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B_c PRODUCTION AT RHIC AS A SIGNAL FOR DECONFINEMENT*

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The B_c meson is the bound state of $b\bar{c}$ (or $\bar{b}c$) whose recent detection is the first step toward completion of the spectroscopy of heavy quark mesonic states. The b-c states have properties that conveniently fill the gap between the J/ψ and the Υ states. Thus it is probable that at RHIC the B_c mesons will serve as a probe of deconfined matter. We find that significant differences arise for B_c formation in deconfined and confined matter. Our initial calculations suggest that:

(a) The rates of normal hadronic production mechanisms at RHIC energies are not sufficient to produce a detectable number of B_c mesons.

(b) If a region of deconfined quarks and gluons is formed, the production (and survival) rate can be enhanced by several orders of magnitude.

(c) The observation of B_c mesons at RHIC would signal a source of deconfined charmed quarks, and the rate of B_c production will be a measure of the initial density and temperature of that source.

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1. Introduction

This work investigates the possibility that the production of B_c mesons at RHIC may serve as a signal for the presence (or absence) of a deconfined state of matter [1]. The study of the b-c sector has the advantage of a long history of potential model analysis in the $b\bar{b}$ and $c\bar{c}$ sectors. These studies have provided robust predictions for the mass and lifetime of the B_c states [2], and the recent measurements by CDF [3] are consistent with those calculations.

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First let us estimate at RHIC the production rate of different heavy quarks and mesons, which one would expect if it results just from a superposition of the initial nucleon-nucleon collisions. For heavy quark production, pQCD calculations for p-p interactions fit present accelerator data and bracket the RHIC energy range. Hard Probes Collaboration [4] estimates indicate about 10 $c\bar{c}$ pairs and 0.05 $b\bar{b}$ pairs per central collision at RHIC. J/ψ and Υ production involves the use of some model, such as the Hard Probes color singlet fits [5], which would predict bound state fractions of order somewhat less than the one percent level.

A similar analysis for B_c production reaches significantly different results[1] Since the b and $\bar{c}$ must be produced in the same nucleon-nucleon interaction, parton subprocesses of order α_s^4 are the leading order contributions. This leads to a substantial reduction of the bound state fraction

$$R_b \equiv \frac{B_c + B_c^*}{b\bar{b}}$$

relative to the few percent levels for the corresponding Υ state fractions. At RHIC energies, typical values are $R_b = 3 - 10 \times 10^{-5}$, with the uncertainty from the scale choice in the pQCD calculations [6].

To convert these numbers into B_c production predictions for RHIC, we have looked at two scenarios for the luminosity. a) The “first year” case assumes a luminosity of 20 inverse microbarns with no trigger. b) The “design” luminosity assumes 65 Hz event rate with a 10% centrality trigger in Phenix, and uses 10^7 sec/year. The predictions we obtain are listed in Table I. Included in the estimates are both the weak branching fraction of the B_c plus the dimuon decay fraction for J/ψ. Similar numbers are shown for the J/ψ and Υ production and detection via $\mu^+\mu^-$, and also the underlying heavy quark production which may be useful to make contact with other estimates. **One sees easily that in this scenario there is no hope of seeing B_c's at RHIC.**

2. Deconfinement scenario

Now the principal reason for our interest - could deconfinement change the B_c production rate at RHIC? We have investigated the following scenario: In those events in which a $b\bar{b}$ pair are produced, one could avoid the small B_c formation fraction if the b-quarks are allowed to form bound states by combining with c-quarks from among the 10 $c\bar{c}$ pairs already produced by independent nucleon-nucleon collisions in the same event. This can occur if

[1] In the following we include in the term B_c also the vector 1S state B_c^*, since its mass splitting should only allow an electromagnetic decay into the pseudoscalar ground state and thus both will contribute identically in the experimental signatures.

TABLE I

RHIC yields for heavy quark systems

Observable events	First year	Design L
$c\bar{c}$-pairs	$2.8\,10^8$	$6.5\,10^9$
$b\bar{b}$-pairs	$1.2\,10^6$	$3.2\,10^7$
$J/\Psi \to \mu^+\mu^-$	$1.6\,10^5$	$3.9\,10^6$
$\Upsilon(1s) \to \mu^+\mu^-$	140	3800
$B_c \overset{2.5\%}{\to} J/\psi l\nu \overset{6\%}{\to} \mu^+\mu^- l\nu$		
(No Deconfined Phase)	0.05–0.18	1.5–4.9
(QGP+$c\bar{c}$ in Chemical Equil.)	18	490
(Only initial $c\bar{c}$ at $T_0 = 500$ MeV)	130	3530
(Only initial $c\bar{c}$ at $T_0 = 400$ MeV)	235	6420
(Only initial $c\bar{c}$ at $T_0 = 300$ MeV)	475	12900

and only if there is a region of deconfinement which allows a spatial overlap of the b and c quarks. In addition, one would expect some $c\bar{c}$ production in the deconfined phase during its lifetime, as a result of the approach toward chemical equilibration. The large binding energy of B_c (840 MeV) would favor their early "freezing out" and they will tend to survive as the temperature drops to the phase transition value. The same effect for the B mesons and indeed for the B_s will not be so competitive, since these states are not bound at the initial high temperatures (or equivalently they are ionized at a relatively high rate by thermal gluons).

To do a quantitative estimate of these effects, we calculate the dissociation rate of bound states due to collisions with gluons, utilizing a quarkonium break-up cross section based on the operator product expansion [7]:

$$\sigma_B(k) = \frac{2\pi}{3}\left(\frac{32}{3}\right)^2\left(\frac{2\mu}{\varepsilon_0}\right)^{1/2}\frac{1}{4\mu^2}\frac{(k/\varepsilon_0-1)^{3/2}}{(k/\varepsilon_0)^5}, \tag{1}$$

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. The magnitude of the cross section is controlled just by the geometric factor $\frac{1}{4\mu^2}$, and its rate of increase in the region just above threshold is due to phase space and the p-wave color dipole interaction.

For the breakup rate λ_B of B_c states in deconfined matter, we calculate the thermal average:

$$\lambda_B = \langle v_g n_g \sigma_B \rangle = \frac{8}{\pi^2} \int_{\varepsilon_0}^{\infty} k^2 dk \; e^{-\frac{k}{T}} \; \sigma_B(k), \tag{2}$$

where $v_g = 1$ and all modes of massless color octet gluons have been included. Numerical results for these rates are shown in Fig. 1. For comparison, breakup rates are also shown for the J/ψ and Υ (and even the B_s, but there the approximations made for this cross section probably have a very marginal validity in view of such a large state). One sees that in the range of temperatures expected at RHIC, these breakup rates for B_c lead to time scales of order $1 - 10$ fm.

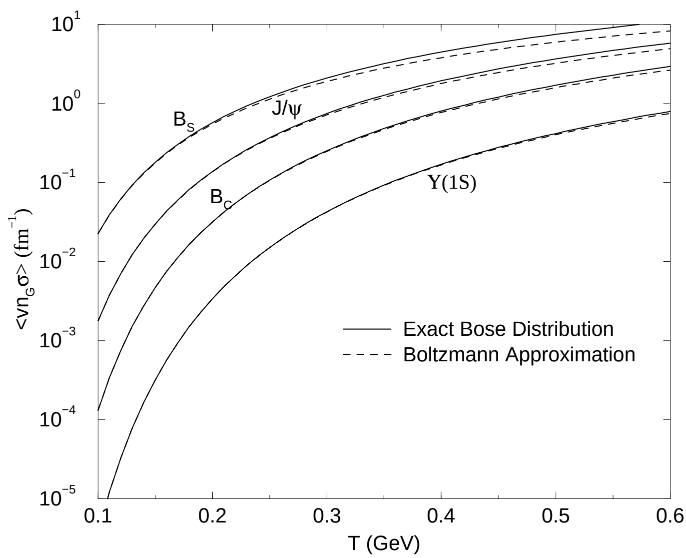

Fig. 1. Thermal QGP quarkonium dissociation rates as functions of temperature.

For an estimate of the corresponding cross section for the formation reaction $\sigma_F(b + \bar{c} \rightarrow B_c + g)$ we utilize detailed balance relations. In the approximation that the massive b-quarks are stationary, which is expected to be a reasonable approximation due to their energy loss in the hot plasma [8], the formation rate is then calculated for a thermal distribution of charm quarks:

$$\lambda_F = \langle v_c n_c \sigma_F \rangle = \frac{3}{\pi^2} \int_0^{\infty} \left(\frac{p}{E_p} \right) p^2 dp \; e^{-\frac{E_p}{T}} \; \sigma_F(p) \,, \tag{3}$$

where $E_p = \sqrt{p^2 + m_c^2}$. These formation rates are shown in Fig. 2. They have been calculated for three different values of charm quark mass. It is apparent that the results are quite sensitive to this choice, due to the strong dependence of total charm quark population. The same values of m_c have very little effect on the breakup rates, since they only change the overall scale in the geometric factor of the breakup cross section.

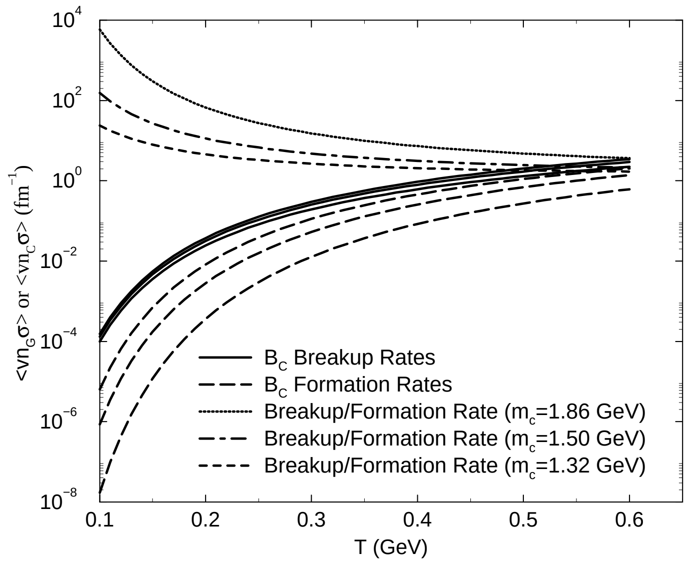

Fig. 2. Thermal QGP B_c formation and dissociation rates as functions of temperature.

Also shown in Fig. 2 are the ratios λ_B/λ_F, which in our normalization is related to the bound state fraction in the equilibrium limit[2]:

$$R_b \equiv \frac{B_c + B_c^*}{b\bar{b}} = \frac{\frac{3}{2}\frac{\lambda_F}{\lambda_B}}{1 + \frac{3}{4}\frac{\lambda_F}{\lambda_B}} \,. \tag{4}$$

Note that this ratio approaches its upper limit of 2 when the formation rate dominates over the breakup rate. This corresponds to the situation in which every b-quark produced in the initial collisions emerges as a B_c bound state.

We choose a transition temperature $T_f = 160\,\text{MeV}$ at which to evaluate the final bound state populations. Here the equilibrium bound state

[2] This bound state fraction is reached if the system has enough time in its dynamical evolution to relax to the steady-state solution at each temperature. We have verified that this is roughly the case down to $T = 300\,\text{MeV}$, at which point the B_c abundance begins to freeze out.

fraction R_b drops to as low as several percent, but it is at least a factor of 100 above what one may expect in the no-deconfinement scenario. We have chosen to use the equilibrium ratios although at this final temperature the rates are not sufficient for them to be approached. This provides an even more conservative estimate for the final bound state populations. The corresponding entries in the Table for numbers of B_c mesons (labeled QGP + $c\bar{c}$ in Chemical Equil.) uses this conservative lower limit estimate.

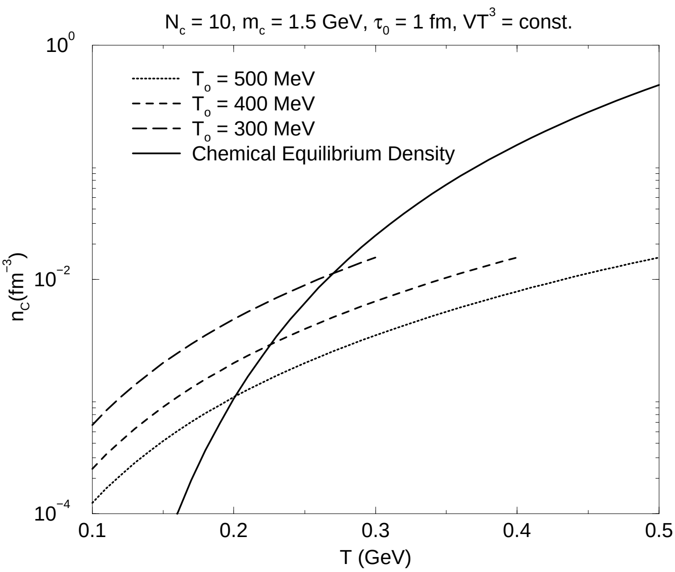

Fig. 3. c-quark density from initial production at RHIC

Implicitly, this analysis uses the full chemical equilibrium density for c-quarks. To get a more realistic limit we repeated the calculation, using only the initially-produced c-quarks in the formation rate. From the initial population of 10 $c\bar{c}$-pairs produced via nucleon-nucleon collisions in a central Au-Au collision at RHIC, and an initial volume $V_0 = \pi(R_{\rm Au})^2\tau_0$ with $\tau_0 =$ 1.0 fm, one concludes that only for initial temperatures $T_0 < 300\,\mathrm{MeV}$ is the initial charm quark density comparable to that for full chemical equilibrium. For initial temperature $T_0 = 500\,\mathrm{MeV}$, for example, the chemical equilibrium charm quark density would be about a factor of 40 higher than that actually provided by the initially-produced charm quarks. As temperature decreases below T_0, the isentropic expansion $VT^3 = \mathrm{Const.}$ leads to a decrease in the c-quark density proportional to T^3, rather than the $e^{-m_c/T}$ of chemical equilibrium. We have verified that the rates of both charm annihilation and production in a deconfined state for $T < 300\,\mathrm{MeV}$ then lead to charm quark occupancies which exceed those for chemical equilibrium as one approaches the transition point. Fig. 3 displays a comparison of chemical equilibrium charm quark densities and those resulting from a constant number of initially-produced charm quarks with isentropic expansion.

These more realistic charm quark densities are used to recalculate the formation rates, and the resulting ratios λ_F/λ_B are shown in Fig. 4 for several values of initial temperature T_0. The last few rows in the Table show the corresponding B_c numbers at RHIC in this scenario, where we have used the equilibrium bound state fractions again at a final temperature $T_f = 160$ MeV. They depend quite strongly on the initial temperature, which determines the final charm density through the assumed isentropic expansion.

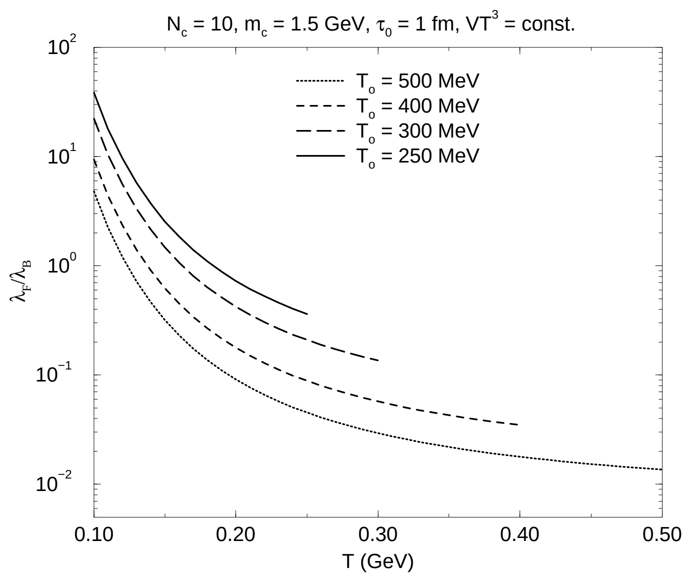

Fig. 4. Ratio of formation to break-up rates of B_c as function of temperature for fixed charm quark abundance.

3. Outlook

We are in the process of refining these preliminary results. We use a simple flow model in which the QGP fluid is described as an isentropically expanding tube that contains ideal relativistic particles in thermal equilibrium. In both opposite longitudinal directions we assume expansion at the speed of light, while radially the transverse radius expands with the speed of sound, $\approx 0.58c$. Initial numerical solutions of the kinetic equations using temperature-dependent formation and breakup rates indicate the final bound state populations saturate at values appropriate to those for equilibrium temperatures somewhat above the transition values. This would be expected, since the rates at low temperatures are not sufficient to reach the equilibrium solutions before the volume expansion reduces the temperature to even lower values. In addition, this effect reduces the sensitivity of the results to the initial temperature.

The results of one such calculation are shown in Fig. 5, where the exact time evolution of B_c production has been followed. We see that the predicted bound state fraction saturates at 3.5%, compared to the equilibrium estimate of $\mathcal{O}(10\%)$ from Fig. 4.

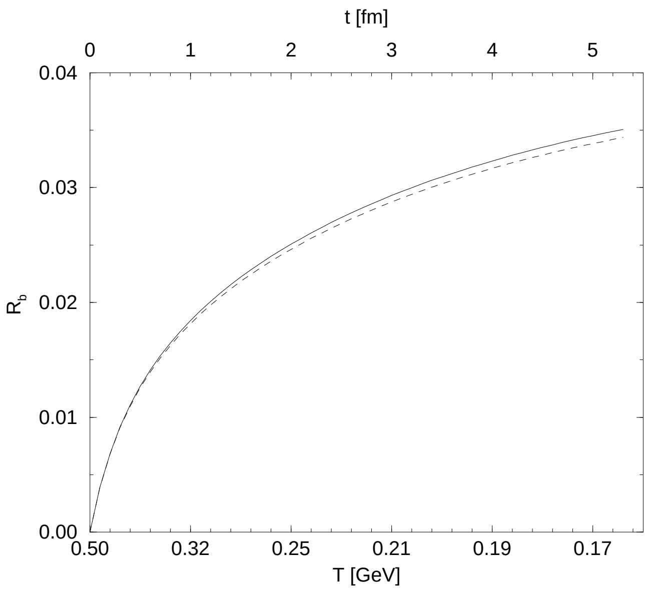

Fig. 5. Bound state fraction for B_c mesons evolving in time [fm] and temperature [GeV] until freeze-out for initial volume 80 fm^3. Dashed line: results without thermal charm production.

We also studied the production and annihilation of additional charm quark pairs by thermal processes which is most effective at higher temperatures. Thermally produced charm by background gluons and light quarks (u, d) was followed through employing the population equation:

$$\frac{d\,N_c}{d\,t} = \frac{1}{2} N_g \rho_g \gamma^{gg \to c\bar{c}} + N_q \rho_{\bar{q}} \gamma^{q\bar{q} \to c\bar{c}} - N_c \rho_{\bar{c}} (\gamma^{c\bar{c} \to gg} + \gamma^{c\bar{c} \to q\bar{q}}), \qquad (5)$$

where N denotes total particles abundance, ρ density and γ reactivity ($\lambda = \rho^{\infty}\gamma$). The thermal charm production rates λ were obtained using running QCD parameters with $\alpha_s(M_Z) = 0.118$ and $m_c(1\,\mathrm{GeV}){=}1.5\,\mathrm{GeV}$ [9]. Fig. 6

shows total charm number for initial QGP sizes between 40 fm^3 (solid) to 160 fm^3 (short dashed) as function of initial temperature. We note that if $T_0 \geq 600$ MeV up to 50% additional charm could be produced. However, for the expected conditions at RHIC this results in only a minor increase of the B_c yield as can be seen in Fig. 5, where the dashed line shows what is expected if thermal charm production is turned off.

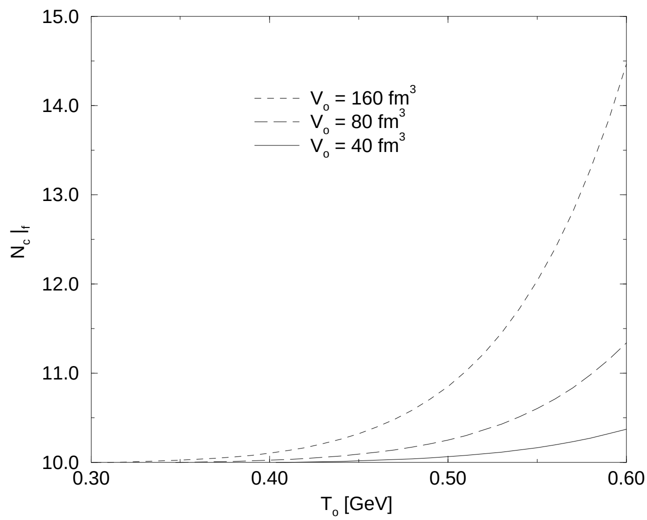

Fig. 6. Total number of charm quarks in the QGP at freeze-out as function of the initial temperature T_0, for initial volumes of 160, 80, and 40 fm^3.

We are presently pursuing the evaluation of the B_c formation in a fully dynamical approach and in particular the sensitivity of our results to the model parameters.

4. Conclusion

The firm conclusion which we are able to make today is that should QGP be formed at RHIC there would be a very significant enhancement of the formation of B_c mesons, to the level of abundance which we believe can be observed. The primary mechanism responsible for this enhancement is the interaction of bottom and charmed quarks produced in completely unrelated reactions. Such collective formation of heavy flavor multi-flavor states in confined phase is expected to be much smaller, if past experience with strangeness [10] and charm [11] applies. Should this be confirmed, the observation of any B_c's at RHIC is thus both a "smoking gun" signal of deconfinement and a probe of the initial conditions that prevailed.

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