Heavy quarks and quarkonia in nuclear environment

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Gluons and the quark sea
INT, Seattle, 2010
Outline

- Multiple color exchanges
- Excitation of color dipoles
- Probing deconfinement with bottom quarks
- Probing the transport coefficient with J/Ψ
- Cold nuclear matter is not cold
Double color exchange

J. Hübner, B.K., A. Zamolodchikov, Z.Phys.A357(1997)113

Glauber double scattering

\[ -\frac{dE}{dz} = \kappa_8 = \frac{1}{2\pi\alpha'_P} \approx 5\text{GeV/fm} \]

Non-Glauber double scattering

\[ \gamma + p \rightarrow J/\psi + X \]
Double color exchange

\[ \nu = 70 \text{ GeV} \]
\[ \nu = 100 \text{ GeV} \]

EMC

Thursday, October 14, 2010
Excitation of color dipoles in nuclei

Other manifestations of the double color exchange?


Momentum distribution of backward protons

Fermi motion

Momentum distribution of backward protons
Excitation of color dipoles in nuclei

\[ \pi^- + \text{Be} \rightarrow p_B + X \quad (40 \text{ GeV}) \]


The shape of the backward momentum distribution is very different from expected for Fermi motion and correlated NN pairs.
Suppression of heavy flavors

Heavy quarks radiate much less than light ones:

\[
\frac{d\sigma_{\text{g}}}{dx \, dk_T^2} = \frac{2\alpha_s(k_T^2)}{3\pi x} \frac{k_T^2 [1 + (1 - x)^2]}{[k_T^2 + x^2 m_q^2]^2}
\]

Radiation of gluons with \( k_T^2 \lesssim x^2 m_q^2 \), i.e. with \( \theta \lesssim m_q/E \) is suppressed: dead cone effect.

A much weaker suppression of heavy flavors in HI collisions was predicted:
Yu. Dokshitzer & D. Kharzeev, 2001

However, heavy flavors turn out to be suppressed as much as light quarks.

The bottom contribution is significant.

While the strong suppression of charm can be understood (see later), suppression of bottom remains a puzzle for the energy loss scenario.
The color field of a parton originated from a hard reaction is not shaken off instantaneously. Radiation of a gluon takes coherence time

\[ l_c^g = \frac{2Ex(1 - x)}{k_T^2 + x^2 m_q^2} \]

so the energy dissipated for gluons radiated over the pass length \( L \) is

\[ \Delta E(L) = E \int \frac{Q^2}{\Lambda^2} \int_0^1 dx \frac{x}{dx} \frac{dn_g}{dk_T^2} \Theta(L - l_c) \]

**Important observations:**

Vacuum radiation following a hard process develops a dead cone, which may be stronger than one caused by the heavy quark mass.

For this reason, charm and light quarks radiate and lose energy similarly during first few fm, which only matter in heavy ion collisions.

While light and charm quarks take long time (100 or 10 fm) to regenerate their color fields, a bottom quark does it promptly, within a fermi after the hard interaction, then stops radiating.
Fast hadronization of a bottom quark

A quark which has regenerated its color field does not radiate gluons, but keeps hadronizing nonperturbatively. The rate of nonperturbative energy loss is given by string tension \(-dE/dl = \kappa \approx 1 \text{ GeV/fm}\)

To respect energy conservation a \textbf{b-q} hadron with fractional momentum \(z\) must be produced not later than on the production length \(l_p \sim \frac{E}{\kappa}(1 - z)\)

For the \(p_T\) distribution of \textbf{b-quarks} \(dn_b/dp_T^2 \propto p_T^n\), the mean production length

\[
\langle l_p \rangle = n \frac{E}{\kappa} \int_0^1 dz \left(1 - z\right) z^{n-1} = \frac{E}{(n + 1)\kappa} \quad \text{is quite short} \sim 2 \text{ fm}
\]

Since the \textbf{b-q} dipole is produced by soft interactions, its initial size is rather large \(\sim 0.5 \text{ fm}\), so it is promptly absorbed in a dense medium. “Absorption” means that the \textbf{b-quark} starts losing energy and becomes unable to produce a hadron with the fractional momentum \(z\).

This explains why bottom quarks are strongly suppressed in heavy ion collisions.
Probing deconfined matter with bottom quarks

In vacuum, or in a confined medium the quark forms a string (color flux tube) and loses energy with a rate equal to the string tension.

In a deconfined matter the quark propagates with no attenuation and easily survives even if it was created in a hard collision deep inside the dense medium.

This offers a solution for the longstanding problem: how can a hard probe discriminate between confined and deconfined media?

If the medium is deconfined, bottom quarks should be produced in AA collisions with no suppression.

Thus, the observed strong suppression of bottom suggests that the medium produced in these events is confined.
The nuclear ratio for all hadronic species fall with $p_T$ and then to level off. Only $J/\Psi$ has a trend to rise.

Charmonium is suppressed differently from jets: no energy loss only absorption (breakup)
Three effects, which can be well calculated explain the puzzling behavior of $R_{AA}^{J/\Psi}(p_T)$.

- **Final state in-medium attenuation of $J/\Psi$ controlled by the transport coefficient $\hat{q}$**
- **Initial state shadowing/attenuation of the $\bar{c}c$ dipole (not $J/\Psi$) passing through both nuclei**
- **Gluon saturation leads to a broadening of $J/\Psi$ and to a strong Cronin enhancement.**

The only fitted parameter is the transport coefficient.
Production time:

In the c.m. of the collision a colorless $\bar{c}c$-pair is produced at the time

$$t_p^* \sim \frac{1}{\sqrt{4m_c^2 + p_T^2}} < 0.07 \text{ fm}$$

is much shorter than the time scale of medium creation, $t_p \ll t_0$

Formation time:

The time of formation of the $J/\Psi$ wave function is also short

$$t_f = \frac{E_{J/\Psi}}{(m_{\Psi} - m_{J/\Psi})m_{J/\Psi}} \lesssim 0.5 \text{ fm}$$

Not a $\bar{c}c$ dipole, but a fully formed $J/\Psi$ propagates through the medium.
1. Final state absorption

The absorption cross section for a dipole propagating through a medium is related to parton broadening, i.e. to the transport coefficient $\hat{q}$.

$$\hat{q} = 2 \rho \left. \frac{d\sigma(r)}{dr^2} \right|_{r=0}$$

Absorption rate

$$\frac{dS(r, l)}{dl} = -\frac{1}{2} \hat{q} r^2$$

$$R(s, p_T) = \frac{1}{\pi} \int_0^\pi d\phi \exp \left[ -\frac{1}{2} \langle r^2_{J/\Psi} \rangle \int_{l_0}^{\infty} dl \, \hat{q}(\vec{s} + \vec{l}) \right]$$

J/Ψ breakup is controlled by the same transport coefficient

We relied on the popular model

$$\hat{q}(b, s, t) = \frac{\hat{q}_0 \, t_0}{t} \frac{n_{\text{part}}(b, s)}{n_{\text{part}}(0, 0)} , \text{ fixed } t_0 = 0.5 \text{ fm}$$

and adjusted $\hat{q}_0 = 0.2 - 0.3 \text{ GeV}^2/\text{fm}$ to reproduce the data.
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$J/\Psi$ breakup is controlled by the same transport coefficient.

We relied on the popular model and adjusted $\hat{q}_0 = 0.2 - 0.3 \text{ GeV}^2/\text{fm}$ to reproduce the data.
2. Initial state suppression

The $\bar{c}c$ production time in the nuclear rest frame is sufficient ($5 < t_p < 13 \text{ fm}$) for quark shadowing.

However, $x_2 > 0.015$ is too large ($l_p^g$ is too short) for gluon shadowing.

Charm shadowing comes together with the breakup cross section, they are not separable. The result, $S_{NA} \approx 0.8$, is known from data. However, the impact parameter dependence is important and can be only calculated.

We assume $S_{AB}(s) = S_{NA}(s) S_{NB}(s)$
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Due to saturation gluons experience broadening $\Delta p_T^2 = 2C(s) T_A(b)$ with the coefficient $C(s)$ known from DIS data.

The $p_T$ distribution of $J/\Psi$ has the form:

$$\frac{d\sigma}{dp_T^2} \propto \left( 1 + \frac{p_T^2}{6\langle p_T^2 \rangle} \right)^{-6}$$

Broadening results in $\langle p_T^2 \rangle \Rightarrow \langle p_T^2 \rangle + \Delta p_T^2$

$$R_T(p_T) = \frac{\left. \frac{d\sigma}{dp_T^2} \right|_{\langle p_T^2 \rangle + \Delta p_T^2}}{\left. \frac{d\sigma}{dp_T^2} \right|_{\langle p_T^2 \rangle}}$$

☆ This can be tested with the E866 data for $J/\Psi$ production in pA at 800 GeV:

Works amazingly well with no adjustment!
Eventually, combining all three mechanisms we arrive at the final result

\[ R^{J/\Psi}_{AA}(p_T) = \frac{\int_0^\infty ds^2 T^2_A(s) R(s, p_T) S_{AA}(s) R_T(s, p_T)}{\int_0^\infty ds^2 T^2_A(s)} \]

in-medium attenuation

+ initial state shadowing/absorption

+ gluon saturation

Cu-Cu

Au-Au
No energy loss, no coherence effects for a charmonium propagating through the medium. Attenuation is controlled by the transport coefficient which is found to be small, \( \hat{q}_0 = 0.2 - 0.3 \text{ GeV}^2/\text{fm} \), compared to the results of jet quenching analyses based on the energy loss scenario.

If any additional source of nuclear suppression was missed, that may lead only to a reduction of \( \hat{q}_0 \).

The transport coefficient at SPS is about twice smaller than at RHIC.

Production of other charmonia and bottomia should be a good test and bring forth more information.
Nontrivial transition from pA to AA

We might have underestimated the initial state suppression

There are several effects, which make the pA - to - AA transition nontrivial and model dependent:

- Double color filtering
- Mutual boosting of the saturation scales
- “Cold nuclear matter” is not cold

B.K, I. Potashnikova, I. Schmidt, 2010
Double color filtering

The survival probability of a color dipole propagating simultaneously through two nuclei is larger than the product of those in each nucleus separately.

\[
\langle S_{pA} \rangle = \left\langle \exp(-C r_T^2 T_A) \right\rangle = \frac{1}{1 + C\langle r_T^2 \rangle T_A}
\]

\[
\langle S_{AA} \rangle = \frac{1}{1 + 2C\langle r_T^2 \rangle T_A} > \langle S_{pA} \rangle^2
\]

Color filtering in one nucleus makes another one more transparent for the dipole.
Saturation scales in AA compared to pA

Mutual multiple interactions increase the saturation scales in AA collisions compared to pA at the same energy.
J/Ψ broadening in AA collisions is about twice as large as in pA on the same path length.
“Cold nuclear matter” is not cold

Interaction with prompt gluons radiated in preceding NN collisions causes an additional suppression of $J/\Psi$ and increases broadening.

$$\langle n_g \rangle = \frac{3}{\sigma_{\text{in}}^{\text{NN}}} \left( \frac{dk^2}{k_{\text{min}}^2} \int \int d\alpha \frac{d\sigma(qN \rightarrow gX)}{d\alpha dk^2} \Theta(\Delta z - l_c^g) \right)$$

$$\frac{d\sigma(qN \rightarrow gX)}{d\alpha dk^2} = \frac{3 \alpha_s(k^2) C}{\pi} \frac{2m_q^2 \alpha^4 k^2 + [1 + (1 - \alpha)^2] (k^4 + \alpha^4 m_q^4)}{(k^2 + \alpha^2 m_q^2)^4} \left[ \alpha + \frac{9}{4} \frac{1 - \alpha}{\alpha} \right]$$

$$l_c^g = \frac{2 E_q \alpha (1 - \alpha)}{\alpha^2 m_q^2 + k^2} \leq \Delta z$$


$$\langle n_g \rangle = \left\{ \begin{array}{l} 6.9 \times 10^{-1} \\ 6.9 \times 10^{-3} \\ 1.2 \times 10^{-3} \end{array} \right.$$ for SPS, RHIC and LHC respectively
Summary

Multiple color exchanges of a charm dipole propagating through a nucleus lead to a feed-down and enhancement of $J/\Psi$'s photoproduced at medium Feynman x. They also create heavy color octet dipoles, which may decay producing nucleons in backward hemisphere.

Bottom quarks regenerate their color field on a very short time scale and become an excellent probe for a deconfined medium.

The observed strong suppression of b-quarks demonstrates that a deconfined medium is not created in HI collisions at RHIC.

$J/\Psi$ provides a less ambiguous probe for the transport coefficient, which turns out to be an order of magnitude smaller than found from jet quenching data within the energy loss scenario.

New data from the NA50/60 experiments demonstrate that so called “cold nuclear matter” is not cold in AA collisions. This data prove that the observed “anomalous” suppression of $J/\Psi$ is an initial state effect.