Enhanced J/ψ Production in Deconfined Quark Matter

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In high energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider (LHC) at CERN, the initial production of heavy quarks will for the first time yield multiple pairs of $c\bar{c}$ (at RHIC) and both $c\bar{c}$ and $b\bar{b}$ (at LHC) in each central event. If a region of deconfined quarks and gluons is subsequently formed, a new mechanism for the formation of heavy quarkonium bound states will be activated. This will result from the mobility of heavy quarks in the deconfined region, such that bound states can be formed from a quark and an antiquark which were originally produced in separate incoherent interactions. Model estimates of this effect for J/ψ production at RHIC indicate that enhancements of an order of magnitude or more are to be expected. Experimental observation of such enhanced production would provide evidence for deconfinement unlikely to be compatible with competing scenarios.

Ultrarelativistic heavy ion collisions at the RHIC and LHC colliders are expected to provide initial energy density sufficient to initiate a phase transition from normal hadronic matter to deconfined quarks and gluons [1].

A decrease in the number of observed heavy quarkonium states was proposed many years ago [2] as a signature of the deconfined phase. One invokes the argument that in a plasma of free quarks and gluons the color forces will experience a Debye-type screening. Thus the quark and antiquark in a quarkonium bound state will no longer be subject to a confining force and diffuse away from each other during the lifetime of the quark-gluon plasma. As the system cools and the deconfined phase disappears, these heavy quarks will most likely form a final hadronic state with one of the much more numerous light quarks. The result will be a decreased population of heavy quarkonium relative to those formed initially in the heavy ion collision.

There is now extensive data on charmonium production using nuclear targets and beams. The results for J/ψ in p-A collisions and also from Oxygen and Sulfur beams on Uranium show a systematic nuclear dependence of the cross section, parameterized as $(A_{beam}B_{target})^{\alpha}$, with $\alpha < 1$ [3]. This behavior points toward an interpretation in terms of a break-up of an initial quarkonium state by interactions with nucleons [4]. Recent results for a Lead beam and target reveal an additional suppression of about 25%, prompting claims that this effect could be the expected signature of deconfinement [5]. The increase of this "anomalous" suppression with the centrality of the collision, as measured by the energy directed transverse to the beam, shows signs of structure which have been interpreted as threshold behavior due to dissociation of charmonium states in a plasma [6]. However, several alternate scenarios have been proposed which do not involve deconfinement effects [7]. These models are difficult to rule out at present, since there is significant uncertainty in many of the parameters. It appears that a precision systematic study of suppression patterns of many states in the quarkonium systems will be necessary for a definitive interpretation.

In all of the above, a tacit assumption has been made: the heavy quarkonium is formed only during the initial nucleon-nucleon collisions. Once formed, subsequent interactions with nucleons or final state interactions in a quark-gluon plasma or with other produced hadrons can only reduce the probability that the quarkonium will survive and be observed. We study in this letter a scenario which will be realized at RHIC and LHC energies, where the average number of heavy quark pairs produced in the initial (independent and incoherent) nucleon-nucleon collisions will be substantially above unity for a typical central heavy ion interaction. Then *if and only if a space-time region of deconfined quarks and gluons is present*, it will be possible for quarkonium states to be formed from combinations of heavy quarks and antiquarks which were initially produced in different nucleon-nucleon collisions. This new mechanism of heavy quarkonium production has the possibility to be the dominant factor in determining the heavy quarkonium population observed after hadronization. To be specific, let N_0 be the number of heavy quark pairs initially produced in a central heavy ion collision, and let N_1 be the number of those pairs which form bound states in the normal confining vacuum potential. The final number N_B of bound states surviving at hadronization will be some fraction ϵ of the initial number N_1, plus the number formed by this new mechanism from the remaining $N_0 - N_1$ heavy quark pairs. (We include in the new mechanism both formation and suppression effects, since they occur simultaneously in the deconfined region.) The instantaneous formation rate of N_B by this new mechanism will be proportional to the square of the number of unbound quark pairs, which we approximate by its initial value. (This is valid as long as $N_B << N_0$, which we demonstrate is valid in our model calculations.) Thus we expect that the number of bound states formed during the deconfinement lifetime will remain proportional to the square of the initial unbound charm population, and introduce a proportionality parameter β. The final population is then

$$N_B = \epsilon N_1 + \beta(N_0 - N_1)^2. \tag{1}$$

For a central collision with N_0 initially-produced heavy quark pairs, we then average over the distribution of N_1, introducing the probability x that a given heavy quark pair was in a bound state before the deconfined phase was formed. (This factor includes the effect of breakup by collisions with target and projectile nucleons). We finally average over the distribution of N_0, using a Poisson distribution with average value $\bar{N}_0$, to obtain the expected $< N_B >$ final population per collision,

$$< N_B >= x\bar{N}_0(\epsilon + \beta(1-x)) + \bar{N}_0(\bar{N}_0 + 1)\beta(1-x)^2. \tag{2}$$

The bound state "suppression" factor S_B is just the ratio of this average population to the average initially-produced bound state population per collision, $x\bar{N}_0$.

$$S_B = \epsilon + \beta(1-x) + \beta\frac{(1-x)^2}{x}(\bar{N}_0 + 1) \tag{3}$$

Without the new production mechanism, $\beta = 0$ and the suppression factor is $S_B = \epsilon < 1$ [8]. However, it is now possible that for sufficiently large values of β and $\bar{N}_0$ this factor could actually exceed unity, i.e. one would predict an **enhancement** in the heavy quarkonium production rates to be the signature of deconfinement! We thus proceed to estimate expected β-values for J/ψ production at RHIC.

We consider the dynamical evolution of the $c\bar{c}$ pairs which have been produced in a central Au-Au collision at $\sqrt{s} = 200$A GeV [9]. For simplicity, we assume the deconfined phase is an ideal gas of free gluons and light quarks. Any J/ψ in this medium will be subject to dissociation via collisions with gluons. (This is the dynamic counterpart of the plasma screening scenario, in which the color-confinement force is screened away in the hot dense plasma [10,11].) The primary formation mechanism is just the inverse of the dissociation reaction, in which a free charm quark and antiquark are captured in the J/ψ bound state, emitting a color octet gluon. Thus it is unavoidable for this model of quarkonium suppression that a corresponding mechanism for quarkonium production must be present. The competition between the rates of these reactions integrated over the lifetime of the QGP then determines the final J/ψ population. Note that in this scenario it is impossible to separate the formation process from the dissociation (suppression) process. Both processes occur simultaneously, in contrast to the situation in which the formation only occurs at the initial times before the QGP is present.

We omit consideration of other reactions involving charm quarks in the QGP, since the rates are much smaller than those above. For example, formation of D and D_s mesons is not possible at the high initial temperatures expected at RHIC since their lower binding energies prevents them from existing in a hot QGP, or equivalently they are ionized on very short time scales. They will be formed predominantly at hadronization, but this process is too late to affect the final J/ψ population. We also neglect the effects of light quarks, since their population is expected to be very much suppressed relative to gluons during the early times when the dissociation reaction rate has its most significant effect [12]. The time evolution if the J/ψ population is then given by

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_{\mathrm{F}} N_c\, \rho_{\bar{c}} - \lambda_{\mathrm{D}} N_{J/\psi}\, \rho_g\,, \tag{4}$$

where τ is the proper time in a comoving volume cell and ρ_i denotes the number density $[L^{-3}]$ of species i. The reactivity λ $\left[L^3/\mathrm{time}\right]$ is the reaction rate $\langle \sigma v_{\mathrm{rel}} \rangle$ averaged over the momentum distribution of the initial participants, i.e. c and $\bar{c}$ for λ_F and J/ψ and g for λ_D. The gluon density is determined by the equilibrium value in the QGP at each temperature. To get a lower bound on the J/ψ production rate, we neglect additional production of charm pairs in the deconfined region, and use only the initial number $N_0 - N_1$ for both charm and anticharm quarks. Exact charm conservation is enforced throughout the calculation. The initial volume at $\tau = \tau_0$ is allowed to undergo longitudinal expansion $V(\tau) = V_0\tau/\tau_0$. The expansion is taken to be isentropic, $VT^3 =$ constant, which then provides a generic temperature-time profile. For simplicity, we assume the transverse spatial distributions are uniform, and use a thermal equilibrium momentum distribution for both gluons and charm quarks. (This last simplification requires large energy loss mechanisms for the charm quarks in the deconfined medium, which is indicated by several recent studies [13]).

For our quantitative estimates, we utilize a cross section for the dissociation of J/ψ due to collisions with gluons which is based on the operator product expansion [14]:

$$\sigma_D(k) = \frac{2\pi}{3}\left(\frac{32}{3}\right)^2\left(\frac{2\mu}{\epsilon_o}\right)^{1/2}\frac{1}{4\mu^2}\frac{(k/\epsilon_o - 1)^{3/2}}{(k/\epsilon_o)^5}, \tag{5}$$

where k is the gluon momentum, ϵ_o the binding energy, and μ the reduced mass of the quarkonium system. This form assumes the quarkonium system has a spatial size small compared with the inverse of Λ_{QCD}, and its bound state spectrum is close to that in a nonrelativistic Coulomb potential. The magnitude of the cross section is controlled just by the geometric factor $4\mu^2$, and its rate of increase in the region just above threshold is due to phase space and the p-wave color dipole interaction.

This same cross section is utilized with detailed balance factors to calculate the primary formation rate for the capture of a charm and anticharm quark into the J/ψ.

With these inputs and assumtions, the solution of Eq. 4 is precisely that anticipated in Eq. 1, with

$$\epsilon(\tau_f) = e^{-\int_{\tau_0}^{\tau_f} \lambda_{\rm D}\, \rho_g \, d\tau}, \tag{6}$$

where τ_f is the hadronization time determined by the initial temperature (T_0 is a variable parameter) and final temperature ($T_f = 150$ MeV ends the deconfining phase), and

$$\beta(\tau_f) = \epsilon(\tau_f) \times \int_{\tau_0}^{\tau_f} \lambda_{\rm F}\, [V(\tau)\, \epsilon(\tau)]^{-1}\, d\tau. \tag{7}$$

Some typical calculated values of the J/ψ final population are shown in Fig. 1. The parameter values for thermalization time $\tau_0 = 0.5$ fm, initial volume $V_0 = \pi R^2 \tau_0$ with R = 6 fm, and a range of initial temperature 300 MeV $< T_0 <$ 500 MeV, are all compatible with expectations for a central collision at RHIC. This calculation maintained exact charm conservation, so that the solutions followed evolution of both bound and free charm quarks.

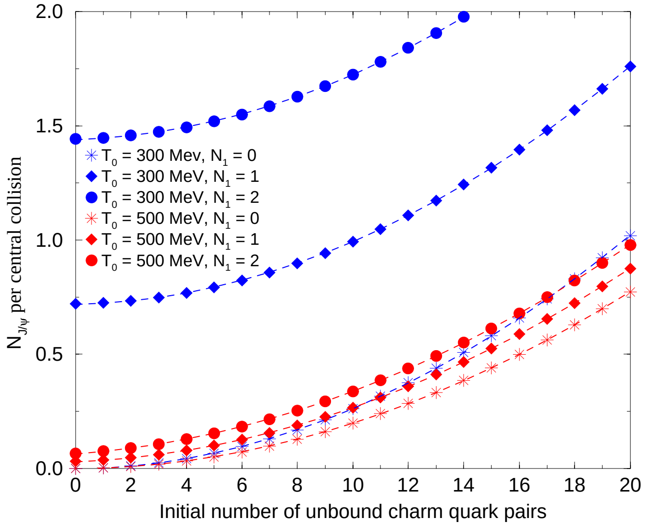

FIG. 1. Calculated J/ψ formation in deconfined matter at several initial temperatures, for central collisions at RHIC as a function of initial charm pair and J/ψ production.

The quadratic fits of Eq.1 are superimposed, verifying our expectations that the decrease in initial unbound charm is a small effect [15]. The fitted ϵ values decrease quite rapidly with increasing T_0 as expected, and give reasonable upper limits [8] for the suppression factor of directly-produced J/ψ in central collisions at RHIC due to gluon dissociation in a deconfined phase. The corresponding β values are relatively insensitive to T_0, remaining in the range $2.0 - 2.6 \times 10^{-3}$. These fitted parameters must be supplemented by values of x and $\bar{N}_0$ to determine the "suppression" factor from Eq. 3 for the new mechanism. We use the nuclear overlap function T_{AA}(b=0) = 29.3 mb^{-1} for Au, and a pQCD estimate of the charm production in p-p collisions at RHIC energy $\sigma(pp->c\bar{c})$ = 350 μb [16] to estimate $\bar{N}_0$ = 10 for central collisions. The parameter x contains the fraction of initial charm pairs which formed J/ψ states before the onset of deconfinement. Fitted values from a color evaporation model [17] are consistent with 10^{-2}, which we adopt as an order of magnitude estimate. This must be reduced by the suppression due to interactions with target and beam nucleons. For central collisions we use 0.6 for this factor, which results from the extrapolation of the observed nuclear effects for p-A and smaller A-B central interactions. With these parameters fixed, we predict from Eq. 3 an **enhancement** factor for J/ψ production of $3.6 < S_{J/\psi} < 5.4$, for initial temperatures between 300 and 500 MeV. This is a huge increase (factors of approximately one to two orders of magnitude) over that which would be predicted from suppression of initially-produced J/ψ alone.

One can also predict how this new effect will vary with the centrality of the collision, which has been a key feature of deconfinement signatures analyzed at CERN SPS energies [5]. To estimate the centrality dependence, we repeat the calculation of the ϵ and β parameters using appropriate variation of initial conditions with impact parameter b. From nuclear geometry and the total non-diffractive nucleon-nucleon cross section at RHIC energies, one can estimate the total number of participant nucleons $N_P(b)$ and the corresponding density per unit transverse area $n_P(b,s)$ [18]. The former quantity has been shown to be directly proportional to the total transverse energy produced in a heavy ion collision [19]. The latter quantity is used, along with the Bjorken-model estimate of initial energy density [20], to provide an estimate of how the initial temperature of the deconfined region varies with impact parameter. We also use the ratio of these quantities to define an initial transverse area within which deconfinement is possible, thus completing the initial conditions needed to calculate the J/ψ production and suppression. The average initial charm number $\bar{N}_0$ varies with impact parameter in proportion to the nuclear overlap integral T_{AA}(b). The impact-parameter dependence of the fraction x is determined by the average path length encountered by initial J/ψ as they pass through the remaining nucleons, $L(b)$ [4]. All of these b-dependent effects are normalized to the previous values used for calculations at $b = 0$.

It is revealing to express these results in terms of the ratio of final J/ψ to initially-produced charm pairs. In Fig.2, the solid symbols are the full results predicted with the inclusion of our new production mechanism at RHIC. The centrality dependence is represented by the total participant number N_P(b). For comparison we also show predictions without the new mechanism, when only dissociation by gluons is included ($\lambda_F = 0$). It is evident not only that the new mechanism dominates the J/ψ production in the deconfined medium at all impact parameters, but also that an increase rather than a decrease is predicted for central collisions. These features should be distinguishable in the upcoming RHIC experiments.

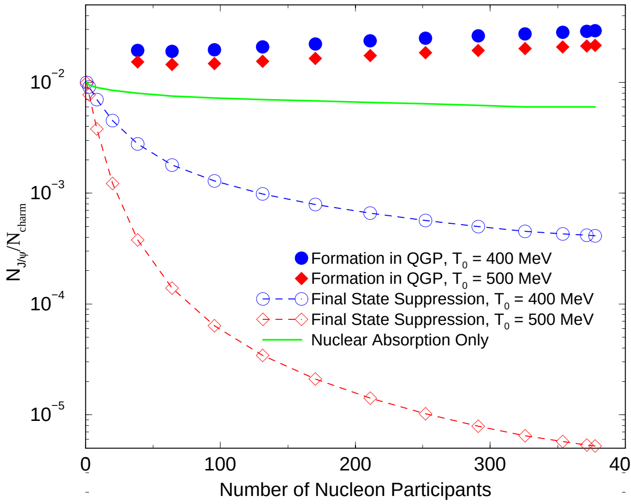

FIG. 2. Ratio of final J/ψ to initial charm as a function of centrality, due to nuclear absorption only (solid line), after final state suppression by a QGP (dashed lines), and with inclusion of the new formation mechanism in the deconfined medium (solid symbols).

Finally, we consider the effects of variations in our parameters and assumptions.

1. The initial charm production at RHIC could be decreased due to nuclear shadowing of the gluon structure functions. Model estimates indicate this effect could result in about a 20% reduction [21]. This factor would directly reduce the new production to charm ratio by the same amount.

2. The validity of the cross section used assumes strictly nonrelativistic bound states, which is somewhat marginal for the J/ψ. Several alternative models for this cross section result in substantially higher values. When we arbitrarily increase the cross section by a factor of two, or alternatively set the cross section to its maximum value (1.5 mb) at all energies, we find an increase in the final J/ψ population of about 15%. This occurs because the kinetics always favors formation over dissociation, and a larger cross section just allows the reactions to approach completion more easily within the lifetime of the QGP.

3. A nonzero transverse expansion will be expected at some level, which will reduce the lifetime of the QGP and reduce the efficiency of the new formation mechanism. We have calculated results for central collisions with variable transverse velocity, and find a decrease in the parameter β of about 15% for each increase of 0.2 in the transverse velocity.

4. In our model of a deconfined region, we have used the vacuum values for masses and binding energy of J/ψ, and assumed that the effects of deconfinement are completely included by the dissociation via gluon collisions. For a complementary viewpoint, we have also employed a deconfinement model in which the J/ψ is completely dissociated when temperatures exceed some critical screening value T_s. Below that temperature, the new formation mechanism will still be able to operate, and we use the same cross sections and kinematics. We find that for T_s = 280 MeV, the final J/ψ population is approximately unchanged, while decreasing T_s to 180 MeV could reduce the J/ψ production by factors of 2 or 3.

5. Model calculations of the approach to chemical equilibrium for light quarks and gluons indicate that the initial density of gluons in a QGP fall substantially below that for full phase space occupancy. We have checked our model predictions in this scenario, using a factor of two decrease in the gluon density at τ_0. As one would expect, this decreases the effectiveness of the dissociation process, such that the final J/ψ production is increased by about 35%.

6. Our model for the new formation mechanism requires that the charm quarks be mobile in the deconfined phase, and that they have sufficient overlap in phase space for the formation process to be effective during the QGP lifetime. Our assumption of thermal energy distributions may be somewhat optimistic. To get an idea of the extreme opposite scenario, we repeated the calculations with charm quark momentum distributions given by the perturbative QCD production processes. At RHIC energies, these involve a relative broad rapidity distribution and a gaussian distribution in transverse momentum. We find that when all charm quarks are restricted to a rapidity interval of one unit, the production process is essentially unchanged from that for a thermal distribution. The maximum possible effect occurs when the charm quark rapidity distribution is flat over the initial range of about seven units, certainly an extreme assumption. The final production numbers then decrease by approximately this same factor (7) for central collisions, but the remaining formation effect is still more than an order of magnitude above that for suppression alone.

7. A hadronic analog of our new production mechanism can also occur for interactions in a hot hadronic gas. This has been investigated for J/ψ production by collisions of D mesons [22]. It was found that the magnitude of these hadronic processes will be entirely negligible at RHIC energies. Even at the LHC, only a small effect may be possible to observe for ψ' production. If there is a period of mixed phase in a first-order transition, additional J/ψ formation may take place also in the deconfined portion. We have not included such a possibility, and hence

work with a lower bound in this respect.

Taken together, all of these changes in our standard scenario for the new production mechanism involve either increases or decreases in the final J/ψ population at RHIC by amounts typically in the tens of percents, with a few factors ranging up to 2 or 3. Thus it is highly unlikely that the orders of magnitude increase for central collisions will be wiped out by the cumulative effect of these variations.

In summary, we predict that at high energies the J/ψ production rate will provide an even better signal for deconfinement than originally proposed. Consideration of multiple heavy quark production made possible by higher collision energy effectively adds another dimension to the parameter space within which one searches for patterns of quarkonium behavior in a deconfined medium. The orders of magnitude increase predicted at RHIC by our new production mechanism, coupled with the dependence on centrality, provide a signal which will be difficult to imitate with conventional hadronic processes. The extension of this scenario to LHC energies will involve hundreds of initially-produced charm quark pairs, and we expect the effects of this new production mechanism to be striking.

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