CGC effects on $J/\psi$ production

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based on work with D. Kharzeev, G. Levin and M. Nardi

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Introduction I
Inclusive light hadron and open charm production at $\sqrt{s}=200$ GeV

Conclusion: at $y=0$ there are no "cold nuclear matter" effects that produce suppression in inclusive $q$ and $G$ production.

BUT: This is true only if there is a factorization between the nuclei!
Theoretical support: an approximate \( k_T \) - factorization holds in G and light q production.

\[
\frac{d\sigma^{pA}}{d^2k \, dy} = \frac{C_F}{\alpha_s \pi (2\pi)^3} \frac{1}{k^2} \int d^2B \, d^2b \, d^2z \left( \nabla_z^2 n_G(z, b - B, 0) e^{-ik_z z} \nabla_z^2 N_G(z, b, 0) \right).
\]

\[
\int d^2k k^2 \frac{d\sigma_{MV}^{pA}}{d^2k \, dy} = A \int d^2k k^2 \frac{d\sigma_{MV}^{pp}}{d^2k \, dy}
\]

One can trace the origin of the (approximate) factorization in that there is no restriction on the quantum numbers of the product (Spin, Color etc.)
Production of the q-anti-q pair: pA

$k_T$-factorization is broken down

Fujii, Gelis, Venugopalan
**Introduction II**

Inclusive $J/\psi$ production at $\sqrt{s}=200$ GeV

Conclusion: at $y=0$ the "cold nuclear matter" effects are insufficient to produce the observed suppression in $J/\psi$ inclusive production

*WRONG!*

Because factorization is badly broken in $J/\psi$ production in pA and AA collisions
The effective absorption cross sections from fits of Ramona's calculations to PHENIX d+Au $R_{CP}$ data are shown for each shadowing model.

This is **not** an attempt to extract physics from the d+Au $R_{CP}$! This is just a parameterization of the data that is independent at each rapidity.

The red points are the averages at $y = -1.7$ and $+1.7$. 

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3 Stolen from T. Frawley
What breaks factorization? Coherence.

\[ l_c = \frac{1}{k_- + (q - k)_- - q_-} \approx \frac{1}{k_-} \]

\[ x = \frac{k_-}{p_-} \]

\[ l_c = \frac{1}{Mx} \]

1) \( l_c \gg R_A \) coherent scattering: all nucleons participate in scattering simultaneously.

2) \( l_c \ll R_A \) incoherent scattering: every nucleon acts as independent scattering center.
Coherence in E&M

Landau-Lifshitz, II §80: “Scattering of waves with large frequencies”

\[ d\sigma = \left( \frac{e^2}{mc^2} \right)^2 \left| \sum e^{-iqr} \right|^2 \sin^2 \theta \, d\theta. \quad q \sim 1/\lambda \]

Coherent scattering:

If \( \lambda >> R \Rightarrow qr << 1 \Rightarrow \exp(i \, q \, r) = 1 \) All scattering centers equally contribute 1.

Incoherent scattering:

If \( \lambda << R \Rightarrow qr >> 1 \Rightarrow \exp[i \, q \, (r_a - r_b)] = 1 \) when \( r_a = r_b \), otherwise 0; i.e. different scattering centers are independent.

QED analogy: coherent vs Raman (combinational) light scattering
Glauber-Gribov model

Glauber: assume projectile-nucleon amplitudes are not correlated.

QCD: if $\alpha_s^2 A^{1/3} \sim 1$

QUASI-CLASSICAL APPROXIMATION

Gribov: hadrons do not diagonalize the scattering matrix $\Rightarrow$ diffraction

UR particle travels along the straight lines in external field $\Rightarrow$

Scattering matrix $S$ is diagonal in the transverse coordinate space.
Beyond Factorization

Relevant variables: transverse coordinates of charges. E.g. for q and anti-q: $\mathbf{x}$ and $\mathbf{y}$ or $\mathbf{r} = \mathbf{x} - \mathbf{y}$ and $\mathbf{B} = (\mathbf{x} + \mathbf{y})/2$

Write the scattering amplitude in terms of transverse coordinates of all excitations $\Rightarrow$ `dipole model'.

\[ \sigma^{q \bar{q} A}_{\text{tot}}(s; \mathbf{r}) = 2 \int d^2 b \, N_A(\mathbf{r}, \mathbf{b}, Y) = 2 \int d^2 b \left( 1 - e^{-\frac{1}{2} \sigma^{q \bar{q} N}_{\text{tot}}(s; \mathbf{r}) \rho T_A(\mathbf{b})} \right) \]

In the Born approximation:

\[ \sigma^{q \bar{q} N}_{\text{tot}}(s; \mathbf{r}) = \frac{\alpha_s}{N_c} \pi^2 r^2 xG(x, 1/r^2) \]
Production of the q-anti-q pair: pA

Heavy quark approximation (valence quark doesn’t interact):

\[
\frac{d\sigma_{\text{tot}}(pA)}{dY \, d^2k \, d^2b} = x_1 G(x_1, m_c^2) \int d^2 r \, e^{-i \frac{1}{2} k \cdot r} \int d^2 r' \, e^{i \frac{1}{2} k \cdot r'} \Phi_G(l_1, r, r', z = 1/2) \times \{ 1 - \exp[-\sigma(x_2, r^2) \rho 2 R_A] - \exp[-\sigma(x_2, r'^2) \rho 2 R_A] + \exp[-\sigma(x_2, (\vec{r} - \vec{r'})^2) \rho 2 R_A] \}.
\]

\[
\left[ \frac{1}{2} \frac{r \cdot r'}{rr'} K_1 (r m_c) K_1 (r' m_c) + K_0 (r m_c) K_0 (r' m_c) \right]
\]

KT, 2004
Production of the $q$-anti-$q$ pair

Inelastic processes:

\[
\frac{d\sigma_{in}(pA)}{dY d^2 k d^2 b} = x_1 G(x_1, m_c^2) \int d^2 r \int d^2 r' \Phi_G(m_c, r, r', z = 1/2) e^{i (z - z') \cdot k} \\
\times \int_0^{2R_A} \rho \tilde{\sigma}_{in}(x_2, r, r') dz_0 e^{-[\sigma(x_2, r^2) + \sigma(x_2, r'^2)]} \rho 2 R_A \\
\times \sum_{n=0}^{\infty} \int_{z_0}^{2R_A} d z_1 \ldots \int_{z_{n-2}}^{2R_A} d z_{n-1} \int_{z_{n-1}}^{2R_A} d z_n \rho^n \tilde{\sigma}_{in}^n(x_2, r, r') \\
(\alpha_s^2 A^{1/3})^n
\]

\[
\tilde{\sigma}_{in}(x_2, r, r') \equiv \sigma(x_2, r^2) + \sigma(x_2, r'^2) - \sigma(x_2, (r - r')^2).
\]
Production of $J/\psi$: pp vs pA

\[ \alpha_s^3 A^{1/3} = \alpha_s (\alpha_s^2 A^{1/3}) \sim \alpha_s \]
\[ \alpha_s^4 A^{2/3} = (\alpha_s^2 A^{1/3})^2 \sim 1 \]

This mechanism is dominant only for central enough collisions

\[ \Psi_G(m_c, r, z) \otimes \Psi_V(r, z) = \sqrt{\frac{3 \Gamma_{J/\psi \rightarrow e^+e^-} M_{J/\psi}}{48 \pi \alpha_{em}}} \frac{m_c^3 r^2}{4} K_2(m_c r) \]
Production of $J/\psi$: relevant time scales

A pre-hadron $cc$ pair is produced over time

$$\tau_P = \frac{l_c}{c} = 7 \, e^y \, \text{fm}$$

$J/\psi$ wave function is formed over time

$$\tau_F = \frac{2 M_{\psi}}{M_{\psi'} - M_{\psi}} l_c = 42 \, e^y \, \text{fm}$$

HIERARCHY OF SCALES REQUIRED FOR THE DIPOLE MODEL: $\tau_F >> \tau_P >> \tau_{\text{INT}}$
At $y \approx 1$ cc is produced coherently over entire nucleus and $J/\psi$ is formed outside of it.

At $-1 < y < 0$ cc is produced coherently over a few nucleons. $J/\psi$ is formed outside the nucleus. Note additional enhancement by $N_{\text{part}}$

**Additional assumptions:**

- $J/\psi$ is non-relativistic. Relativistic correction depends on $m$ but not on energy - included in prefactor.
- Parametrically small corrections due to the real part and off-diagonal matrix elements are neglected.
Propagation of c-anti-c through nucleus

Only even number of inelastic interactions with the nucleus are allowed.

\[
\frac{d\sigma_{\text{in}}(pA)}{dY d^2b} = C_F x_1 G(x_1, m_c^2) \times \int_0^{2RA} \rho \hat{\sigma}_{\text{in}}(x_2, r, r') d z_0 \int d^2 r \Psi_G(l_1, r, z = 1/2) \Psi_V(r) \otimes \int d^2 r' \Psi_G(l_1, r', z = 1/2) \Psi_V(r')
\]

\[
\times \left( e^{-(\sigma(x_2,r^2)+\sigma(x_2,r'^2)) \rho 2RA} \sum_{n=0}^{\infty} \int_{z_0}^{2RA} d z_1 \int_{z_1}^{2RA} d z_2 \ldots \int_{z_{2n}}^{2RA} d z_{2n+1} \rho^{2n+1} \hat{\sigma}_{\text{in}}^{2n+1}(x_2, r, r') \right)
\]

\[
\frac{1}{2} \left\{ \exp \left( -\sigma \left( x_2, (r - r')^2 \right) \rho 2RA \right) + \exp \left( -\left(\sigma(x_2,r)+\sigma(x_2,r')+\hat{\sigma}_{\text{in}}(x_2,r,r')\right) \rho 2RA \right) - 2 \exp \left( -\left(\sigma(x_2,r)+\sigma(x_2,r')\right) \rho 2RA \right) \right\}
\]

Exponentiation works only at large $N_c$
Our model vs PHENIX data

Kharzeev, Levin, Nardi KT, 2009 -
Breakdown of $x_F$-scaling

$\sigma_{PA} = A^\alpha \sigma_{pp}$

$\alpha = \frac{2}{3}$ plateau: black disk regime.

Kharzeev, KT, 2005
We have to sum over all **odd** number of interactions with both nuclei

\[
\{ \ldots \} = \int_0^{2R_{A_2}} \int_0^{2R_{A_1}} \left( \frac{1}{8} Q_{s,A_2}^2 \right) \left( \frac{1}{8} Q_{s,A_1}^2 \right) (2 \bar{r} \cdot r')^2 \, dz_0 \, dz_0' \exp \left\{ -\frac{1}{8} (r^2 + r'^2) (Q_{s,A_1}^2 + Q_{s,A_2}^2) \right\} \\
\times \sum_{k=1}^{2n-2} \int_{z_0}^{2R_{A_2}} \, dz_1 \int_{z_1}^{2R_{A_1}} \, dz_2 \ldots \int_{z_{k-2}}^{2R_{A_2}} \, dz_{k-1} \rho^k \left( \frac{1}{8} Q_{s,A_2}^2 2 \bar{r} \cdot r' \right)^{k-1} \\
\times \sum_{n=2}^{\infty} \int_{z_0'}^{2R_{A_2}} \, dz_1' \int_{z_1'}^{2R_{A_1}} \, dz_2' \ldots \int_{z_{2n-k-2}'}^{2R_{A_2}} \, dz_{2n-k-1}' \rho^{2n-k-1} \left( \frac{1}{8} Q_{s,A_1}^2 2 \bar{r} \cdot r' \right)^{2n-k-2}
\]

\[
= \sum_{n=2}^{\infty} \left\{ \frac{1}{(2n-1)!} \left( \frac{1}{8} (Q_{s,A_1}^2 + Q_{s,A_2}^2) 2 \bar{r} \cdot r' \right)^{2n-1} - \frac{1}{(2n-1)!} \left( \frac{1}{8} Q_{s,A_1}^2 2 \bar{r} \cdot r' \right)^{2n-1} \\
- \frac{1}{(2n-1)!} \left( \frac{1}{8} Q_{s,A_2}^2 2 \bar{r} \cdot r' \right)^{2n-1} \right\} \\
= \sinh \left( \frac{1}{8} (Q_{s,A_1}^2 + Q_{s,A_2}^2) 2 \bar{r} \cdot r' \right) - \sinh \left( \frac{1}{8} Q_{s,A_1}^2 2 \bar{r} \cdot r' \right) - \sinh \left( \frac{1}{8} Q_{s,A_2}^2 2 \bar{r} \cdot r' \right)
\]
\[
\frac{1}{S_A} \frac{d\sigma(AA)}{dY \, d^2b} = \frac{C_F^2}{4\pi^2\alpha_s} \int d^2r \, \Psi_G(l_1, r, z = 1/2) \otimes \Psi_V(r) \int d^2r' \, \Psi_G^*(l_1, r', z = 1/2) \otimes \Psi_V^*(r') \\
\times \frac{1}{2z \cdot r'} \left\{ \exp \left( -\frac{1}{8} (r - r')^2 (Q_{s, A_1}^2 + Q_{s, A_2}^2) \right) - \exp \left( -\frac{1}{8} (r + r')^2 (Q_{s, A_1}^2 + Q_{s, A_2}^2) \right) \right. \\
- \exp \left( -\frac{1}{8} (r - r')^2 Q_{s, A_1}^2 - \frac{1}{8} (r^2 + r'^2) Q_{s, A_2}^2 \right) + \exp \left( -\frac{1}{8} (r + r')^2 Q_{s, A_1}^2 - \frac{1}{8} (r^2 + r'^2) Q_{s, A_2}^2 \right) \\
- \exp \left( -\frac{1}{8} (r - r')^2 Q_{s, A_2}^2 - \frac{1}{8} (r^2 + r'^2) Q_{s, A_1}^2 \right) + \exp \left( -\frac{1}{8} (r + r')^2 Q_{s, A_2}^2 - \frac{1}{8} (r^2 + r'^2) Q_{s, A_1}^2 \right) \right\}
\]

Approximately (for \( r >> r' \)):

\[
\frac{dN^{AA}(Y, b)}{dY} = C \frac{dN^{pp}(Y)}{dY} \int d^2s \, T_{A_1}(s) \, T_{A_2}(b - s) \left( Q_{s, A_1}^2 (x_1, s) + Q_{s, A_2}^2 (x_2, b - s) \right) \frac{1}{m_c^2} \\
\times \int_0^\infty d\zeta \, \zeta^9 \, K_2(\zeta) \exp \left( -\frac{\zeta^2}{8m_c^2} \left( Q_{s, A_1}^2 (x_1, s) + Q_{s, A_2}^2 (x_2, b - s) \right) \right) .
\]

Fitted to Phenix DAu data

\[ x_1 = \frac{m_{J/\Psi,t}}{\sqrt{s}} e^{-Y} , \quad x_2 = \frac{m_{J/\Psi,t}}{\sqrt{s}} e^Y \]
1. Rapidity dependence is reproduced well.

2. The width of the distribution decreases with $N_{\text{part}}$.
Mechanism of suppression: large relative momentum between c and anti-c makes the J/ψ formation less probable.
Outlook

1. Better description of peripheral data: need to calculate a contribution of $A + A \rightarrow J/\psi + g$ mechanism

2. Prediction for higher energies and for $\chi$’s
Summary

I discussed hadron production in nuclear collisions at high energies: **Generally, traditional factorization schemes are broken**, although sometimes they approximately hold.

I showed that **J/ψ production mechanism in pp and pA/AA collisions is different** due to strong coherence effects. **Factorization is strongly violated.**

**We are convinced, that most of J/ψ suppression in AA is a cold nuclear matter effect.**