J/ψ SUPPRESSION

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24/05/2006
Outline

- Introduction
- Anomalous suppression
- Normal suppression
Introduction to the $J/\psi$ meson

- **Quark composition:** $c\bar{c}$ (1 charm & 1 anti-charm)
- **Discovery:** Burton Richter and Samuel Ting in 1974
- **Mass:** $(3096.916 \pm 0.011)$ MeV/c$^2$
- **Lifetime:** $7.2 \times 10^{-21}$s (half life)
- **Decay modes:** hadrons $(87.7 \pm 0.5)\%$, $e^+e^-$ $(5.93 \pm 0.10)\%$, $\mu^+\mu^-$ $(5.88 \pm 0.10)\%$
Suppression

- **Anomalous suppression of \( J/\psi \):**
  \( c\bar{c} \) become unbound in the plasma and hadronize by combing with light quarks/antiquarks.
  → a signature for the quark-gluon plasma.

- **Normal suppression of \( J/\psi \):**
  The produced \( J/\psi \) particles may interact with hadrons and these \( J/\psi \)-hadron interactions may lead to the breakup of the \( J/\psi \) particles.
Anomalous suppression

- **Quark-gluon plasma (QGP):**
  A hot, dense state of matter in which partons are deconfined (within the region of the plasma), as opposed to the normal hadronic state. It is characterized by high energy density ($\mathcal{E} > \text{few GeV} \, \text{fm}^{-3}$) and high temperature ($T > 150$-$200 \, \text{MeV}$) or baryon density ($n > 0.72 \, \text{fm}^{-3}$) relative to normal nuclear matter.
Anomalous suppression

- The potential energy for a $c\bar{c}$ system (without the QGP):

\[ V(r) = \kappa r - \frac{\alpha_{\text{eff}}}{r}. \]

where $\alpha(\text{eff}) = q^2/4\pi$ is the effective coupling constant and $\kappa \sim 1/T$ is the string tension coefficient.
Anomalous suppression

- The influence of the QGP on a $c\bar{c}$ system:
  1. The effect of the string tension with respect to temperature in the plasma.
  2. The effect of Debye screening, due to the spatial re-distribution of quarks and antiquarks in the plasma.
Anomalous suppression

- **Inside the QGP:**
  The string tension (linear term) between $c$ and $\bar{c}$ will disappear as $T$ approaches the critical temperature $T(c)$. But, they remain interacting with each other with the Coulomb-type color interaction $-\alpha(\text{eff})/r$. This mutual Coulomb interaction is however modified by Debye screening.
Anomalous suppression

- Debye screening in the QGP:
  In a medium of charged particles, the interactions of one charge will be reduced or cancelled out by the surrounding charges. This effect is known as Debye screening, and while originally defined for electromagnetic plasmas, it has been extended to plasmas of colour charge as well.
Anomalous suppression

- The potential energy for a $c\bar{c}$ system in the QGP:

\[ V(r) = -\frac{\alpha_{\text{eff}} e^{-r/\lambda_D}}{r} \]

where $\lambda(D)$ is the Debye screening length.
Anomalous suppression

• **Debye screening length:**
  From lowest-order perturbative QCD, the screening radius is given by

\[
\lambda_D(T) = \sqrt{\frac{2}{9\pi \alpha_{\text{eff}}} \frac{1}{T}}.
\]

Within this distance \(\lambda(D)\), the attractive interaction between the constituents \(c\) and \(\bar{c}\) is effective but beyond this range the attractive interaction is ineffective, as the magnitude of the interaction diminishes exponentially with distance.
Anomalous suppression

- Temperature dependence of the Debye screening length:
  At high temperatures, the range of the attractive interaction becomes so small as to make it impossible for the $c\bar{c}$ pair to form a bound state. When this happens, the $c\bar{c}$ system dissociates into a separate $c$ quark and a $\bar{c}$ antiquark in the plasma. The $c$ quark and $\bar{c}$ antiquark subsequently hadronize by combining with light quarks/antiquarks. This is the so-called anomalous suppression of $J/\psi$ production.
Anomalous suppression

- Estimation of the critical temperature $T(c)$:
  In 1986, Matsui and Satz showed that the Debye screening radius in the QGP would become smaller than the radius of the $J/\psi$, leading to the dissolution of the $J/\psi$ bound state.

When this happens?
At, which $T(c)$?
Anomalous suppression

- **Estimation of the critical temperature** \(T(c)\): The semiclassical Bohr radius of the \(c\bar{c}\) comes from minimizing the energy equation for a \(c\bar{c}\) system (\(\mu = 1840 \text{ MeV}/2\)) with the modified potential and \(\langle p^2 \rangle \sim 1/r^2\), in the limit \(\lambda(D) \rightarrow \infty\):

\[
E(r) = \frac{1}{2\mu r^2} - \frac{\alpha_{\text{eff}}(T) e^{-r/\lambda_D(T)}}{r}.
\]

By minimizing this equation, we obtain the Bohr radius for \(\alpha(\text{eff}) = 0.52\):

\[r(c\bar{c}) = \frac{1}{(\alpha(\text{eff}) \times \mu)} = 0.41 \text{ fm}.
\]
Anomalous suppression

- **Estimation of the critical temperature** $T(c)$:
The $c\bar{c}$ system will not be bound if $\lambda(D) < 1/(0.84 \times \alpha(\text{eff}) \times \mu)$. Thus, the critical dissociation temperature $T(c)$, above which a $c\bar{c}$ system cannot be a bound system, is given for the lowest-order perturbative QCD theory by

$$T_c = \frac{\mu}{0.840} \sqrt{\frac{2\alpha_{\text{eff}}}{9\pi}} = 0.291 \sqrt{\alpha_{\text{eff}}} \text{GeV}$$
Anomalous suppression

• Results:

<table>
<thead>
<tr>
<th></th>
<th>$T = 0$</th>
<th>$T = 200$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{\text{eff}}$</td>
<td>0.52</td>
<td>0.2</td>
</tr>
<tr>
<td>$\lambda_D$</td>
<td>$\infty$</td>
<td>0.59 fm</td>
</tr>
<tr>
<td>$R_{\text{Bohr}}$</td>
<td>0.41 fm</td>
<td>1.07 fm</td>
</tr>
</tbody>
</table>

However, in the QGP, the QCD coupling constant decreases with temperature. Thus, the temperature above which the $c\bar{c}$ system cannot be bound is of the order of 100-200 MeV.
Normal suppression

- $J/\psi$ suppression in hadron environment: Suppression due to $J/\psi$-hadron interactions has been observed, and the experimental data can be explained in terms of the breakup of the produced $J/\psi$ particles by collisions with hadrons, without invoking the presence of the quark-gluon plasma.
Normal suppression

• $J/\psi$-hadron interaction:
  For example, a $J/\psi$ particle can interact with a hadron $h$ via the reaction $J/\psi + h \rightarrow D + \bar{D} + X$, which turns a $J/\psi$ particle into a $D\bar{D}$ pair. Thus, $J/\psi$-hadron interactions will give rise to a suppression of $J/\psi$ production.
  For a $J/\psi$ particle to interact with a nucleon by the reaction $J/\psi + N \rightarrow D + \bar{D} + X$, the threshold energy of the $J/\psi$ particle is $E(J/\psi) = 6.34$ GeV in the nucleon rest frame.
Normal suppression

- **Cross section without \(J/\psi\)-hadron interaction:**
  In the absence of \(J/\psi\)-hadron interactions to break up the produced \(J/\psi\) particles, the ratio of the cross sections is

\[
\frac{\Delta \sigma_{J/\psi}^{AB}}{\Delta \sigma_{J/\psi}^{NN}} = AB
\]

What is the ratio of the cross sections when the produced \(J/\psi\) particles interact with projectile and target nucleons, leading to the breakup of \(J/\psi\) particles and the suppression of \(J/\psi\) production?
Normal suppression

- **Cross section with $J/\psi$-hadron interaction:**
  In the presence of $J/\psi$-nucleon interactions leading to the absorption of $J/\psi$ particles, the ratio of the cross sections is then given by

\[
\frac{\Delta \sigma_{J/\psi}^{pA}}{A \Delta \sigma_{J/\psi}^{NN}} = \int dB_A \int_{-\infty}^{\infty} dz_A \rho_A(b_A, z_A) [1 - T_A>(b_A, z_A) \sigma_{abs}]^{A-1}
\]

We note that

\[
d \left( [1 - T_A>(b_A, z_A) \sigma_{abs}]^A \right) = d \left( \left[ 1 - \int_{z_A}^{\infty} dz_A' \rho_A(b_A, z_A') \sigma_{abs} \right]^A \right)
\]

\[
= A [1 - T_A>(b_A, z_A) \sigma_{abs}]^{A-1} \rho_A(b_A, z_A) dz_A \sigma_{abs}
\]
Normal suppression

- Cross section with $J/\psi$-hadron interaction:
  Substituting the above into the first equation, the ratio becomes

\[
\frac{\Delta \sigma^{pA}_{J/\psi}}{\Delta \sigma^{NN}_{J/\psi}} = \frac{1}{\sigma_{abs}} \int d\mathbf{b}_A \int_{z_A=-\infty}^{z_A=\infty} d \left( \left[ 1 - \int_{-\infty}^{\infty} d\bar{z}'_A \rho_A(b_A, \bar{z}'_A) \sigma_{abs} \right] A \right)
\]
\[
= \frac{1}{\sigma_{abs}} \int d\mathbf{b}_A \left( 1 - \left[ 1 - \int_{-\infty}^{\infty} d\bar{z}'_A \rho_A(b_A, \bar{z}'_A) \sigma_{abs} \right] A \right)
\]
\[
= \frac{1}{\sigma_{abs}} \int d\mathbf{b}_A \left( 1 - \left[ 1 - T_A(b_A) \sigma_{abs} \right] A \right)
\]

Experimental data indicate that

\[
\frac{\Delta \sigma^{pA}_{J/\psi}}{\Delta \sigma^{NN}_{J/\psi}} \approx A^\alpha
\]

with $\alpha$ close to, but slightly less than, unity.
Normal suppression

- Cross section with $J/\psi$-hadron interaction: This implies that the degree of absorption is small. By expanding the latter in powers of $\sigma(abs)$, we get

$$\frac{\Delta \sigma_{J/\psi}^{pA}}{\Delta \sigma_{J/\psi}^{NN}} \approx \frac{1}{\sigma_{abs}} \int d\mathbf{b}_A \left( 1 - \left[ 1 - A T_A(b_A) \sigma_{abs} + \frac{A(A - 1)}{2} (T_A(b_A) \sigma_{abs})^2 \right] \right)$$

$$= \frac{1}{\sigma_{abs}} \int d\mathbf{b}_A \left[ A T_A(b_A) \sigma_{abs} - \frac{A(A - 1)}{2} (T_A(b_A) \sigma_{abs})^2 \right]$$

$$= A \left[ 1 - \frac{A - 1}{2} \sigma_{abs} \int d\mathbf{b}_A (T_A(b_A))^2 \right]$$

$$= A \left[ 1 - \left( \frac{A - 1}{A} \right) \left( \frac{2\pi r_0^3 A}{3} \int d\mathbf{b}_A (T_A(b_A))^2 \right) \left( \frac{3}{4\pi r_0^3} \right) \sigma_{abs} \right]$$
Normal suppression

- Cross section with $J/\psi$-hadron interaction:
  It is useful to write the above equation as
  \[
  \frac{\Delta \sigma_{pA}^{J/\psi}}{\Delta \sigma_{NN}^{J/\psi}} = A (1 - L \rho_0 \sigma_{abs}) \quad \text{or} \quad \frac{\Delta \sigma_{pA}^{J/\psi}}{\Delta \sigma_{NN}^{J/\psi}} \approx Ae^{-L \rho_0 \sigma_{abs}}
  \]
  where the effective path length $L$ is
  \[
  L = \frac{2\pi}{3} R_A^3 \int db_A (T_A(b_A))^2 \frac{A - 1}{A} ; \quad R_A = r_0 A^{1/3}
  \]
  and $\rho(0) = \frac{3}{4\pi r(0)^3} \sim 0.14 \text{ fm}^{-3}$, the equilibrium nuclear matter density.
Normal suppression

- Cross section with $J/\psi$-hadron interaction: The experimental parametrization and the theoretical parametrization are approximately equivalent. By using these two parametrizations, the effective $J/\psi$-nucleon cross section leading to the breakup of the $J/\psi$ particle is given by

\[ \sigma_{abs} = 6.2 \pm 0.3 \text{mb} \]

corresponding to an $\alpha$ value of about 0.92 for heavy nuclei.