Enhanced J/ψ production in deconfined quark matter

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(Received 29 August 2000; published 23 April 2001)

In high energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider at CERN, each central event will contain multiple pairs of heavy quarks. If a region of deconfined quarks and gluons is formed, a mechanism for additional formation of heavy quarkonium bound states will be activated. This is a result of the mobility of heavy quarks in the deconfined region, such that bound states can be formed from a quark and an antiquark that were originally produced in separate incoherent interactions. Model estimates of this effect for J/ψ production at RHIC indicate that significant enhancements 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 Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) 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 (QGP). 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 [3] that points toward an interpretation in terms of interactions of an initial quarkonium state 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 that have been interpreted as threshold behavior due to dissociation of charmonium states in a plasma [6]. However, several alternate scenarios have been proposed that 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. Here we explore a scenario that 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*, quarkonium states will be formed from combinations of heavy quarks and antiquarks that were initially produced in different nucleon-nucleon collisions.

This mechanism of heavy quarkonium production has the potential 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 that 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 particular mechanism from the remaining N_0-N_1 heavy quark pairs. (We include in this mechanism both formation and dissociation in the deconfined region.) The instantaneous formation rate of N_B 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 $N_B \ll N_0$, which we demonstrate is valid in our model calculations. We also show in our model calculations that the time scales for the formation and dissociation processes are typically somewhat larger than the expected lifetime of the deconfined state. Thus there will be insufficient time for the relative populations of bound and unbound heavy quarks to reach an equilibrium value, and we anticipate that the number of bound states existing at the end of the deconfinement lifetime will remain proportional to the square of the initial unbound charm population. We introduce a proportionality parameter β, to express the final population as

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

We then average over the distributions of N_1 and N_0,

introducing the probability x that a given heavy quark pair was in a bound state before the deconfined phase was formed.

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, $x\bar{N}_0$.

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

Without this production mechanism, $\beta = 0$ and the suppression factor S_B is bounded by $\epsilon < 1$. But for sufficiently large values of $\bar{N}_0$ 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.

Let us emphasize at the outset that we are not attempting a detailed phenomenology of J/ψ production at RHIC. The goal is merely to estimate if our formation mechanism could have a significant impact on the results. We consider the dynamical evolution of the $c\bar{c}$ pairs that have been produced in a central Au-Au collision at $\sqrt{s} = 200A$ GeV. This is adapted from our previous calculation of the formation of B_c mesons [8]. For simplicity, we assume the deconfined phase is an ideal gas of free gluons and light quarks. To describe the ''standard model'' scenario for suppression of J/ψ in the deconfined region, we utilize the collisional dissociation via interactions with free thermal gluons. (This is the dynamic counterpart of the static plasma screening scenario [9].) Our formation mechanism is just the inverse of this dissociation reaction, when a free charm quark and antiquark are captured in the J/ψ bound state, emitting a color octet gluon. Thus it is an unavoidable consequence in 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. Our estimates result from numerical solutions of the kinetic rate equation

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_F N_c \rho_{\bar{c}} - \lambda_D N_{J/\psi} \rho_g, \qquad (3)$$

where τ is the proper time, ρ denotes number density, and the reactivity λ 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. Formation of other states containing charm quarks is expected to occur predominantly at hadronization, since their lower binding energies prevent them from existing in a hot QGP, or equivalently they are ionized on very short time scales.

The gluon density is determined by the equilibrium value in the QGP at each temperature. Initial charm quark numbers are given by N_0 and N_1, and 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. We use 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, which are all compatible with expectations for a central collision at RHIC. For simplicity, we assume the transverse spatial distributions are uniform, and use a thermal momentum distribution for gluons. Sensitivity of the results to these parameter values and assumptions will be presented later.

The formation rate for our mechanism has significant sensitivity to the charm quark momentum distribution, and we thus consider a wide variation for this quantity. At one extreme, we use the initial charm quark rapidity interval and transverse momentum spectrum unchanged from the perturbative QCD production processes. We then allow for energy loss processes in the plasma by reducing the width of the rapidity distribution, terminating with the opposite extreme when the formation results are almost identical to those that would result if the charm quarks were in full thermal equilibrium with the plasma. This range approximately corresponds to changing the rapidity interval Δy between one and four units.

We utilize a cross section for the dissociation of J/ψ due to collisions with gluons that is based on the operator product expansion [10]:

$$\sigma_D(k) = \frac{2\pi}{3}\left(\frac{32}{3}\right)^2 \left(\frac{2\mu}{\epsilon_0}\right)^{1/2} \frac{1}{4\mu^2} \frac{(k/\epsilon_0 - 1)^{3/2}}{(k/\epsilon_0)^5}, \qquad (4)$$

where k is the gluon momentum, ϵ_0 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. 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.

We have also considered a scenario in which a static screening of the color force replaces the gluon dissociation process, and dominates the suppression of initially-produced J/ψ. Equivalently, the binding ϵ_0 decreases from its vacuum value and vanishes at high temperature. As a simple approximation to this behavior, we multiply the vacuum value by a step function at some screening temperature T_s, such that total screening is active at high temperature and the formation mechanism is active at low temperatures. The numerical results for these two scenarios are identical for a screening temperature $T_s = 280$ MeV. The screening scenario predictions fall somewhat below the gluon dissociation results for lower T_s. They differ by a maximum factor of 2 when T_s decreases to 180 MeV (we have used a deconfinement temperature of 150 MeV).

We show in Fig. 1 sample calculated values of J/ψ per central event as a function of initial number of unbound charm quark pairs. Quadratic fits of Eq. (1) are superimposed. This is a direct verification of our expectations that the final J/ψ population in fact retains the quadratic dependence of the initial formation rate. This also verifies that the decrease in initial unbound charm is a small effect. (These
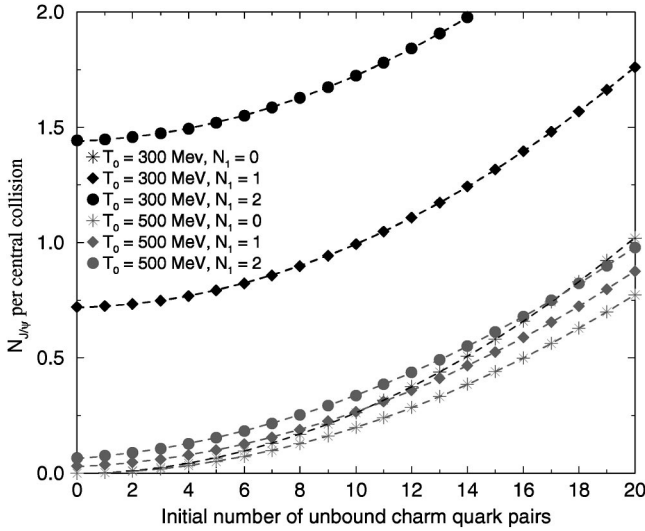
FIG. 1. Calculated J/ψ formation in deconfined matter at several initial temperatures, $\Delta y = 1$, for central collisions at RHIC as a function of initial charm pair (N_0) and J/ψ (N_1) values.

fits also contain a small linear term for the cases in which N_1 is nonzero, which accounts for the increase of the unbound charm population when dissociation occurs.) We then extract the fitted parameters over our assumed range of initial temperature and charm quark rapidity width. The fitted ϵ values decrease quite rapidly with increasing T_0 as expected, and are entirely insensitive to Δy. The corresponding β values have a significant dependence on Δy. They are less sensitive to T_0, but exhibit an expected decrease at large T_0 due to large gluon dissociation rates at initial times (counterpart of color screening).

These fitted parameters must be supplemented by values of x and $\bar{N}_0$ to determine the ''suppression'' factor from Eq. (2) for this mechanism. We use the nuclear overlap function $T_{AA}(\text{b}=0) = 29.3$ mb^{-1} for Au, and a pQCD estimate of the charm production in p-p collisions at RHIC energy $\sigma(pp \rightarrow c\bar{c}) = 350$ μb [11] to estimate $\bar{N}_0 = 10$ for central collisions.

The parameter x contains the fraction of initial charm pairs that formed J/ψ states before the onset of deconfinement. Fitted values from a color evaporation model [12] 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. (2) an *enhancement* factor for J/ψ production of $1.2 < S_{J/\psi} < 5.5$, where this range of values includes the full range of initial parameters, i.e., initial temperatures between 300 and 500 MeV and charm quark rapidity ranges between 1 and 4. This is to be compared with predictions of models that extrapolate existing suppression mechanisms to RHIC conditions, resulting in typical suppression factors of 0.05 for central collisions [13]. Note that in addition to the qualitative change between suppression and enhancement, the actual numerical

difference should be easily detectable by the RHIC experiments.

One can also predict how this 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 nondiffractive 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 $n_P(b,s)$ [14]. The former quantity has been shown to be directly proportional to the total transverse energy produced in a heavy ion collision [15]. The latter quantity is used, along with the Bjorken-model estimate of initial energy density [16], 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, both of which will be measurable at RHIC. (This normalization automatically eliminates the trivial effects of increased collision energy and phase space.) In Fig. 2, the solid symbols are the full results predicted with the inclusion of our production mechanism. We include full variation of these results with initial temperature (squares, circles, and diamonds are $T_0 = 300$, 400, 500 MeV, respectively), charm quark distribution (full lines are thermal, combinations of dashed and dotted lines use Δy ranging from 1 through 4), and also variation with screening temperature for the alternate scenario (triangles with $T_s = 200$, 240, and 280 MeV).

The centrality dependence is represented by the total participant number $N_P(b)$. The effect is somewhat obscured by the log scale, but the ratio predictions typically increase about 50% between peripheral and central events. Note that this increase is in addition to the expected dependence of total charm production on centrality, so that the quadratic nature of our production mechanism is evident.

We also show for contrast the results without our mechanism, when only dissociation by gluons is included ($\lambda_F = 0$ for curves with open symbols). These results have the opposite centrality dependence, and the absolute magnitudes are very much smaller. It is evident that our mechanism dominates J/ψ production in a deconfined medium at all but the largest impact parameters, and that this situation survives uncertainties associated with variation in model parameters.

For completeness, we list a few effects of variations in our other parameters and assumptions that have relatively minor impact on the results.
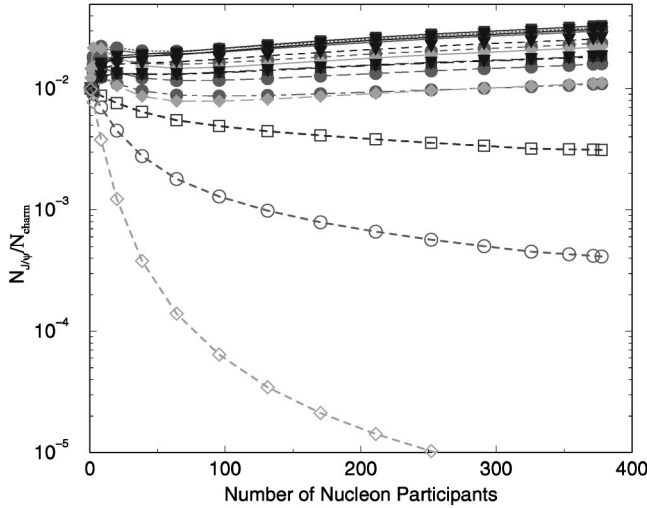
FIG. 2. Ratio of final J/ψ to initial charm as a function of centrality. The solid symbols are with the inclusion of our formation mechanism in the deconfined medium. Initial plasma temperature T_0 is coded by squares (300 MeV), circles (400 MeV), and diamonds (500 MeV). Different charm quark momentum distributions are indicated by the solid lines (thermal) and combinations of dashed and dotted lines ($\Delta y = 1,2,3,4$). The alternate screening model results are given by triangles, using $T_s = 200$, 240, and 280 MeV. Curves with open symbols are the same calculations with our formation mechanism omitted.

FIG. 3. Predicted energy dependence of J/ψ at RHIC.

(1) The initial charm production at RHIC could be decreased due to nuclear shadowing of the gluon structure functions. Model estimates [17] indicate this effect could result in up to a 20% reduction.

(2) The validity of the cross section used assumes strictly nonrelativistic bound states. Several alternative models for this cross section result in substantially higher values. When we arbitrarily increase the cross section by a factor of 2, 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 formation mechanism. We have calculated results for central collisions with variable transverse expansion, and find a decrease in the parameter β of about 15% for each increase of 0.2 in the transverse velocity.

(4) 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 2 decrease in the gluon density at τ_0. This decreases the effectiveness of the dissociation process, such that the final J/ψ production is increased by about 35%. We also justify neglecting dissociation via collisions with light quarks in this scenario, since the population ratio of quarks to gluons is expected to be a small
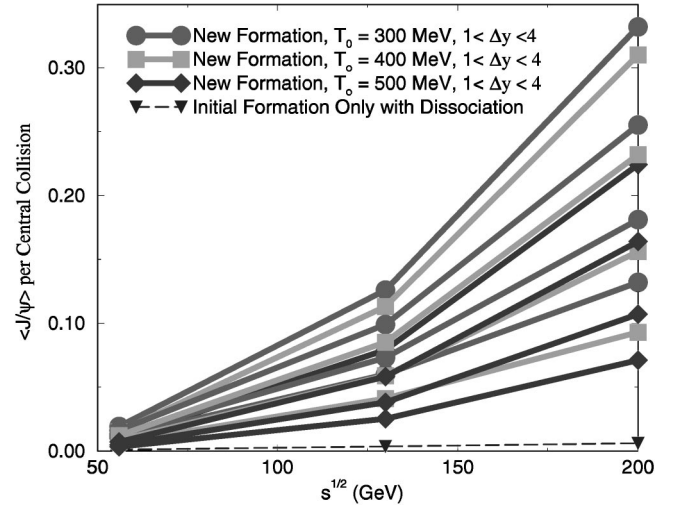
fraction. This is potentially important, since the inverse process is inhibited by the required three-body initial state.

(5) The effect of a finite J/ψ formation time may also be considered. The total effect is a competition between delayed dissociation (J/ψ cannot be dissociated before formation) and a possible loss of states whose formation started just before the hadronization point. A conservative upper limit would bound any decrease by the ratio of formation to QGP lifetime, certainly in the 15% range.

(6) Although our formation mechanism is large compared with dissociation, it is small on an absolute basis, with J/ψ yields only a few percent of total charm. These small values can be traced in part to the magnitude of spatial charm density, which enters in the calculation of time-integrated flux of charm quark pairs. Our assumption of constant spatial density certainly underestimates the charm density, since it is likely somewhat peaked toward the center of the nuclear overlap region in each collision. A correspondingly smaller deconfined region is also to be expected, but it will still contain virtually all initial charm and have a similar time and longitudinal expansion profile. Thus a more realistic spatial model should increase the formation yield beyond our simple estimates.

Overall, 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 recent initial operation of RHIC at $\sqrt{s} = 56$ and 130 GeV provides an opportunity to test the predicted energy dependence of this new mechanism. We show in Fig. 3 the expected energy variation of the total J/ψ yield per central collision at RHIC. The individual lines include full variation over the initial temperature and charm quark momentum distributions. The strong increase with energy comes from the quadratic dependence on initial charm production, coupled with the increase of the charm production cross section with

energy as calculated in pQCD [11]. For comparison, we show the energy dependence that results from just initial production, followed by dissociation alone. If such a strong increase is observed at RHIC, it would signal the existence of a production mechanism nonlinear in initial charm.

Taken together, the enhanced magnitude and centrality and energy dependence predict signals that 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 production mechanism to be striking.

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