Initial results indicated that an enhancement of $J/\psi$ production at RHIC (relative to scaling of binary nucleon-nucleon collisions) could occur. However, the magnitude of this effect was found to be very sensitive to the momentum spectrum of the participating charm quarks, in addition to the overall quadratic dependence on initial charm quark production. The initial calculations used Gaussian transverse momentum distributions in a flat rapidity interval of varying width. Subsequent calculations used more realistic distributions taken from pQCD results\cite{20}, which allowed the identification of a restricted region of model parameter space constrained by the initial PHENIX results. Owing to the large experimental uncertainties, however, these restrictions do not allow either a confirmation or refutation of the basic formation process.

However, the model also makes predictions for the transverse momentum and rapidity spectra of $J/\psi$ which are formed in medium. We would expect in general that these spectra will differ from initial production or statistical hadronization. For this calculation, we have generated a sample of $c\bar{c}$ pairs using pQCD at NLO for RHIC energy\cite{21}, which are used to define the initial quark momentum distribution. All
possible pairs of one $c$ and one $\bar{c}$ are then weighted by a formation cross section to generate a set of formation events. For purposes of identification, we denote the pairs in which the $c$ and $\bar{c}$ originated from the same initial pair as “diagonal” and all other pairs as “off-diagonal”. We use the “OPE-motivated” cross section, which can be viewed as the QCD analog of atomic photodissociation. The inverse process then provides the cross section for quarkonium formation. These cross sections must be supplemented by the differential dependence, which we adapt from the matrix element appropriate for the coupling of the bound state color dipole with gluons. The resulting set of weighted differential formation probabilities can then be used to calculate the spectra of formed $J/\psi$.

$$\frac{dN_{J/\psi}}{d^3P_{J/\psi}} = \int dt \frac{V(t)}{V(t)} \sum_{i=1}^{N_c} \sum_{j=1}^{N_{\bar{c}}} \nu_{rel} \frac{d\sigma}{d^3P_{J/\psi}}(P_i + P_j \rightarrow P_{J/\psi} + X)$$

Note that the formation magnitude exhibits the explicit quadratic dependence on total charm, normalized by the inverse of the system volume.

As a baseline test, we first compare with PHENIX data for $J/\psi$ rapidity and transverse momentum in pp interactions[22]. We use only the diagonal pairs as appropriate for the pp case. To emphasize the formation kinematics, we will concentrate on the normalized spectra. Figure 1 shows the rapidity spectra. One sees that the diagonal $c\bar{c}$ spectrum (triangles) agrees quite well with the data. For comparison, we show the effect of weighting the pairs with the formation probability in a color-deconfined scenario (squares), which is inconsistent with the pp data. This confirms our expectations that the formation model is not applicable in pp interactions.

Figure 1: Rapidity distribution for diagonal $c\bar{c}$ pairs.

Figure 2: Transverse momentum distribution for diagonal $c\bar{c}$ pairs.

Figure 2 shows the corresponding transverse momentum spectra. The set of curves from the unbiased diagonal $c\bar{c}$ pairs result from augmenting the quark initial momenta with a transverse momentum “kick” to simulate confinement and initial state effects. One sees that the data restricts the magnitude of this kick, parameterized by a Gaussian distribution with $<k_t^2>_{pp} = 0.5 \pm 0.1 GeV^2$. To extend this to formation in Au-Au
Heavy flavor probes of quark matter

collisions, we must extract the appropriate $k_t$ for initial state effects in the nucleus. We use PHENIX data for $J/\psi$ in d-Au collisions, which shows that the $p_t$ spectra are broadened relative to that in pp interactions[23]. This results in an estimate for $< k_t^2 >_{Au-Au} = 1.3 \pm 0.3 \text{GeV}^2$, which was utilized in the formation calculations in Au-Au interactions. Figure 3 shows rapidity spectra for $J/\psi$ formation utilizing both diagonal and off-diagonal pairs. For comparison the data and diagonal pair curves in pp interactions are also shown. One sees that the $k_t$ kick has virtually no effect, and that the formation mechanism predicts a narrowing of the rapidity distribution compared to pp interactions.

Figure 3: Prediction for $J/\psi$ rapidity distribution from formation process in Au-Au collisions at RHIC.

Figure 4 shows the corresponding transverse momentum spectra for the allowed range of $k_t$ in Au-Au collisions. For comparison we show the distribution utilizing only unbiased diagonal $c\bar{c}$ pairs with $< k_t^2 > = 1.3 \text{ GeV}^2$, which should be relevant if all of the $J/\psi$ were produced directly from the initial pairs. Again the prediction of this formation mechanism is for a narrowing of the transverse momentum distribution. (Of course, both of these distributions would be modified by the competing dissociation process during the expansion phase, but one would anticipate a similar effect on each which would preserve the relative comparison.)

Finally, we contrast these formation transverse momentum predictions with results which follow if the initially-produced quarks were to thermalize and flow with the medium, and subsequently form $J/\psi$ via the kinetic model. For these calculations we used a “blast wave” parameterization for the charm quark transverse momentum distribution and a flat rapidity plateau over four units:

$$ \frac{dN_{c,\bar{c}}}{dp_t^2} \propto m_t \int_0^R rdr I_0 \left( \frac{p_t}{T} \sinh \left( \frac{r y_t^{max}}{R} \right) \right) K_1 \left( \frac{m_t}{T} \cosh \left( \frac{r y_t^{max}}{R} \right) \right)$$

(2)

The parameter $y_t^{max}$ specifies the maximum rapidity for the linear transverse expansion profile. In Figure 5 we show the results for thermal charm quarks with $T = 128 \text{ MeV}$, and for thermal plus flow ($y_t^{max} = 0.65$). Shown for comparison is formation
with pQCD charm quarks. One sees that the effects of thermal distributions with or without flow for the charm quarks would be readily distinguishable from the situation in which pQCD charm quarks participate directly in the formation process without further interaction in the medium.

![Figure 5: Comparison of J/ψ formation p_t spectra for different charm quark distributions.](image1)

![Figure 6: Comparison of charm quark thermal density with N_{c\bar{c}}=20 in expanding plasma.](image2)

6.2. **Statistical hadronization model**

The initial formulation of the statistical hadronization model for multiple charm pairs in nuclear collisions was done by Braun-Munzinger and Stachel[24]. It is clear that charm density exceeds chemical equilibrium density for T less than T_c for typical volumes and temperatures appropriate for RHIC conditions. This is shown in Figure 6. One sees that the decrease in density due to expansion (solid curves) is much less dramatic than the corresponding decrease in thermal equilibrium density due to the temperature decrease (solid circles).

The extension of the model to accommodate heavy flavor hadrons is accomplished by introducing a nonequilibrium parameter \( \gamma_c \) which is determined by conservation of total charm and anticharm. Since the thermal density is dominated by the open charm states due to their lower mass, the factor \( \gamma_c \) is directly proportional to the number of initially-produced c\bar{c} pairs. Then the square of \( \gamma_c \) modifies the thermal equilibrium density for hidden charm mesons, producing the expected quadratic dependence on \( N_{c\bar{c}} \). To get the absolute hadron species yields one must input a volume, which is usually parameterized as the ratio of total yield to thermal density of charged hadrons. The final expression is

\[
N_{J/\psi} = 4 \frac{n_{ch} n_{J/\psi}}{(n_{open})^2} \frac{N_{c\bar{c}}^2}{N_{ch}}.
\]

For application to collider experiments which do not have full kinematic coverage, one must extend the formalism to rapidity densities. This necessitates additional
input, in particular the magnitude and centrality dependence of the hadronization volume for rapidity density. Two groups\cite{25, 26} have produced results which can be compared with the initial PHENIX data on $J/\psi$ production in Au-Au at 200 GeV\cite{14}. Both are in general agreement with the one data point and one upper limit for two centrality regions, within the statistics-limited experimental uncertainties. However, two different assumptions were used by the separate groups for the total charm production cross section, varying from 390 to 650 $\mu$b. Since these numbers enter the predictions quadratically, one sees that there must be substantial flexibility remaining in these model predictions. Again, it is anticipated that the upcoming experimental results will place much more severe constraints on models of this type.

**Acknowledgments**

This work was supported by a grant from the U.S. Department of Energy, DE-FG02-04ER41318.

**References**

[1] Kharzeev D and Tuchin K 2004 *Nucl. Phys.* A **735** 248
[2] Dokshitzer Y L and Kharzeev D E 2001 *Phys. Lett.* B **519** 199
[3] Zhang B W, Wang E and Wang X N 2003 *Preprint* nucl-th/0309040
[4] Thomas R, Kampfer B and Soff G 2004 *Preprint* hep-ph/0405189
[5] Djordjevic M and Gyulassy M 2004 *Nucl. Phys.* A **733** 265
[6] Armesto N, Salgado C and Wiedemann U 2004 *Phys. Rev.* D **69** 114003
[7] Dainese A 2004 *Preprint* nucl-ex/0405008 and these proceedings
[8] Batsouli S, Kelly S, Gyulassy M and Nagle J 2003 *Phys. Rev.* C **68** 044901 and Molnar D 2004 these proceedings
[9] Laue F 2004 (PHENIX Collaboration), these proceedings
[10] Matsui T and Satz H 1986 *Phys. Lett.* B **178** 416
[11] Kharzeev D and Satz H 1994 *Phys. Lett.* B **334** 155
[12] Cortese P 2004 (NA50 collaboration), these proceedings
[13] Adler S S et al 2004 (PHENIX Collaboration) *Phys. Rev.* C **69** 014901
[14] Bass S A et al 1999 *Nucl. Phys.* A **661** 205
[15] Schroedter M, Thews R L and Rafelski J 2000 *Phys. Rev.* C **62** 024905
[16] Thews R L, Schroedter M and Rafelski J 2000 *Phys. Rev.* C **63** 054905
[17] Datta S, Karsch F, Petreczky P and Wetzorke I 2004 *Phys. Rev.* D **69** 094507
[18] Asakawa M and Hatsuda T 2004 *Phys. Rev. Lett.* **92** 012001
[19] Thews R L 2004 *J. Phys.* G **30** S369
[20] Mangano M L and Thews R L 2004 Work in progress
[21] Adler S S et al 2004 (PHENIX Collaboration) *Phys. Rev. Lett.* **92** 051802
[22] Granier de Cassagnac R 2004 (for the PHENIX Collaboration) *Preprint* nucl-ex/0403030
[23] Braun-Munzinger P and Stachel J 2000 *Phys. Lett.* B **490** 196
[24] Kostyuk A P, Gorenstein M I, Stocker H and Greiner W 2003 *Phys. Rev.* C **68** 041902