Quarkonium Suppression from SPS to RHIC
(and from p+A to A+A)

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Abstract

Heavy quarkonium production is expected to be sensitive to the formation of a quark gluon plasma (QGP). It was (and still is with ongoing data analyses) extensively studied at the CERN SPS, at collision energy $\sqrt{s_{NN}}$ of the order of 20 GeV. An anomalous suppression was clearly observed. The PHENIX experiment at RHIC has presented preliminary results that exhibit a similar amount of $J/\psi$ suppression, at ten times higher collision energy. I review the results obtained at both facilities. While interpreting and comparing them, the importance of understanding normal nuclear effects is emphasized. A new method to derive a reference for Au+Au collisions from the centrality dependence of d+Au measurements at RHIC is presented.

1 Nuclear effects from p+A or d+A collisions

When trying to interpret all the quarkonia yields observed in p+A collisions at various energies and kinematical domains, we find ourselves facing a real puzzle [1]. Various effects are invoked, including normal nuclear absorption of quarkonia or pre-resonant $c\bar{c}$ pairs, parton shadowing and corresponding anti-shadowing, contribution from the intrinsic charm existing in the nucleon wave function, or energy loss and related transverse momentum broadening, all of them being further complicated by feed-down from higher mass states. Explaining all the available p+A data is beyond the scope of this article. In the following, I restrict my interest for p+A data and nuclear effects to the energies and kinematical domains where A+A collisions are also measured, in order to set up references for QGP studies.

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Fig. 1. Normal nuclear matter effects. Left) At SPS, the $J/\psi$/Drell-Yan cross-section ratio versus the average nuclear length $L$, for several collision systems [2]. The line stands for a normal nuclear absorption of $\sim 4.2$ mb. Right) At RHIC, $J/\psi$ nuclear modification factor $R_{dA}$ as a function of the number of nucleon-nucleon collisions $N_{coll}$ for backward (top, $y = -1.7$) mid (middle, $y = 0$) and forward (bottom, $y = 1.8$) rapidities [6]. Theoretical curves from Vogt [7], assuming EKS shadowing and 0, 1, 2 or 3 mb normal absorption cross-sections (from top solid to bottom dot-dashed).

1.1 Normal nuclear absorption at SPS

Figure 1 (left) summarizes the published $J/\psi$ production yield (normalized to Drell-Yan) observed at SPS energies, from $p+p$ to $Pb+Pb$ collisions [2], excluding In+In data from the NA60 experiment [3]. It is plotted here as a function of the average length $L$ of nuclear matter traversed by the $\bar{\psi}\psi$ state. Looking only at $p+A$ collisions, we observe a clear exponential suppression. This behavior is expected if the only nuclear effect is an absorption by the nucleons in the incoming nuclei. The line of figure 1 (left) stands for such a normal nuclear absorption, with a fitted $J/\psi$-nucleon cross-section of $\sigma_{abs}^{J/\psi} = 4.18 \pm 0.35$ mb. Although this simple picture does a splendid job in reproducing the data, all the way from $p+p$ up to peripheral Pb+Pb collisions (including the whole S+U range), one can oppose theoretical arguments against it. First, the $p+A$ data are rescaled to a lower collision energy $\sqrt{s_{NN}}$ (from 27 or 29 GeV to 17 and 19 GeV). The NA60 collaboration is currently analyzing $p+A$ data at 17 GeV. Second, according to various theoretical predictions [4], shadowing (or rather anti-shadowing) could play a role at the SPS experiments regime, namely for momentum fraction $x$ of the order of $10^{-1}$. The SPS experiments can hardly address this question because of their limited rapidity (or $x$) range. Still, the rapidity asymmetry observed in $J/\psi$ yields in $p+A$ collisions might be a hint of such an effect [5]. Third, the $p+A$ absorption might not be straightly applica-
ble to A+A, for instance if there are complications due to changing feed-down ratios. Indeed, the $\psi'$ is known not to suffer the same nuclear effects as the $J/\psi$: its absorption cross-section extracted from p+A is $\sigma_{ab{s}}^{\psi'} = 7.7 \pm 0.9$ mb and its anomalous suppression already sets in S+U collisions [5]. However, one should not forget that the simple picture of nuclear absorption perfectly describes a large amount of data (p+p, various p+A, S+U and peripheral Pb+Pb). The departure from the absorption curve for more central Pb+Pb collisions is clearly a new phenomenon.

1.2 Shadowing and absorption at RHIC

At $\sqrt{s_{NN}} = 200$ GeV, the only available data on quarkonia from p+A like collisions are $J/\psi$ seen by the PHENIX experiment in d+Au [6], probing a wide rapidity range, from $-2.2$ to $2.4$, corresponding to momentum fractions $x$ of gluons in the gold nuclei ranging from $\sim 10^{-3}$ to $\sim 10^{-1}$. The minimum bias points of figure 1 (right) show that the measured nuclear modification factors $R_{dA}$ depend on rapidity. This is interpreted as due to shadowing and/or anti-shadowing. While the strength of gluon shadowing is not heavily constrained by theory (models predictions [4] differ by a factor of three), PHENIX data favor moderate shadowing schemes such as the Eskola-Kolhinen-Salgado (EKS). In addition to this, a moderate normal nuclear absorption is allowed, not larger than 3 mb. The addition of these two ingredients is performed by Vogt in [7] and can describe both the rapidity and centrality dependencies, as shown on figure 1 (right).

1.3 From d+Au to Au+Au at RHIC

To interpret $J/\psi$ production in A+A collisions at RHIC, we need a model capable of reproducing the d+Au nuclear modification factors $R_{dA}$ and extrapolating them to A+A. Such a model, including inhomogeneous shadowing and nuclear absorption is given by [8] and shown on figure 1 (right). Another attempt to derive a reference from d+Au can be found in [9] where the authors derive dissociation cross-sections from the centrality dependence of $R_{dA}$. They assume that nuclear effects are proportional to $\exp(-\rho_0\sigma_{diss}L)$, $\rho_0$ being the normal nuclear density and $L$ the average length of nuclear matter seen by the $J/\psi$. However, there is no fundamental reason for this function to reflect the centrality dependence of shadowing. I propose here an alternate method, with a concern to be as much data-driven as possible. First, I perform phenomenological fits of the modification factors $R_{dA}(y,b)$ as a function of the impact parameter $b$ (given by a Glauber model), for the three rapidities $y$ of the PHENIX measurements. Given the experimen-
tal uncertainties, linear fits are sufficient to describe the data. I then run a A+A Glauber model. For each A+A collision occurring at a given impact parameter $b_{AA}$, the positions of the $N_{coll}$ elementary nucleon+nucleon collisions are randomly distributed (following the nuclear densities) providing the locations $b_i^1$ and $b_i^2$ of each collision $i$, relative to the center of nucleus 1 and nucleus 2. For the considered A+A collision, the predicted nuclear modification factor is given by the following summation over the elementary collisions:

$$R_{AA}(|y|, b_{AA}) = \frac{\sum_{i=1}^{N_{coll}} (R_{dA}(-y, b_i^1) \times R_{dA}(+y, b_i^2))}{N_{coll}}.$$ 

This formula assumes that a $J/\psi$ produced in a A+A collision at a given rapidity $y$ suffers the product of the nuclear effects that were observed in d+A at this rapidity, by the ones of the opposite rapidity $y$ (equivalent to a A+d collision). This assumption is correct for the only two effects considered so far to explain RHIC data, namely shadowing and nuclear absorption. Quarkonia production is proportional to the parton distribution functions ($pdf$) in each nucleus, while the average length is the sum of the length in each nucleus, so that the production is finally proportional to $pdf_1 \times pdf_2 \times \exp(-\rho\sigma(L_1 + L_2))$. This method has two advantages$^2$. First, the statistical and systematical uncertainties of the d+A measurements can be directly propagated to the A+A prediction. Second, since it is based on a Glauber calculation, it is easy to predict modification factors for experimental centrality classes. This is done on figure 2 where predictions are given for the Au+Au PHENIX centrality classes. No systematic uncertainties from the method itself (Glauber parameters) are calculated. The amount of predicted suppression is compatible with Vogt’s predictions. In the forward rapidity case (left) its uncertainty is smaller than the allowed variation between the 1 and 3 mb absorption cross-sections and seem to favor intermediate ones. In the mid-rapidity case (right) the uncertainty is larger. At both rapidities, the $J/\psi$ suppression seen by PHENIX [10] in the most central data is larger than the one predicted by Vogt or by the model described above, pointing out that there is an anomalous suppression at RHIC energy.

2 Anomalous suppressions

In both SPS (figure 1 left) and RHIC (figure 2) data, the most central A+A $J/\psi$ measurements depart from the nuclear effect predictions, suggesting that other mechanisms are involved. Such an anomalous suppression was early predicted by Matsui and Satz as a signature of the QGP [11].

1 A similar assumption is made in [9] while summing dissociation cross-sections.

2 Despite these advantages it will be difficult to apply it at LHC where p+A and A+A collisions are planed to be measured at difference collision energies and $J/\psi$ in ALICE will only be measured at positive or negative rapidity for p+A.
Fig. 2. Nuclear modification factor $R_{AA}$ as a function of centrality (given here by the number of participants $N_{\text{part}}$) for Au+Au at $y = 1.7$ (left) and $y = 0$ (right). Squares are preliminary data from PHENIX [10]. Theoretical curves are nuclear effects predictions from Vogt [8], solid and dashed lines being for 1 and 3 mb normal nuclear absorption cross sections, respectively. The circles within the shaded bands show the prediction from the model presented here.

2.1 From SPS to RHIC

Various models account for the $J/\psi$ anomalous suppression seen in Pb+Pb collisions at SPS. They were used to predict the expected $J/\psi$ yield at RHIC energy. Three of these predictions are compared to PHENIX Au+Au preliminary data [10] on figure 3 (left). In [12] (solid line), $J/\psi$’s are absorbed by comoving particles (of undetermined partonic/hadronic nature). In [13], the authors describe the dynamical interplay between suppression and regeneration of $J/\psi$’s in a QGP. The suppression mechanism is dominant for NA50 energies and is the only one presented here as a dashed line (see figure 4 for the full prediction). In [14] (dot-dashed line), a QGP statistical charm coalescence model is used. All three models fail to reproduce PHENIX data, overestimating the measured suppression. Other models such as percolation [15] also over-predicts the suppression, suggesting that new mechanisms take place at RHIC energy. It is interesting to note that the same models also failed to reproduce the In+In data shown by the NA60 experiment [3].

2.2 Alternate explanations for RHIC suppression

Three classes of models exist that can accommodate the amount of anomalous suppression seen in the most central collisions. The accuracy of present data and the nuclear effects uncertainty, do not allow to favor one over the other.
Fig. 3. RHIC Nuclear modification factor $R_{AA}$ as already presented on figure 2 versus predictions derived from models reproducing SPS data. Theoretical curves are predictions from models that describe the SPS anomalous suppression. Left) Most of the models over-predict the suppression [12,13,14]. Right) One model [16] reproduces the most central suppression (solid/dashed are without/with plasma, top/bottom assume 1/3 mb normal absorption cross-section).

- Detailed transport: One paper [16], simulating $J/\psi$ transport in a hydrodynamical model, predicts an amount of suppression that matches the most central data. It is shown on figure 3 (right) where the authors have added nuclear matter effects (nuclear absorption only, 1 or 3 mb) with respect to the published paper. The suppression they obtain is not large probably because of their description of the boundary between the QGP and the nuclear phase.

- Sequential melting: An important fraction (30 to 40%) of $J/\psi$’s comes from decays of excited states ($\psi'$, $\chi_c$) as it is shown by the HERA-B experiment [17]. They are taken into account in most of the approaches. Recent lattice computations indicate that $J/\psi$’s could melt at a much higher temperature than the one that was originally thought. One possible hypothesis, defended in [9], is that, both at SPS and RHIC, only the excited states melt, leaving all the initially produced $J/\psi$’s untouched.

- Recombination: At RHIC energies, multiple $c\bar{c}$ pairs are produced, 10 to 20 in central collisions [18]. Quark mobility in a deconfined medium could allow uncorrelated charm quarks to recombine when the QGP fireball freezes, raising the quarkonium yield with centrality. A balance between suppression and enhancement could lead to the intermediate suppression observed at RHIC. Figure 4 (left) shows a collection of predictions from various recombination or coalescence models [13,19,20,21]. Unfortunately, the lack of knowledge concerning yields and distributions of the initially produced charm quarks, as well as of the recombination mechanism, make these predictions hardly predictive. A way to search for recombination is to look at its impact on the distributions of kinematical variables, such as transverse...
Recombination is expected to modify transverse momentum distributions. To properly predict the modified $p_T$ spectra, one first needs to quantify the $p_T$ broadening coming from normal nuclear effects (Cronin effect). This effect was clearly seen at SPS by comparing $p$+$p$ and $p$+$A$ $\langle p_T^2 \rangle$, as well as in PHENIX at forward rapidity $^3$ $\langle p_T^2 \rangle$ values from $p$+$p$ up to $Pb$+$Pb$: $\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + \rho \sigma \delta(\langle p_T^2 \rangle) \times L$ where $L$ is the average thickness of nuclear matter seen by a $J/\psi$. The factor $\rho \sigma \delta(\langle p_T^2 \rangle)$ stands for the nuclear density $\rho$, times the elastic gluon-nucleon scattering cross section $\sigma$, times the average $p_T$ kick given at each scattering $\delta(\langle p_T^2 \rangle)$. A review of SPS (including some FNAL data) was made in [22] together with a similar fit to RHIC forward data. This is presented as a solid line (with associated errors) on figure 4 (right). The shaded bands are predictions from [21], corresponding to either $J/\psi$’s from recombination (lower band) or to directly produced $J/\psi$’s (upper band). No clear sign for modification is seen and the $A$+$A$ $\delta(\langle p_T^2 \rangle)$ can be interpreted in terms of normal broadening.

$^3$ The midrapidity $p$+$p$ has too poor statistics to claim for a modification with respect to the $d$+$Au$ measurement.
The rapidity spectra are also expected to be modified by recombination, but there is also no sign of this so far [10].

As a conclusion, I stress that RHIC and SPS data are not so easy to compare, even if they exhibit similar suppression at their highest energy densities. The amount of normal nuclear suppression is poorly known, especially at RHIC where it demands more d+A data. Nevertheless, RHIC preliminary suppression seems anomalous and all the different models that can accommodate it suppose the formation of a QGP. To distinguish between them, a better precision on data, and in particular on the kinematical distributions, is required.

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