Charmonium Production at High $p_t$ at RHIC

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Abstract. We calculate transverse-momentum ($p_t$) spectra and elliptic flow of $J/\psi$'s in $Au-Au$ and $Cu-Cu$ collisions at RHIC. We employ an earlier constructed 2-component approach for direct and regenerated charmonia which is fairly consistent with the centrality dependence of inclusive $J/\psi$ yields at SPS and RHIC. Discrepancies with high-$p_t$ data in $Cu-Cu$ collisions are addressed by implementing effects of a finite formation time and an estimate of $B$ meson feeddown, which largely resolve the problem. The sensitivity of the spectra to the Cronin effect and different in-medium dissociation rates is studied. The predicted elliptic flow in semicentral $Au-Au$ collisions is rather small, ∼2-3%.

Keywords: Ultra relativistic heavy-ion collisions, Quark-gluon plasma, Charmonium production.
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1. Introduction

An “anomalous” suppression of $J/\psi$ mesons produced in ultrarelativistic heavy-ion collisions (URHICs) has long been suggested as a signature of Quark-Gluon Plasma (QGP) formation [1]. However, experiments at the CERN Super Proton Synchrotron (SPS) and the Brookhaven Relativistic Heavy-Ion Collider (RHIC) show a very comparable suppression of $J/\psi$'s, despite much larger energy densities believed to be created at RHIC compared to SPS. Such a result has, in fact, been predicted in approaches [2] where suppression mechanisms are supplemented by secondary charmonium production, e.g., via the coalescence of $c$ and $\bar{c}$ quarks at hadronization transition [3, 4]. However, significant uncertainties in these approaches remain, most notably due to the total charm cross section and the degree of thermalization of the charm-quark spectra. It is therefore essential to find additional means to discriminate suppression and regeneration mechanisms. Transverse-momentum ($p_t$) [5, 6, 7, 8, 9] and rapidity ($y$) [6] spectra, as well as elliptic flow [7, 9, 10, 11] of $J/\psi$'s are hoped to provide such tools.
In the present paper we first discuss our recent extension \cite{12} of the two-component model \cite{2,13} to compute $p_t$ spectra, augmented by predictions for elliptic flow, $v_2(p_t)$, in Sec. 2. In Sec. 3 we evaluate additional mechanisms relevant to $J/\psi$ production at high $p_t > 5\text{GeV}/c$. Sec. 4 contains our conclusions.

2. $p_t$ Spectra and Elliptic Flow in the 2-Component Approach

Within the two-component approach, the $p_t$ spectra of charmonia ($\Psi = J/\psi, \chi_c, \psi'$) in URHICs are decomposed into contributions from direct production and regeneration \cite{12}. The former is based on initial spectra in elementary $N$-$N$ collisions including a Cronin effect (i.e., nuclear $p_t$ broadening implemented via a Gaussian smearing) and primordial nuclear absorption estimated from $p$-$A$ collisions; the resulting spectra serve as an input to a Boltzmann transport equation to compute subsequent suppression in an expanding thermal fireball through the QGP, mixed and hadron gas (HG) phase. The charmonium dissociation rates in the QGP account for in-medium reduced binding energies and are therefore calculated using inelastic quasifree cross sections \cite{2} (rather than gluo-dissociation \cite{14}), while HG dissociation is estimated using $SU(N_f=4)$ effective theory. We also take into account the “leakage” effect \cite{15,16}, i.e., charmonia traveling outside the fireball boundary before freeze-out are not subject to dissociation. The leakage effect reduces suppression primarily for high-$p_t$ charmonia. The inclusive yield of the regeneration component is computed from $c$-$\bar{c}$ coalescence using detailed balance (i.e., the inverse of quasifree dissociation) within a momentum-independent thermal rate equation \cite{13}. Regeneration processes are suppressed by a schematic relaxation-time factor to simulate incomplete kinetic equilibration of the charm quarks. The $p_t$ spectra of regenerated $\Psi$'s are approximated by a local thermal blastwave distribution \cite{17} at the hadronization transition based on the same fireball as used for the direct component. The input charm cross section, $\sigma_{cc} = 570\mu b$, is consistent with recent PHENIX data \cite{18}. Our approach yields a reasonable overall description of the nuclear modification factor, $R_{AA}(N_{part})$, for inclusive $J/\psi$ production, as well as its $p_t$ dependence in $Pb$-$Pb$ and $Au$-$Au$ collisions at SPS and RHIC, respectively \cite{12}. At SPS and for peripheral collisions at RHIC, the regeneration contribution is small, but it becomes significant for $p_t \leq 2-3\text{ GeV}$ for semi-/central collisions $Au$-$Au$ collisions at RHIC, see, e.g., the left panel of Fig. 1.

We now apply our approach to estimate the elliptic flow of $J/\psi$'s according to

$$v_2(p_t) = f_{dir}v_{2,dir}^0(p_t) + f_{reg}v_{2,reg}^0(p_t),$$

where the fractions $f_{dir}$ and $f_{reg}$ follow from the decomposition provided by the two-component model for 20-40% central $Au$-$Au$ at RHIC. For the underlying $v_2$ spectra we take guidance from the suppression calculations in Refs. \cite{9,10} for the direct component, $v_{2,dir}^0(p_t)$, and from the coalescence models in Refs. \cite{7,11} for the regenerated component, cf. the right panel in Fig. 1. The weighted sum is shown by the green band reflecting the uncertainties in the input $v_2$ of the 2 components. It is
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### 3. Charmonium Production at High \( p_T \)

The predictions of our approach for \( p_T \) spectra in 200 AGeV \( Cu-Cu \) collisions are compared to data in the left panel of Fig. 2 (solid lines). While the agreement is fair up to \( p_T \approx 4 \) GeV, at higher momenta a significant discrepancy develops. In the following, we will investigate several potential sources of this discrepancy related to high-\( p_T \) production which have not been included in our baseline calculations [12].

First we check whether the increasing trend of \( R_{AA}(p_t) \) can be attributed to a stronger Cronin effect, which at RHIC energies is currently not well constrained by \( d-Au \) data, cf. the right panel of Fig. 2. In our baseline calculations, we used the same broadening as at SPS, according to \( \langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + a_{gN} L \) with \( a_{gN} = 0.1 \text{GeV}^2/\text{fm} \) (\( L \) is an average gluon path length prior to the hard process for charm production). With a larger \( a_{gN} = 0.4 \text{GeV}^2/\text{fm} \), which might still be acceptable for the \( d-Au \) data, the high \( p_T \) regime in the \( Cu-Cu \) spectra indeed improves (dashed lines in the right panel of Fig. 2), which is, however, somewhat at the expense of the low-\( p_T \) region. Clearly, more accurate \( d-Au \) data will be very valuable.

somewhat sobering to find that the resulting \( v_2(p_t) \) is small, around 2-3%, over the entire \( p_T \) range. The reason is that a large \( v_2 \) for the coalescence component only develops above \( p_T \approx 2 \) GeV, where, however, its weight is already small. On the other hand, in the low \( p_T \) region, where the coalescence component carries a significant weight, its \( v_2 \) is still small. The \( v_2 \) of the direct component, which solely derives from the path length dependence relative to the reaction plane, is always small. This puts a rather high requirement on the accuracy of future measurements of \( J/\psi \) elliptic flow in order to extract information about \( J/\psi \) production mechanisms.

\[ \text{Fig. 1. (Color online). Left panel: 2-component approach for } J/\psi \text{ } R_{AA}(p_t) \text{ in 20-40}\% \text{ } Au-Au \text{ at RHIC, compared to PHENIX data [19]. Right panel: estimated } v_2(p_t) \text{ based on the partition in the left panel. The band represents uncertainties due to differences between two independent input } v_2(p_t) \text{ calculations for each of the two components.} \]
to constrain the initial nuclear $p_t$ broadening.

Second, we consider the following two effects primarily relevant at high $p_t$: (1) Finite formation times \[16, 23, 24\] and (2) Bottom feeddown. Concerning (1), one expects reduced dissociation cross sections for a "pre-hadronic" $c\bar{c}$ pair relative to a fully formed charmonium due to a finite formation time, $\tau_f$, required to build up the hadronic wave function. For a schematic estimate we parameterize the evolution of the pre-hadronic dissociation rate as

$$\Gamma_{c\bar{c}} = \Gamma_\Psi \frac{\tau}{f_{lab}}, \quad \tau \leq \tau_{f} = \frac{m_t}{m_\Psi}$$

with $\Gamma_\Psi$: (nuclear, partonic or hadronic) dissociation rates for a formed charmonium, $\tau$: fireball proper time, $\tau_f = 0.89(2.01,1.50) \text{ fm}/c$, formation time of $J/\psi(\chi_c, \psi')$ in its rest frame, and $m_t = (m_\Psi^2 + p_t^2)^{1/2}$. In essence, (pre-) charmonium dissociation rates acquire an additional momentum dependence through Lorentz time dilation, being reduced at high $p_t$. Also note that the longer formation times of $\chi_c$ and $\psi'$ imply less suppression relative to $J/\psi$, quite contrary to standard dissociation and statistical regeneration mechanisms, thus constituting a rather unique signature of the formation time effect. Concerning (2), the left panel of Fig. 3 shows recent data on the $B \to J/\psi$ feeddown fraction in elementary $p-p(\bar{p})$ collisions, which is quite significant. As an estimate of this contribution, we use the Tevatron data \[25\] with an extra uncertainty of $\pm 50\%$ and replace that part of our direct component. Combining formation time effects and $B$-meson feeddown we obtain as our current best estimate the green band in the right panel of Fig. 3 which is not far off the experimental data.

Finally, we compare the impact of different QGP dissociation mechanisms on $J/\psi$ $p_t$ spectra. In addition to quasifree destruction, we have employed the tra-

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**Fig. 2.** (Color online). Left panel: $J/\psi$ $R_{AA}(p_t)$ in $Cu-Cu$ at RHIC within our 2-component approach using $a_gN=0.1,0.4 \text{ GeV}^2/\text{fm}$ (solid, dot-dashed lines), compared to PHENIX \[20\] and STAR data \[21\]. Right panel: Cronin effect for $J/\psi$ $R_{dA}(p_t)$ implemented via Gaussian smearing with $a_gN=0.1,0.4 \text{ GeV}^2/\text{fm}$ (solid, dashed line), compared to PHENIX $d-Au$ data \[22\].
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$J/\psi$ from $B$-meson feeddown to inclusive $J/\psi$ [26]. Right panel: $J/\psi R_{AA}(p_T)$ within the 2-component approach including formation time effects and $B$-meson feeddown (green band) in 0-60% Cu-Cu, compared to our previous results (solid lines) and RHIC data [20, 21].

This indeed leads to somewhat harder $p_T$ spectra (see right panel of Fig. 4), but we note that the use of vacuum $J/\psi$ binding energies in the QGP may not be very realistic.

Fig. 4. (Color online). Left panel: Comparison [12] of the momentum dependence of quasifree (solid lines) and gluo-dissociation rates (dashed lines) for $J/\psi$ at different temperatures. Right panel: $J/\psi R_{AA}(p_T)$ with gluo-dissociation (dashed lines) compared to quasifree destruction (solid lines) and RHIC data [20, 21]. Formation time effects and $B$ meson feeddown are not included.
4. Conclusions

Employing a 2-component model extended to calculate charmonium $p_t$ spectra in URHICs, we have computed $J/\psi$ elliptic flow and studied additional effects relevant at high $p_t$. We find a rather small $v_2$ due to the smallness of the regeneration component at high $p_t$. A fair description of available high-$p_t$ spectra seems to be possible upon inclusion of formation time effects and $J/\psi$’s from $B$-meson feeddown.

Acknowledgments

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