

Transverse Momentum Spectra of J/ψ in Heavy-Ion Collisions

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We investigate J/ψ transverse-momentum (p_t) distributions and their centrality dependence in heavy-ion collisions at SPS and RHIC within the framework of a two-component model, which includes (i) primordial production coupled with various phases of dissociation, (ii) statistical coalescence of c and \bar{c} quarks at the hadronization transition. The suppression of the direct component (i) is calculated by solving a transport equation for J/ψ , χ_c and ψ' in an expanding fireball using momentum dependent dissociation rates in the Quark-Gluon Plasma (QGP). The coalescence component is inferred from a kinetic rate equation with a momentum dependence following from a blast wave approach. At SPS energies, where the direct component dominates, the interplay of Cronin effect and QGP suppression results in fair agreement with NA50 p_t spectra. At RHIC energies, the p_t spectra in central $Au+Au$ collisions are characterized by a transition from regeneration at low p_t to direct production above. At lower centralities, the latter dominates at all p_t .

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I. INTRODUCTION

It has long been suggested that the suppression [1] of J/ψ mesons can be utilized as a probe of Quark-Gluon Plasma (QGP) formation in ultrarelativistic heavy-ion collisions (URHICs). This effect has indeed been observed in $Pb-Pb$ collisions at the Super Proton Synchrotron (SPS) [2], consistent with theoretical models invoking charmonium dissociation reactions in a QGP [3, 4, 5, 6]. At collider energies, however, a copious production of $c\bar{c}$ pairs has led to the suggestion that charmonia can be regenerated by a coalescence of c and \bar{c} quarks close to the hadronization transition [3, 7, 8]. The presence of this mechanism is supported by data from the Relativistic Heavy-Ion Collider (RHIC) [9], where, despite the higher temperatures of the putative QGP, the observed suppression is similar to SPS energies (as, *e.g.*, predicted in Ref. [3]). However, a quantitative assessment of the regeneration and suppression mechanisms at RHIC has not been achieved yet.

Transverse momentum (p_t) spectra of charmonia are hoped to provide additional means of discrimination. In Ref. [4], the average $\langle p_t^2 \rangle$ of primordial J/ψ 's with QGP suppression has been computed, while in Refs. [10, 11] the regeneration component has been studied within a blast wave description based on thermalized J/ψ mesons at the QCD phase boundary. In Refs. [12, 13] the impact of non-thermalized c quark distributions on the p_t spectra resulting from recombination has been studied, but no direct component was accounted for. In Ref. [14] the average $\langle p_t^2 \rangle$ and elliptic flow at RHIC has been calculated including both direct and regenerated components using gluo-dissociation rates with vacuum binding energies for the J/ψ and χ_c .

In the present Letter we provide a comprehensive description of p_t spectra at both SPS and RHIC, including their centrality dependence and absolute yields. A proper description of the inclusive yields vs. centrality

turns out to be particularly important for interpreting p_t spectra in terms of direct and regeneration contributions. We adopt a previously constructed two-component approach [3] employing inelastic charmonium reaction rates (extended to finite 3-momentum) which account for reduced binding energies in the QGP. The latter point is essential to allow for a realistic treatment of χ_c and ψ' states, which are expected to be measured in the future but also make up 30-40% of the inclusive initial J/ψ yield. In the following, we recall the basic ingredients of the 2-component model and its extension to finite momentum (Section II), apply our approach to heavy-ion collisions at SPS and RHIC (Section III) and conclude (Section IV).

II. TWO-COMPONENT APPROACH

In analogy to the case of light hadrons, one may decompose p_t spectra of charmonia ($\Psi = J/\psi, \chi_c, \psi'$) in URHICs according to their production mechanism into hard (high- p_t) and soft (low- p_t) components,

$$\left. \frac{dN_\Psi}{p_t dp_t} \right|_{tot} = \left. \frac{dN_\Psi}{p_t dp_t} \right|_{dir} + \left. \frac{dN_\Psi}{p_t dp_t} \right|_{coal}, \quad (1)$$

where the direct component (first term) is associated with hard production in primordial $N-N$ collisions, subject to suppression in the subsequent medium evolution. The soft component (second term) is conceptually simpler than in the light sector, based on the notion that c and \bar{c} quarks are exclusively produced primordially, leaving their coalescence as the only source of secondary charmonium formation. Since regeneration is governed by the phase space density of c and \bar{c} quarks in the medium, it is sensitive to the c -quark momentum spectra. Indirect measurements of c -quark spectra at RHIC (via semileptonic decay electrons) [15, 16] indicate strong rescattering effects which in theoretical models [17] imply an approximate thermalization up to c -quark momenta

of $p_t^c \sim 2 - 2.5$ GeV [18]. Thus, following our earlier developed 2-component model [3, 19], we approximate the coalescence component with a thermal blast wave description, while direct production is computed in a microscopic suppression calculation in QGP and hadronic phase, as will be detailed in the remainder of this section. Both terms in Eq. (1) are evaluated in the same expanding fireball model.

Let us first address the direct component. Since the charmonium masses are much larger than the typical temperature of the medium, a Boltzmann transport equation is appropriate to describe the time evolution of the phase space distribution, $f_\Psi(\vec{x}, \vec{p}, \tau)$, through the QGP, mixed and hadron gas (HG) phase,

$$p^\mu \partial_\mu f_\Psi(\vec{x}, \vec{p}, \tau) = -E_\Psi \Gamma_\Psi(\vec{x}, \vec{p}, \tau) f_\Psi(\vec{x}, \vec{p}, \tau), \quad (2)$$

where $E_\Psi = \sqrt{m_\Psi^2 + p^2}$ is the energy of Ψ with 3-momentum modulus p , and \vec{x} is its position in the fireball. For simplicity, we constrain our calculation to the longitudinal rest frame of the charmonium [4], *i.e.*, solve the Boltzmann equation in (2+1)-dimensions. For the initial charmonium distribution we assume a factorization into spatial and momentum dependencies, $f(\vec{x}_t, \vec{p}_t, \tau_0) = f(\vec{x}_t, \tau_0) \cdot f(\vec{p}_t, \tau_0)$, where τ_0 is the initial (thermalization) time of the medium (QGP or mixed phase). The spatial part of the initial distribution is obtained from a Glauber model including nuclear absorption,

$$f_\Psi(\vec{x}_t, \tau_0) = \sigma_{pp}^\Psi \int d^2s dz dz' \rho_A(\vec{s}, z) \rho_B(\vec{x}_t - \vec{s}, z') \\ \times \exp \left\{ - \int_z^\infty dz_A \rho_A(\vec{s}, z_A) \sigma_{nuc} \right\} \\ \times \exp \left\{ - \int_{z'}^\infty dz_B \rho_B(\vec{x}_t - \vec{s}, z_B) \sigma_{nuc} \right\}, \quad (3)$$

where $\rho_{A,B}$ are Woods-Saxon profiles [20] of nuclei A and B and σ_{pp}^Ψ is the Ψ production cross section in $p+p$ collisions (we use $d\sigma_{pp}^{J/\psi}/dy(y=0)=25(750)$ nb at SPS (RHIC) [21, 22]). The nuclear absorption cross section, σ_{nuc} , serves as a parameter to account for pre-equilibrium charmonium suppression due to primordial nucleons passing by, estimated from $p-A$ collisions; at SPS we adopt the values of Refs. [23, 24], $\sigma_{nuc}=4.4$ mb for J/ψ , χ_c and 7.9 mb for ψ' . At RHIC, we use $\sigma_{nuc}=1.5$ mb (for J/ψ , χ_c) based on Ref. [25], which is compatible with a recent update [26] (for $\sigma_{nuc}=2.7$ mb the total J/ψ yield in our model decreases by 8% for central $Au-Au$ at RHIC). For ψ' , we employ an accordingly increased value of 2.7 mb. The initial momentum spectra are obtained from $p+p$ data, augmented by a Gaussian smearing to simulate nuclear p_t -broadening (Cronin effect),

$$f_\Psi(\vec{p}_t, \tau_0) = \frac{1}{2\pi\sigma^2} \int d^2p'_t \exp\left(-\frac{p'_t{}^2}{2\sigma^2}\right) f_{NN}(|\vec{p}_t - \vec{p}'_t|), \quad (4)$$

where $f_{NN}(p_t)$ is the spectrum in elementary $N-N$ collisions. At SPS, $f_{NN}(p_t) = \frac{1}{\pi \langle p_t^2 \rangle} \exp(-p_t^2/\langle p_t^2 \rangle)$

with $\langle p_t^2 \rangle = 1.15$ GeV²/c² [27, 28], and at RHIC $f_{NN}(p_t) = A(1 + p_t^2/B^2)^{-6}$ with $B=4.1$ GeV² yielding $\langle p_t^2 \rangle_{pp} = 4.14$ GeV² [22]. The Cronin effect is computed using $2\sigma^2 = a_{gN} \cdot \langle l \rangle$ where $\langle l \rangle$ represents the centrality dependent mean nuclear path length of the gluons before fusing into Ψ [29]. At SPS, the extracted coefficient is $a_{gN}=0.076$ GeV²/fm [27, 28], while a fit to $d-Au$ data at RHIC gives $a_{gN} \simeq 0.1$ GeV²/fm with a rather large uncertainty (*e.g.*, $a_{gN}=0.6$ GeV²/fm is still compatible with $d+Au$ data, but results in $R_{AA}(p_t=6 \text{ GeV}) \simeq 9$ before QGP suppression in 0-20% central $Au+Au$).

The most important microscopic ingredient to the transport Eq. (2) are the charmonium dissociation rates, Γ_Ψ , which can be expressed via inelastic cross sections, $\sigma_{\Psi i}^{diss}$, for Ψ scattering on medium constituents i as

$$\Gamma_\Psi(\vec{x}, \vec{p}, \tau) = \sum_i \int \frac{d^3k}{(2\pi)^3} f^i(\omega_k; T(\tau)) \sigma_{\Psi i}^{diss} v_{rel} \quad (5)$$

with $v_{rel} = F/(E_\Psi E_i)$, $E_i = (k^2 + m_i^2)^{1/2}$, flux factor $F = ((p^\mu k_\mu)^2 - m_\Psi^2 m_k^2)^{1/2}$, k_μ : parton/meson 4-momentum, $f^i(\omega_k; T)$: thermal Fermi/Bose distribution. In the QGP, color Debye screening is expected to reduce charmonium binding energies, ϵ_B (which eventually vanish), which is supported by recent lattice QCD calculations [30, 31]. Under these circumstances, gluo-dissociation reactions, $\Psi + g \rightarrow c + \bar{c}$, become inefficient and should be replaced by quasifree dissociation, $i + \Psi \rightarrow i + c + \bar{c}$ ($i=g, q, \bar{q}$) [3]. Here we extend these calculations to finite 3-momentum and compare the rates to gluo-dissociation (using vacuum binding energies and vanishing thermal gluon mass) [32] in Fig. 1. The strong coupling constant α_s in the quasifree cross section is one of two adjustable parameters in our approach and is fixed to reproduce the J/ψ yield in central $Pb-Pb$ collisions at the SPS (resulting in $\alpha_s=0.24$). Except for J/ψ 's at rather low temperatures and 3-momenta, the gluo-dissociation rate decreases with increasing p due to a pronounced maximum in the pertinent cross section (at a gluon energy $\omega \simeq 1.43\epsilon_B$ in the rest system of the J/ψ [33]). On the other hand, the quasifree rate always increases with p due to a smoothly increasing cross section with center-of-mass energy, similar to Ref. [34]. This reiterates the importance of using the quasifree rate (rather than gluo-dissociation) for small binding energies, especially at finite momentum. The increase of the quasifree rate with p is more pronounced at low temperature since at high temperature most partons are energetic enough to destroy a J/ψ irrespective of its momentum. This trend is weaker for the χ_c (lower panel) due to its small binding energy: even at low temperature most partons carry sufficient energy to destroy it.

In the HG, we employ inelastic cross sections with π and ρ mesons from a flavor- $SU(4)$ effective Lagrangian approach [35, 36].

The final ingredient required to solve the transport equation (2) is the space-time and temperature evolution of the system, which we model by an isentropically

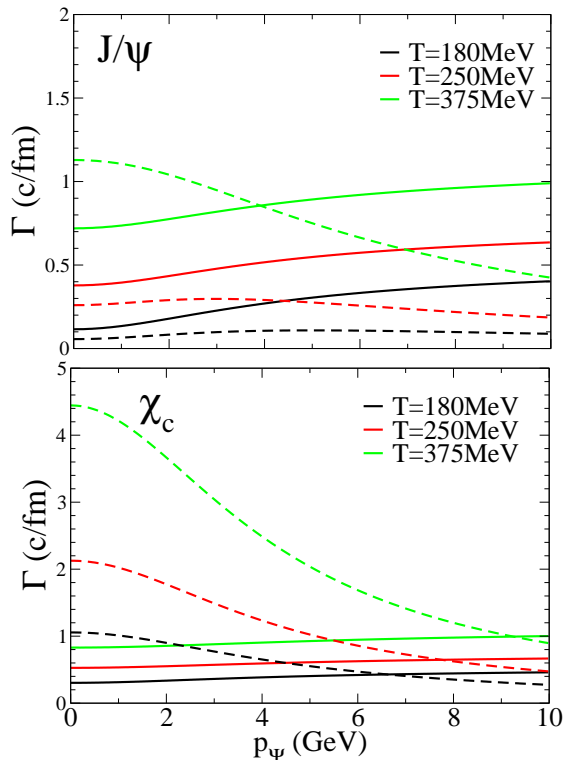


FIG. 1: (Color online) Comparison of the momentum dependence of quasifree (solid lines) and gluo-dissociation rates (dashed lines) for J/ψ (upper panel) and χ_c (lower panel) at different temperatures.

expanding fireball model represented by a cylindrical volume,

$$V_{FB}(\tau) = (z_0 + v_z\tau + \frac{1}{2}a_z\tau^2) \pi (r_0 + \frac{1}{2}a_\perp\tau^2)^2, \quad (6)$$

where z_0 , v_z , a_z , r_0 and a_\perp are the initial longitudinal length, longitudinal expansion velocity and acceleration, initial transverse radius and transverse acceleration, respectively. At fixed total entropy (matched to the observed hadron multiplicity at given centrality and collision energy), the temperature of the system follows from the equation of state (massive partons in QGP and resonance gas in HG). We update the transverse acceleration to $a_\perp=0.08$ c^2/fm and 0.1 c^2/fm at SPS and RHIC as used in recent applications of the fireball model to dilepton [37] and heavy-quark [17] observables. The initial temperature for central A - A collisions at SPS (RHIC) is 210(370) MeV, with thermal freezeout at $T_{fo} \simeq 110$ MeV.

The Boltzmann transport equation (2) can now be solved for the final phase-space distribution $f_\Psi(\vec{x}_t, \vec{p}_t, \tau_f)$ of J/ψ , χ_c and ψ' at the freeze-out time τ_f for fixed centrality and collision energy. Upon integration over the transverse plane of the medium we obtain the p_t spectrum of the direct component as

$$\left. \frac{dN_\Psi}{p_t dp_t} \right|_{dir} = \int d^2x_t f(\vec{x}_t, \vec{p}_t, \tau_f), \quad (7)$$

It is worth noting that the leakage effect [38] is implemented by switching off the suppression if a charmonium state moves outside the fireball, *i.e.*, $\Gamma_\Psi(\vec{x}, \vec{p}, \tau) \equiv 0$ for $x_t(\tau) > r_0 + \frac{1}{2}a_\perp\tau^2$. As we will see below this effect is significant for charmonia at high p_t .

Let us now turn to the coalescence component, *i.e.*, the second term on the right-hand side of Eq. (1). As stated above, we assume the regenerated charmonia to follow a local thermal equilibrium distribution with transverse flow velocity given by the blastwave expression [39],

$$\left. \frac{dN_\Psi}{p_t dp_t} \right|_{coal} \propto m_t \int_0^R r dr K_1 \left(\frac{m_t \cosh y_t}{T} \right) I_0 \left(\frac{p_t \sinh y_t}{T} \right) \quad (8)$$

($m_t = \sqrt{m_\Psi^2 + p_t^2}$). Since charmonium regeneration is inoperative in the HG [33, 40], we evaluate the blast wave formula at the hadronization transition as following from the fireball model, Eq. (6), with $T=T_c=170(180)$ MeV and transverse rapidity $y_t = \tanh^{-1} v_t(r)$ using a linear flow profile $v_t(r) = v_s \frac{r}{R}$ with surface velocity $v_s = 0.33(0.49)c$ and transverse radius $R = 7.3(7.9)$ fm for central collisions at SPS (RHIC). To determine the normalization of the coalescence component we utilize a momentum-independent rate equation [40],

$$\frac{dN_\Psi}{d\tau} = -\Gamma_\Psi (N_\Psi - N_\Psi^{eq}), \quad (9)$$

where $\Gamma_\Psi \triangleq \Gamma_\Psi(p=0)$ and N_Ψ^{eq} is the equilibrium number of charmonia for a given number of $c\bar{c}$ pairs in the system (based on total cross sections $\sigma_{pp}^{c\bar{c}} = 5.5(570)$ μb at SPS (RHIC)). The charmonium yield due to the gain term is identified with the abundance of the coalescence component. As in Refs. [19, 40] a thermal relaxation time, τ_c^{therm} , for charm quarks is introduced to mimic a reduced charmonium equilibrium limit due to incomplete kinetic equilibration via a relaxation factor $\mathcal{R} = 1 - \exp(-\int d\tau/\tau_c^{\text{therm}})$. Due to the current uncertainties in $\sigma_{pp}^{c\bar{c}}$, τ_c^{therm} and its schematic implementation we cannot quantitatively predict the coalescence yields. Therefore we adjust τ_c^{therm} to the inclusive J/ψ yield in central Au - Au at RHIC. This point will be improved in future work by solving the rate equation at finite p with (time-dependent) c -quark momentum distributions as obtained from Langevin simulations [17] which result in fair agreement with the semileptonic single-electron R_{AA} and v_2 at RHIC [15, 16]. Here, we employ $\tau_c^{\text{therm}} = 7$ fm/ c (in line with the microscopic approach of Ref. [41]), compared to ~ 2 -4 fm/ c in Ref. [40]. This update reduces the regeneration yield by 30-50% in central collisions at SPS and RHIC (see Sec. III below).

III. J/ψ YIELDS AND SPECTRA AT SPS AND RHIC

We start our phenomenological analysis at SPS energies. The centrality dependence of inclusive J/ψ produc-

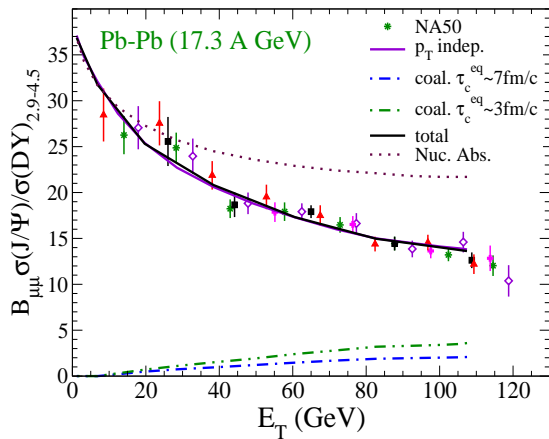


FIG. 2: (Color online). NA50 data [2] for the centrality dependence of J/ψ /Drell-Yan dimuons at SPS compared to our results with (black line) and without (purple line) 3-momentum dependence (both lines essentially coincide). The sensitivity of the coalescence component to the charm-quark relaxation time is indicated by the dash-dotted ($\tau_c^{\text{therm}}=7$ fm/c) and dash-double-dotted ($\tau_c^{\text{therm}}=3$ fm/c) lines.

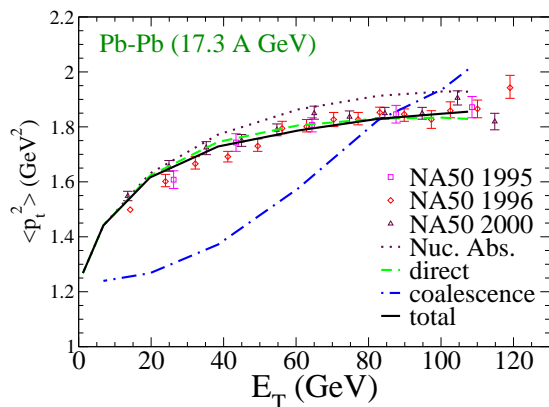


FIG. 3: (Color online). $\langle p_t^2 \rangle$ as a function of centrality at SPS. NA50 data [27, 28] are compared to our model calculations. The $\langle p_t^2 \rangle$ for the direct component (dashed line) and coalescence component (dash-dotted line) are compared to the $\langle p_t^2 \rangle$ with nuclear absorption only including Cronin p_t -broadening effect (dotted line).

tion (including feeddown) is summarized in Fig. 2. To recover previous results from the momentum-independent calculations for central collisions, a minor reduction of α_s from 0.26 to 0.24 in the quasifree dissociation rate has been applied (since the rate increases with p). After this adjustment, there is no visible modification in the inclusive centrality dependence left compared to the previous $p=0$ results [40] (an increase of the leakage of J/ψ 's for smaller system sizes is essentially compensated by a decrease in the fireball lifetime). The sensitivity to the coalescence contribution is small, but this will be different at RHIC. Our calculated J/ψ p_t spectra are used to compute its average $\langle p_t^2 \rangle$ as a function of centrality, and

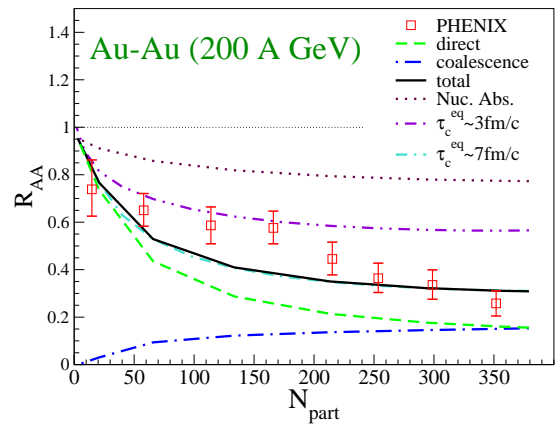


FIG. 4: (Color online). Results of the 2-component model for $R_{AA}^{J/\psi}(N_{part})$ at RHIC, compared to PHENIX data [9]. The previous (momentum-independent) model [40], corresponds to the dash-double-dotted line ($\tau_c^{\text{therm}}=3$ fm/c) and the double-dash-dotted ($\tau_c^{\text{therm}}=7$ fm/c) line. The latter closely coincides with the total (solid line) using p -dependent rates (also with $\tau_c^{\text{therm}}=7$ fm/c). The dotted line represents the primordial input, while the dashed line additionally includes QGP and HG suppression. The coalescence yield for $\tau_c^{\text{therm}}=7$ fm/c is given by the dash-dotted line.

compared to NA50 data [27, 28] in Fig. 3. Most of the observed p_t dependence follows from the Cronin effect of the primordial component, represented by the dotted line. The QGP suppression, which is stronger at high p_t due to the increase of the dissociation rate with p (recall Fig. 1), leads to a slight reduction of $\langle p_t^2 \rangle$, improving the agreement with data. The coalescence component is rather insignificant.

Next, we proceed to the centrality dependence of inclusive J/ψ production in Au - Au collisions at RHIC, as represented by the nuclear modification factor, $R_{AA}(N_{part})$ (the number of J/ψ 's for a given number of participant nucleons, N_{part} , relative to that in p - p collisions multiplied by the number of binary collisions), cf. Fig. 4. Previous $p=0$ results [40] with the updated nuclear absorption cross section (but with identical coalescence contribution) overestimate the most recent PHENIX data for $N_{part}>200$; increasing τ_c^{therm} to 7 fm/c improves this part at the expense of more peripheral collisions. The inclusion of the 3-momentum dependence (with $\alpha_s=0.24$) does not resolve this potential discrepancy, despite the presence of the leakage effect, for similar reasons as described above for SPS energies. We note that the roughly equal partition of the 2 components for central collisions is quite similar to the results of Ref. [14] (where the vacuum gluon dissociation mechanism has been employed).

The key point is now how the inclusive centrality dependence of the two components reflects itself in the p_t spectra. Our results for $R_{AA}(p_t)$ for different centrality selections (approximated by the average number of binary N - N collisions) is compared to PHENIX data [9] in Fig. 5. As anticipated, the coalescence contribution

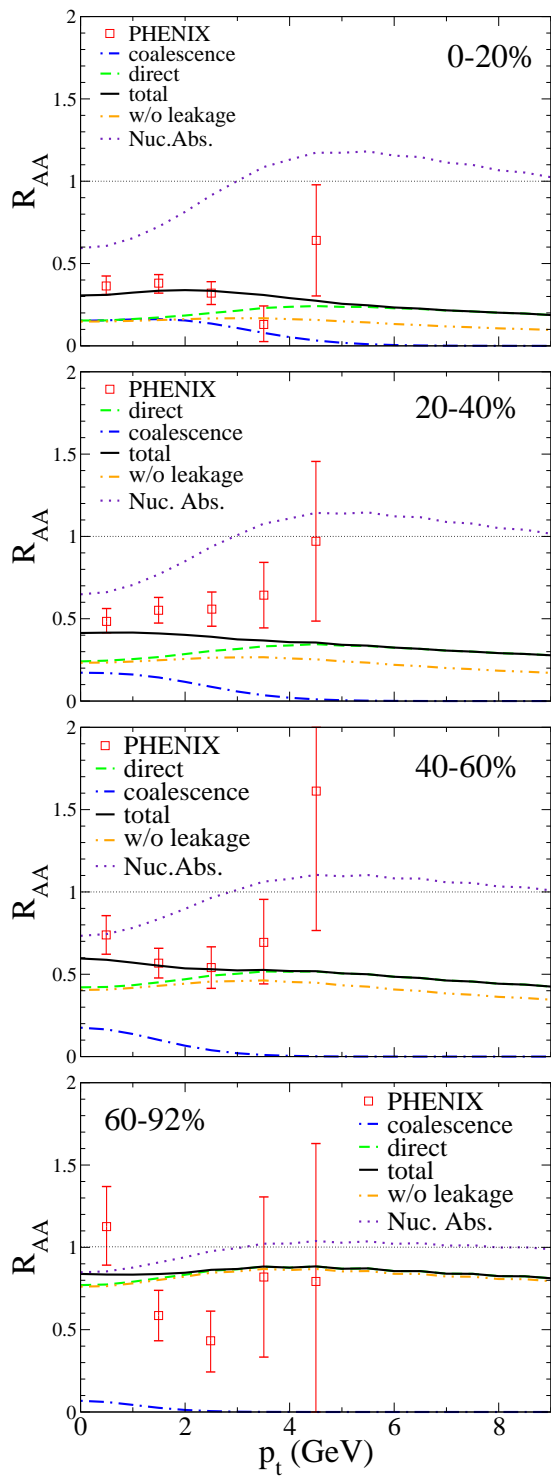


FIG. 5: (Color online). R_{AA} vs. transverse momentum for different centrality selections of $Au-Au$ at RHIC. PHENIX data [9] are compared to our model calculations: initial primordial component (dotted line), including QGP and HG suppression (dashed line), and with leakage effect switched off (dash-double-dotted line); the coalescence contribution is given by the dash-dotted line.

is concentrated at low p_t (up to 2-4 GeV), most notably

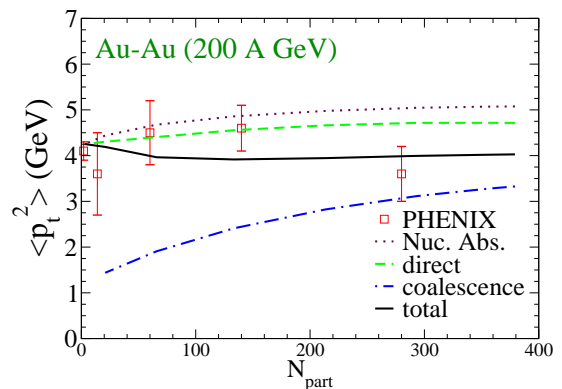


FIG. 6: (Color online). Centrality dependence of $\langle p_t^2 \rangle$ within the 2-component model at RHIC, compared to PHENIX data [9]. The dotted line corresponds to the primordial input distribution (with nuclear absorption and Cronin effect), the dashed line includes QGP and HG suppression, and the dot-dashed line represents the coalescence component.

for central collisions but quickly ceasing for more peripheral ones. For the direct component, the p_t -broadening of the Cronin effect induces an appreciable rise of $R_{AA}(p_t)$ in the region from 2-5 GeV (cf. the dotted lines). This trend is largely counter-balanced by the QGP suppression (dash-double-dotted line, with leakage effect off, implemented by ignoring the spatial fireball boundary), due to the increase of the quasifree dissociation rate with momentum. The leakage effect finally restores significant strength at higher p_t (up to $\sim 40\%$ for $p_t > 5$ GeV) in the direct component (dashed lines). The opposite p_t dependence of the direct and coalescence spectrum combines into a rather flat total $R_{AA}(p_t)$ which is quite compatible with experiment. We emphasize that a proper description of the absolute yields is an important ingredient to this finding (the underestimate for 20-40% central collisions could be improved upon with a somewhat smaller c -quark thermalization time). *E.g.*, a pure coalescence spectrum can be compatible with the central data, but it would be less convincing for more peripheral collisions. Therefore, $R_{AA}(p_t)$ data may indeed discriminate a two-component from a one-component model, especially if the experimental uncertainty can be reduced.

We have checked that within the current experimental accuracy of $R_{AA}(p_t)$ it is not possible to exclude different suppression mechanisms in the QGP medium. The data are also consistent with calculations employing a dissociation rate based on gluo-dissociation [32] with vacuum binding energy and zero thermal gluon mass, since the relevant suppression regime is for temperatures $T \leq 300$ MeV where the J/ψ rate is only weakly momentum dependent.

We finally condense the p_t spectra into a centrality dependence of $\langle p_t^2 \rangle$, as computed from our spectra and compared to PHENIX data [9] in Fig. 6. This plot reiterates the importance of the soft coalescence spectra in central collisions to provide a near-flat centrality dependence.

We recall, however, the currently large uncertainty in the Cronin effect as inferred from d - Au collisions.

IV. SUMMARY AND CONCLUSIONS

We have studied the 3-momentum dependence of J/ψ production in heavy-ion collisions based on a previously developed two-component model which accounts for primordial production with subsequent suppression and secondary regeneration close to the QCD phase boundary. For the direct component, we adopted a transport approach including up-to-date empirical input for nuclear absorption and a Cronin effect in the initial state. The key microscopic ingredient is the charmonium dissociation rate in the QGP. We argued that the quasifree destruction mechanism provides a realistic treatment for small (in-medium) binding energies and the extension to finite 3-momentum. For the coalescence component, we adopted a blast wave description at the hadronization transition within the same fireball model used for the direct spectra. Our approach has essentially two parameters: the strong coupling constant in the quasifree rate, which we adjust to the suppression in central Pb - Pb at SPS, and the thermal relaxation time of c quarks, which controls the magnitude of the coalescence component, adjusted to the J/ψ yield in central Au - Au at RHIC. Within reasonable values for these parameters, $\alpha_s \simeq 0.24$ and $\tau_c^{\text{therm}} \simeq 5$ -7 fm/ c , an approximate overall description

of the centrality dependence of inclusive J/ψ production at SPS and RHIC emerges. The key point of our Letter is that, without further assumptions, the calculated p_t spectra are largely consistent with available SPS and RHIC data. We argued that this supports the underlying momentum dependence of the dissociation rate in connection with reduced binding energies, as well as the presence of a $\sim 50\%$ coalescence contribution in central Au - Au collisions at RHIC. More work is required to scrutinize these findings, *e.g.*, an extension to NA60 data at SPS, forward rapidities at RHIC, predictions for LHC, as well as more accurate input from d/p - A experiments. A microscopic transport treatment with c -quark spectra constrained by open-charm observables will be pursued and used to predict elliptic flow. Ultimately, the underlying charmonium properties in the QGP should be consistent with lattice QCD results to establish model-independent connections between the QCD phase diagram and the matter created in heavy-ion collisions.

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