J/Psi Production at RHIC in a QGP

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In central collisions at RHIC, the initial production of heavy quarks will for the first time yield multiple pairs of $c\bar{c}$ 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. Our model estimates of this effect predict a dramatic increase in the number of observed $J/\psi$ at RHIC, over that predicted from extrapolation of color-screening or gluon dissociation mechanisms from the lower CERN-SPS energies. The centrality and energy dependence of this effect should be readily observable by the Star and Phenix detectors. Thus the $J/\psi$ abundance at RHIC will continue to provide a signature of QGP formation. However, it is in this environment a more useful probe, since contrary to prior expectations this large predicted $J/\psi$ abundance should be relatively easy to measure.

1. Introduction

The pattern of “anomalous suppression” of $J/\psi$ observed by the NA50 experiment in Pb-Pb collisions at CERN \textsuperscript{[1]} has been interpreted in terms of the effects of quark-gluon plasma formation.\textsuperscript{[2]} A straightforward extension of this scenario to RHIC collisions would predict that virtually all of the initially-produced $J/\psi$ would be suppressed, even for relatively peripheral collisions.\textsuperscript{[3,4]} In these pictures, the formation of $J/\psi$ from a pair of charm quarks only occurs at the initial times. Subsequent to that, the final state effects of interactions with nucleonic matter, plasma screening, and dissociation by collisions with deconfined gluons lead to the observed suppression. Recombination of the charm quarks into a $J/\psi$ at hadronization is much less likely than formation of open charm particles, thus preserving the suppression effect. A tacit assumption in this chain of arguments is that there is no recombination of charm quarks while in the deconfined state. While this may be approximately true in terms of numerical significance, it is of course theoretically inconsistent to neglect the recombination process. For example, formation by capture from an octet state with single gluon emission is precisely the inverse of the primary gluon dissociation process. The existence of both of these processes depend on the ability of deeply-bound states such as the $J/\psi$ to exist above the deconfinement transition.\textsuperscript{[5]}

\textsuperscript{*}Supported in part by U.S. Department of Energy Grant DE-FG02-95ER40213
These considerations have the potential to become numerically significant at RHIC energies and above. Estimates of initial production from pQCD calculations indicate that approximately 10 charm quark pairs will be present in each central Au-Au collision at 200A GeV energy. Since the formation rate will be proportional to the square of the number of unbound charm quarks, there is a possibility that the recombination effect can increase dramatically. It has been noted recently that a statistical recombination model utilizing increased heavy quark production at high energy will also result in formation of hidden-flavor enhanced by a quadratic dependence on total heavy flavor.\[6,7\] We emphasize that our mechanism is quite distinct, in that a space-time region of color deconfinement is a necessary condition for the existence of our formation and dissociation processes.

2. Kinetic model

We estimate the expected $J/\psi$ population at RHIC in a detailed kinetic model, in which the competing rates of formation and dissociation are controlled by input densities.

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_F N_c \rho_c - \lambda_D N_{J/\psi} \rho_g,$$

(1)

where $\tau$ is the proper time, $\rho$ denotes number density, and the reactivity $\lambda$ is the reaction rate $\langle \sigma v_{\text{rel}} \rangle$ averaged over the momentum distribution of the initial participants, i.e. $c$ and $\bar{c}$ for $\lambda_F$ and $J/\psi$ and $g$ for $\lambda_D$.

The gluon density is that of an ideal gas in thermal and chemical equilibrium. The initial charm quark population is due to initial production of charm quark pairs according to pQCD calculations. We assume one-dimensional isentropic expansion to get a generic time-temperature profile. The formation process is radiative (gluon) capture from a c-cbar pair in a color octet state. The formation process is just the inverse reaction, and the final $J/\psi$ population will be determined by the time integral of the rates for these competing reactions. (Note that in this scenario the D mesons and other hidden charm bound states do not appear in the kinetic equation, since their relatively small binding energies prohibit their existence in a deconfined medium.) For further details of our kinetic model see \[8\]. The magnitude of the formation term is quite sensitive to the momentum distribution of the charm quarks. We consider a wide range of possible distributions, ranging from a thermal distribution at the plasma temperature to the initial momentum distribution of the pQCD production process.

3. Results

The time evolution of the $J/\psi$ population is shown in Figure 1 for a typical choice of parameters. Also shown are the formation and dissociation rates. One sees that the formation rate drops due to the reduced charm quark density as the system expands, but remains larger than the dissociation rate at all times. This feature originates in the detailed balance factors which favor the exothermic formation process. Note that the final population of about 0.2 $J/\psi$ per collision is greater than that expected from a simple superposition of nucleon-nucleon interactions, typically about 1% of the 10 initial charm quark pairs produced. In Figure 2 we verify the anticipated quadratic dependence on the
initial number of charm quark pairs (exact charm conservation was enforced throughout the numerical solution of the kinetic equations).

We then average over a distribution of initial charm and $J/\psi$ to obtain the final $J/\psi$ population as a function of average initial charm. The results are shown in Figure 3 for various charm quark momentum distributions. We parameterize those from the initial pQCD calculations in terms of an effective rapidity width $\Delta y$.

One sees that even within the variation due to the momentum distribution, the final $J/\psi$ population exceeds that expected from a superposition of nucleon-nucleon collisions (the canonical 1 % of initial charm indicated by the short dashed line), and is very far above that which would follow from a screening suppression factor typically 0.05 for RHIC (the long dashed line).

Variation with centrality can also be calculated in this model. We predict a unique behavior in this case, since the quadratic dependence on total charm produces an effect which grows with centrality. This is in strong contrast with a pure screening scenario, in which the maximum suppression occurs for central events. For details, see Ref. [8].

Finally, we consider the energy dependence within the RHIC range. The effect here is due to the energy dependence of the initial quark production, which is not far from linear in this limited range. The results are shown in Figure 4 for a full range of possible charm quark momentum distributions. One sees a similar behavior with respect to initial production and screening suppression as was noted in Figure 3. Thus it is possible to scan through the initial charm to see the quadratic dependence by performing an equivalent scan through a corresponding energy range.
4. Discussion

The magnitude of enhanced $J/\psi$ yields at RHIC depends on model parameters which may be subject to some changes as details of the deconfined region emerge from data. However, inclusion of the formation process will always lead to an enhancement of $J/\psi$ yields over any calculation in which dissociation from deconfined gluon collisions plays a role. Independent of magnitudes, some key characteristics of the basic physics process will always remain. Especially significant are the quadratic dependence on initial charm and the increase with centrality. These features are quite distinct from those obtained by simple extrapolation of deconfinement scenarios at SPS energies, and should provide model-independent tests. Since our mechanism is operable only for the deeply-bound states, the predictions also differ from statistical hadronization scenarios. We also anticipate significant differences in the momentum spectra, which will be the subject of future work.

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