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Two-Component Approach to J/Ψ Production in High-Energy Heavy-Ion Collisions*

L. Grandchamp^{ab†}, R. Rapp^{ac}

^aState University of New York at Stony Brook, Stony Brook, NY 11794-3800

^bIPN Lyon, IN2P3-CNRS et UCBL, 43 Bd. du 11 Novembre 1918, 69622 Villeurbanne

^cNORDITA, Blegdamsvej 17, DK-2100 Copenhagen

The production of charmonia in ultrarelativistic heavy-ion collisions is investigated including two sources. These are a primordial contribution coupled with various phases of dissociation, and a statistical coalescence of c and \bar{c} quarks at the hadronization phase transition. Within a schematic fireball evolution, SPS data on J/Ψ production can be reasonably well reproduced. Remaining discrepancies in the Ψ'/Ψ ratio are discussed. Predictions for the J/Ψ centrality dependence at RHIC energies are confronted with first data from PHENIX. The pertinent excitation function of the $N_{J/\Psi}/N_{c\bar{c}}$ ratio exhibits a characteristic minimum structure signaling the transition from the standard J/Ψ suppression scenario (SPS) to predominantly statistical production (RHIC).

1. Introduction

In the standard picture of J/Ψ production in heavy-ion collisions [1,2], charmonium states are (pre-) formed in primordial N - N collisions and subject to subsequent nuclear absorption, Quark-Gluon Plasma (QGP) and hadronic dissociation. Hence, the magnitude of J/Ψ suppression reflects on the plasma effect provided that nuclear and hadronic suppression are known and/or small. Recently, an alternative mechanism of J/Ψ production in relativistic heavy-ion collisions has been suggested [3–5]. The underlying idea is that charmonium states are formed by statistical coalescence of c and \bar{c} quarks at the hadronization transition according to thermal weights, with the total $c\bar{c}$ abundance being determined by primordial parton fusion.

In the following, we present a combined approach of direct and statistical J/Ψ production [6,7], constructed within a thermal framework that is consistent with basic hadrochemistry and expansion dynamics at both SPS and RHIC, and also reproduces electromagnetic observables at the SPS. In particular, we do not invoke any “anomalous” open-charm enhancement beyond expectations from N - N collision scaling.

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†Email: loic@tonic.physics.sunysb.edu

2. Two-component model of J/Ψ production

The first (“direct”) component of J/Ψ yield is attributed to primordial J/Ψ ’s arising from early (hard) parton-parton collisions. A first suppression factor, \mathcal{S}_{nuc} , is due to nuclear absorption evaluated in the Glauber picture with a phenomenological (constant) cross-section $\sigma_{\Psi N} \simeq 6.4$ mb. Subsequent QGP suppression is based on inelastic scattering of thermal partons off the c or \bar{c} quark within the bound state, using a quasifree approximation with account for in-medium modified charmonium binding energies [6]. Hadronic dissolution cross sections are estimated within a $SU(4)$ -symmetric effective theory [8,9]. The pertinent dissociation rates for both QGP and hadron gas (HG) are convoluted over a thermal fireball evolution [10,11] for a heavy-ion collision at given impact parameter, yielding charmonium suppression factors \mathcal{S}_{QG}^X and \mathcal{S}_H^X ($X = J/\Psi, \psi', \chi$), respectively. This leads to the number of direct J/Ψ ’s from primordial production (including feeddown),

$$\mathcal{N}_{J/\Psi}^{dir} = \sigma_{pp}^{J/\Psi} AB T_{AB}(b) \mathcal{S}_{nuc} \left[0.6 \mathcal{S}_{QG+H}^{J/\Psi} + 0.032 \mathcal{S}_{QG+H}^X + 0.08 \mathcal{S}_{QG+H}^{\Psi'} \right] . \quad (1)$$

The second (“statistical”) component of J/Ψ yield originates from coalescence of c and \bar{c} quarks at hadronization. The abundances of charmed particles follow from hadronic thermal weights at the critical temperature T_c , with the absolute number matched to the amount of charm quarks created in primordial N - N collisions. This necessitates the introduction of an effective fugacity factor γ_c which is determined enforcing exact (local) charm conservation. The statistical J/Ψ production, including feeddown, is then given by

$$\mathcal{N}_{J/\Psi}^{th} = \gamma_c^2 V_H \left[n_{J/\Psi} \mathcal{S}_H^{J/\Psi} + \sum \mathcal{BR}(X \rightarrow J/\Psi) n_X \mathcal{S}_H^X \right] \mathcal{R} , \quad (2)$$

where the volume at hadronization, V_H , is taken from our fireball evolution. The factor $\mathcal{R} \leq 1$ approximates the effects of incomplete charm-quark thermalization (calculated in a relaxation time approach), inducing a relative reduction of statistical production.

The total number of J/Ψ ’s observed per heavy-ion collision follows as $\mathcal{N}_{J/\Psi} = \mathcal{N}_{J/\Psi}^{dir} + \mathcal{N}_{J/\Psi}^{th}$. The model involves essentially two parameters: the strong coupling constant figuring into the QGP dissociation cross section, as well as the c -quark thermalization time.

3. SPS

Our results for the centrality dependence of the J/Ψ yield in the $Pb(158 \text{ AGeV})$ - Pb system are compared to NA50 data [12] in Fig. 1. Direct production (dashed line) always prevails over the thermal component (dot-dashed line). The latter sets in once a QGP starts forming, which, coupled with the rather strong QGP suppression, mimics the first drop at around $E_T \simeq 40$ GeV. The overall good description of the NA50 data extends beyond $E_T > 100$ GeV (not shown here) when incorporating transverse energy fluctuations [13] and a careful assessment of the minimum bias analysis [14], cf. ref. [7]. In addition, the model also reproduces the NA38 results for the S - U system reasonably well. We note that the relative smallness of statistical production stems from *not* invoking any “anomalous” open-charm enhancement.

Within our two-component model, the Ψ'/Ψ ratio can be extracted without further assumptions. The results (Fig. 2) for both S - U (dashed) and Pb - Pb (solid) indicate

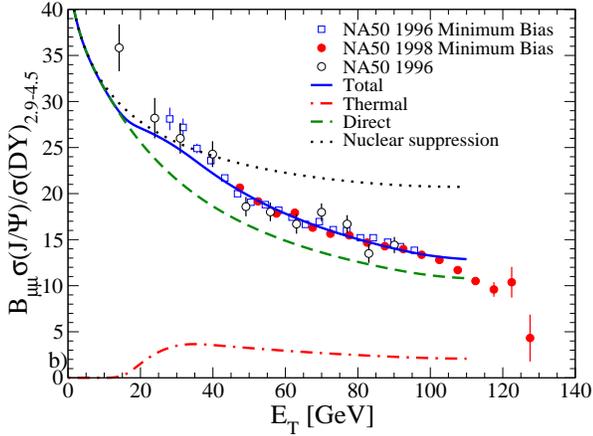


Figure 1. J/Ψ over Drell-Yan ratio at SPS for $Pb(158 \text{ AGeV})\text{-}Pb$ collisions.

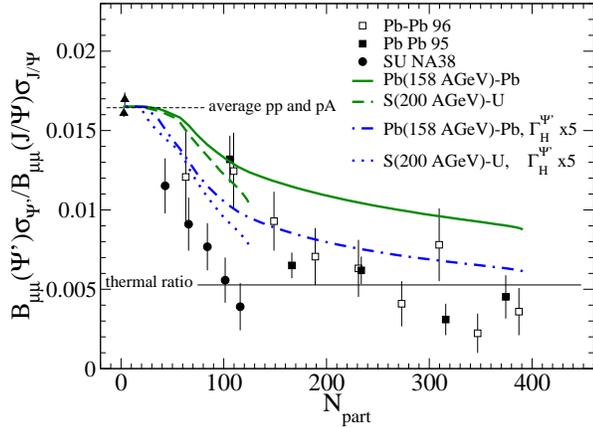


Figure 2. Ψ'/Ψ ratio for $Pb(158 \text{ AGeV})\text{-}Pb$ and $S(200 \text{ AGeV})\text{-}U$ systems at SPS.

significant discrepancy with NA38/NA50 data. We believe the deficiency in our description to reside in the hadronic phase, cf. also ref. [15]. Indeed, an artificial increase of the hadronic Ψ' dissociation cross-section by a factor of 5 clearly improves the agreement with the data. Further analysis is required by addressing, *e.g.*, in-medium effects on D -mesons.

4. Predictions for RHIC and excitation function

At RHIC, due to much more abundant primordial charm-quark production and due to a stronger plasma suppression, the statistical J/Ψ production prevails over the direct component. This is apparent from Fig. 3 where the number of J/Ψ 's per binary collision is plotted as a function of centrality. The full curve represents our *prediction* of ref. [7], with a minor adjustment of the input parameters from pp collisions according to the (central values of the) recent PHENIX measurements [16] which reported $\sigma_{J/\Psi}^{pp}(\sqrt{s}=200 \text{ GeV}) = 3.8 \pm 0.6(\text{stat}) \pm 1.3(\text{sys}) \mu\text{b}$ and $\sigma_{c\bar{c}}^{pp}(\sqrt{s}=200 \text{ GeV}) \simeq 650 \mu\text{b}$. Despite the large error bars, it appears that scenarios involving standard J/Ψ suppression only, as well as more extreme recombination scenarios, are disfavored by the data.

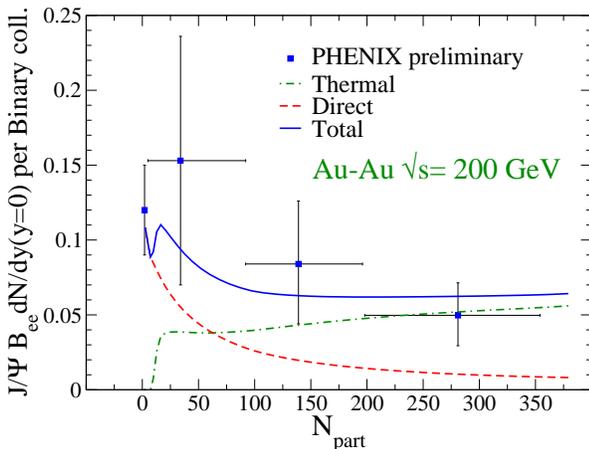


Figure 3. RHIC centrality dependence of the number of J/Ψ 's per binary collision.

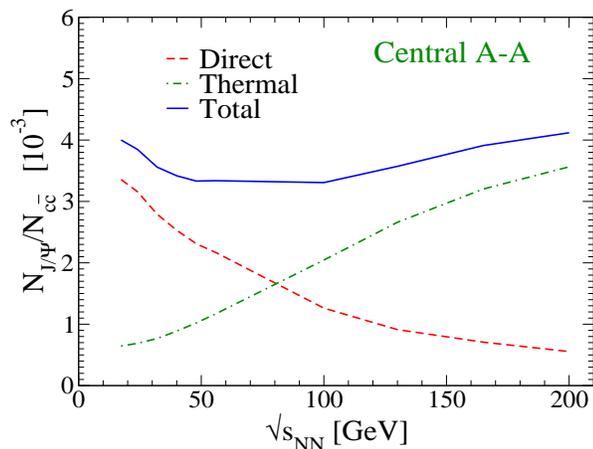


Figure 4. Excitation function of the ratio $N_{J/\Psi}/N_{c\bar{c}}$ in central heavy-ion collisions.

We also note that the probabilistic treatment of nuclear absorption, valid in the low energy regime, is not justified at RHIC energies. However, evaluations of nuclear absorption at collider energies using a more rigorous quantum-field theoretical approach [17] find that the suppression effects are quantitatively very close to the ones in the probabilistic treatment.

The transition between the regimes of predominantly direct (SPS) to statistical (RHIC) charmonium production can be further scrutinized experimentally at RHIC in terms of an excitation function for the ratio $N_{J/\Psi}/N_{c\bar{c}}$, cf. Fig. 4. This ratio exhibits a nontrivial shallow minimum structure, a direct consequence of the interplay between suppressed and thermal production (assuming no anomalies in open-charm production).

5. Conclusions

We have shown that a two-component model for charmonium production in heavy-ion collisions, including both “direct” J/Ψ ’s arising from primordial N - N collisions subject to nuclear, QGP and hadronic suppression, as well as “thermal” J/Ψ ’s emerging from coalescence of c and \bar{c} quarks at hadronization, accounts well for J/Ψ centrality dependencies measured at SPS. A potential discrepancy has been identified in the Ψ'/Ψ ratio, which might hint at shortcomings in the evaluation of hadronic Ψ' dissociation. Extrapolating our approach to higher energies, the centrality dependence of J/Ψ production at RHIC is in line with preliminary PHENIX data. We furthermore emphasized the importance of an excitation function to determine a potential transition from (predominantly) direct to (mostly) statistical production, as indicated by an almost flat (but nontrivial) structure of the $N_{J/\Psi}/N_{c\bar{c}}$ ratio as a function collision energy.

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