RHIC Results on $J/\psi$

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Abstract. Quarkonia ($J/\psi$, $\psi'$, $\Upsilon$) production provides a sensitive probe of gluon distributions and their modification in nuclei; and is a leading probe of the hot-dense (deconfined) matter created in high-energy collisions of heavy ions. We will discuss the current understanding of the production process and of the cold-nuclear-matter effects that modify this production in nuclei in the context of recent p+p and p(d)+A quarkonia measurements. Then we will review the latest results for nucleus-nucleus collisions from RHIC, and together with the baseline results from d+A and p+p collisions, discuss several alternative explanations for the observed suppressions and future prospects for distinguishing these different pictures.

1. Introduction

We will give an overview of the physics and the most recent measurements from RHIC for $J/\psi$ production and suppression starting with 1) production issues as seen in p+p collisions, then 2) cold nuclear matter effects as seen in p+A or d+A collisions, and finally 3) effects of the hot-dense partonic matter created in heavy-ion collisions and interpretation of the latest PHENIX heavy-ion data. For more details on these and related topics please see other contributions to this proceedings including those from A. Bickely (PHENIX p+p $J/\psi$); A. Glenn and T. Gunji (PHENIX A+A $J/\psi$); P. Djawotho (STAR Upsilon and $J/\psi$); R. Granier de Cassanac and R. Vogt (cold nuclear matter effects on $J/\psi$); E. Scomparin (NA60 $J/\psi$’s); and A. Suaide (open charm at RHIC).

2. $J/\psi$ Production in p+p Collisions

Gluon fusion dominates the production of quarkonia, but the configuration of the produced state and how it hadronizes remain uncertain. Absolute cross sections can be reproduced by NRQCD models that involve a color octet state[1], but these models predict transverse polarization of the $J/\psi$ at large $p_T$ which is not seen in the data[2]. A complication in understanding the $J/\psi$ results is the fact that $\sim 40\%$ of the $J/\psi$’s come from decays of higher mass resonances ($\psi'$ and $\chi_c$)[3] - a feature that may contribute to the lack of polarization seen.

The most recent $J/\psi$ cross section measurements for p+p collisions at $\sqrt{s} = 200$ GeV from PHENIX[4] are shown in Fig. 1. These data slightly favor a flatter rapidity
Figure 1: $J/\psi$ cross section vs rapidity for 200 GeV p+p collisions at RHIC[4]. Also shown are fits using shapes from two theoretical models and from a double Gaussian.

Forw/Mid-Rapidity $p_T$ distribution at mid rapidity than most model calculations which have shapes similar to the NRQCD calculation (dashed curve) in the figure. A more recent pQCD calculation[5] that includes explicit treatment of the third gluon, necessary to give the final color singlet state, gives good agreement with the cross sections and polarization seen in other measurements, but does not reproduce the steep falloff at large rapidity of the PHENIX results. In Fig. 2 the $p_T$ distributions are also shown. The distribution is harder at mid-rapidity than for forward rapidity with $<p_T^2> = 4.14 \pm 0.18 + 0.30 - 0.20$ (mid rapidity) and $3.59 \pm 0.06 \pm 0.16$ (forward rapidity), and both are harder than at lower energies. These $<p_T^2>$ values are obtained from a fit to the data using the standard form, $A \times (1 + (p_T/B)^2)^{-6}$.

3. Cold Nuclear Matter Effects and $J/\psi$ Suppression in p(d)+A Collisions

When quarkonia are produced in nuclei their yields per nucleon-nucleon collision are known to be significantly modified. This modification, shown vs. rapidity in Fig. 3 at RHIC energy and vs. $x_F$ in Fig. 4b, is thought to be due to several cold nuclear matter (CNM) effects including gluon shadowing, initial-state gluon energy loss and multiple scattering, and absorption (or dissociation) of the $c\bar{c}$ in the final-state before it can form a $J/\psi$.

Shadowing is the depletion of low-momentum partons (gluons in this case) in a nucleon embedded in a nucleus compared to their population in a free nucleon. The predicted strength of the depletion differs between numerous models by up to a factor of three. Some models are based on phenomenological fits to deep-inelastic scattering and
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Figure 3: Rapidity dependence of the J/ψ nuclear modification factor, $R_{dAu}$ for 200 GeV d+Au collisions at RHIC[6].

Figure 4: Test of scaling vs $x_2$ and $x_F$ for J/ψ suppression data for three different collision energies. J/ψ data is from Refs.[7, 8, 6] and $D^0$ point is from Ref.[9].

Drell-Yan data[10], while others obtain shadowing from coherence effects in the nuclear medium[11, 12]. In addition, models such as the Color Glass Condensate (CGC)[13] obtain shadowing through gluon saturation pictures where non-linear effects for the large gluon populations at very small x in a nucleus generate a deficit of gluons per nucleon at small x.

In the final state, the produced $c\bar{c}$ can be disassociated or absorbed on either the nucleus itself, or on light co-moving partons produced when the projectile proton or deuteron enters the nucleus. The latter is probably only important in nucleus-nucleus collisions as the number of co-movers created in a p+A or d+A collisions is small.

However, J/ψ suppression in p(d)+A collisions remains a puzzle given that one does not find a universal suppression vs $x_2$ as would be expected from shadowing, Fig. 4a; while vs. $x_F$ the dependence is similar for all energies, Fig. 4b. This apparent $x_F$ scaling supports explanations such as those that involve initial-state energy loss or Sudakov suppression[14].

**4. J/ψ Suppression in the Hot-dense Partonic matter created in Nucleus-Nucleus Collisions**

One of the leading predictions for the hot-dense matter created in high-energy heavy-ion collisions was that if a deconfined state of quarks and gluons is created, i.e. a quark-gluon plasma (QGP), the heavy-quark bound states would be screened by the deconfined colored medium and destroyed before they could be formed[15]. This screening would depend on the particular heavy-quark state, with the $ψ'$ and $χ_C$ being dissolved first; next the J/ψ and then the Υ’s only at the highest QGP temperatures. The CERN SPS measurements[16] showed a suppression for the J/ψ and $ψ'$ beyond what was
expected from CNM effects - as represented by a simple absorption model constrained to p+\(A\) data. In addition to explanations involving creation of a QGP, a few theoretical models\cite{17} were also able to explain the data without including a QGP, so the evidence that a QGP was formed was controversial.

Figure 5: \(J/\psi\) suppression in Au+Au\cite{18} and Cu+Cu\cite{19} collisions for forward rapidity and central rapidity\cite{19} compared to predictions for CNM from the same calculations as shown in Fig. 6\cite{20}.

Final results from PHENIX for Au+Au collisions\cite{18} along with preliminary results for Cu+Cu collisions\cite{19} are now available, and are shown in Fig. 5. First it is important to understand what normal CNM \(J/\psi\) suppression contributes in these A+A collisions. This is illustrated by the blue error bands for A+A collisions in the figure which represent theoretical calculations identical to those for the analogous blue error band in Fig. 6 for d+Au collisions. As can be seen, although the present d+Au data lack the precision to constrain the CNM effects very well, there is still a clear suppression beyond CNM effects in Au+Au collisions particularly for the forward rapidity data (blue points) and for the most central mid-rapidity data (red points). Note that these CNM calculations probably do not explore all possibilities for the resulting effects on A+A collisions, since they tend to be flat with rapidity due to the approximate cancelation at forward rapidity of the shadowing of the small-x gluon and the anti-shadowing of the other gluon. For example, gluon saturation may not provide this cancelation. For Cu+Cu collisions the deviations below the CNM expectations are less clear.

Looking just at the Au+Au data in Fig. 7 one can see (top panel) that the suppression for forward rapidity is significantly stronger than that for mid rapidity. In the bottom panel the ratio of the \(R_{AA}\) for forward rapidity to that for mid rapidity is shown, and here the stronger forward rapidity suppression is quite distinct and this
Figure 7: Nuclear modification factor, $R_{AA}$, for $J/\psi$ production in 200 GeV/c Au+Au collisions\cite{18} vs centrality (number of participants) in the top panel for mid (red) and forward (blue) rapidity. In the bottom panel the ratio of the forward over mid rapidity $R_{AA}$’s is shown.

Figure 8: Comparision of final Au+Au results\cite{18} to preliminary Cu+Cu results\cite{19} for the nuclear modification factor vs number of participants.

ratio appears to show a saturation, within the experimental uncertainties, at about 0.6 for centralities above $N_{part} \sim 100$. The features of this ratio are undoubtedly the most interesting from the new data and will challenge theoretical interpretations. Also, as shown in Fig. 8 we see that the Cu+Cu results agree well with the Au+Au data at small values of $N_{part}$ where they overlap.

Numerous theoretical models\cite{17,21,22} were successful in describing the lower energy SPS data, but all over-predict the suppression compared to the preliminary mid-rapidity data at RHIC - unless a regeneration mechanism is added as was done by Rapp\cite{22} and by Thews\cite{24}. The regeneration models provide an additional production mechanism for $J/\psi$s, where if the total production of charm is high enough then charm densities in the final state will be sufficient to give substantial formation of $J/\psi$s from coalescence of the large number of independent charm quarks created in the collision. This production mechanism is predicted to be almost insignificant at SPS energies but at RHIC may be substantial. This leads to a scenario in which strong screening or dissociation by a very high-density gluon density occurs to a level of suppression stronger than that observed in the RHIC data, but the regeneration mechanism compensates for this and brings the net suppression back up to where the data lies. One of the recent calculations\cite{23,22,24} of this type is shown in Fig. 9.

In the regeneration picture, the stronger suppression at forward rapidity would result from the lower density of charm at forward rapidity, which may be small enough to give no substantial regeneration there. In this case the forward rapidity suppression
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Figure 9: J/ψ nuclear modification factor ($R_{AA}$) for Au+Au collisions at 200 GeV/c vs centrality (number of participants) for mid rapidity (red) and forward rapidity (blue) compared to theoretical calculations that include recombination[23].

Figure 10: Survival fraction ($R_{AA}/CNM$) vs energy density comparison of PHENIX Au+Au suppression to that from NA38/50 at CERN.

would reflect the stronger suppression from the QGP expected at RHIC compared to the SPS. While at mid rapidity the higher charm density would provide substantial regeneration bringing the net suppression back up to the same level as has been observed at the SPS. However both the screening and the regeneration should increase with centrality, so the saturation in the forward/mid rapidity suppression ratio challenges this picture.

An alternative interpretation of the preliminary results, sequential screening, is given by Karsch, Kharzeev and Satz[25]. In this picture, they assume that the J/ψ is never screened, as supported by recent Lattice QCD calculations for the J/ψ - not at the SPS nor at RHIC. Then the observed suppression comes from screening of the higher-mass states alone (ψ′ and χC) that, by their decay, normally provide ~40% of the observed J/ψ/ψs. This scenario is consistent with the apparently identical suppression patterns seen at the SPS and RHIC for mid rapidity shown in Fig. 10.

However, the comparison shown in Fig. 10 should be taken with caution, as it is not very clear how to quantitatively compare the energy densities achieved at the SPS with those at RHIC. Here we have used the Bjorken formula[26] with a $\tau_0 = 1 \text{ fm/c}$ in both cases to estimate the energy density, $\epsilon_B = \frac{dE_T}{dy} \frac{1}{\tau_0 \pi R^2}$. Since the crossing time at the SPS is about 1.6 fm/c it may be more realistic to use a larger $\tau_0$ there, while at RHIC the $\tau_0$ could be smaller than 1 fm/c. The survival fraction ($R_{AA}/CNM$) for the PHENIX points in this figure are obtained using CNM calculations like those shown in Fig. 5 with an absorption cross section of 1 mb and with uncertainties of ±1 mb added into the systematic uncertainties shown. For the SPS data we have estimated that an additional systematic of about 17% is appropriate - this is indicated on the figure but
not added into the SPS uncertainties shown.

In the sequential screening picture the stronger suppression at forward rapidity could come from gluon saturation, which according to the CGC model\[13\], would not result in the flat rapidity distributions obtained for CNM calculations like those shown in Fig. 7 but instead would produce a substantially smaller initial production at forward rapidities compared to mid rapidity. However, this picture would also appear to be challenged by the saturation in the forward over mid rapidity suppression ratio, since gluon saturation should continue to increase up to the most central collisions.

Regeneration models also predict both narrowing of the $p_T$ distribution relative to the usual Cronin broadening seen in p+A collisions, and, given that recent charm measurements show flow, this flow should be inherited by the $J/\psi$s that are produced by regeneration. Some evidence for narrowing of the $p_T$ has been observed - Fig. 11 but a more reliable d+A CNM baseline will be necessary to establish this clearly. Measurements of flow await the higher statistics of a new Au+Au run at RHIC. As a result we are left with two different scenarios that provide explanations for the RHIC A+A data. Both include the QGP in their picture, either through color screening in the QGP or through dissociation of the $J/\psi$ by large gluon densities.

![Figure 11: Mean $p_T^2$ vs centrality (number of collisions) of p+p, Cu+Cu and Au+Au data compared to model calculations\[24\].](image1)

![Figure 12: Preliminary measurements of the 200 GeV/c p+p cross section for $\Upsilon$ production from PHENIX\[28\] and STAR\[29\].](image2)

Further advances in these important studies await higher luminosity runs for d+Au to solidify our understanding of the baseline CNM effects, and higher luminosity A+A runs in order to capture sufficient statistics for the rare quarkonia probes. A promise for the future can be seen in the recent $\Upsilon$ measurements from PHENIX and STAR shown in Fig. 12.
5. Summary

Substantial uncertainties remain in the understanding of the production cross sections and the polarization of charmonia. There are also a number of cold nuclear matter effects that influence their production in nuclei and cloud our understanding of the suppression seen in nucleus-nucleus collisions. Two competing pictures are able to explain the $J/\psi$ suppression seen in nucleus-nucleus collisions at RHIC - one involving sequential screening in the plasma of the various charmonia states; the other with strong dissociation of all charmonia states by a dense gluon field but recombination of independently produced charm quarks. More precise measurements in the future will be necessary to distinguish between these two quite different scenarios.

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