Quarkonium at RHIC

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Theory: Quarkonia suppression

Charmonia \((c \bar{c})\): \(J/\psi, \psi', \chi_c\)
Bottomonia \((b \bar{b})\): \(\Upsilon (1S), \Upsilon (2S), \Upsilon (3S), \chi\)

Key idea (1986): quarkonia melt in plasma (T.Matsui, H.Satz)
- color screening of static potential between heavy quarks
- suppression of states determined by \(T_c\) and binding energy
- sequential melting of quarkonia: a thermometer of QGP

\(J/\psi\) suppression by quark-gluon plasma

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If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, it is expected that quarkonia, which are bound states of heavy quarks, will melt in the plasma. The melting of quarkonia can be used as a thermometer to measure the temperature of the quark-gluon plasma (QGP). The melting temperatures of various charmonia and bottomonia states are indicated by the color temperature scale. Below the critical temperature \(T_c\), the quarkonia are stable, while above \(T_c\), they begin to melt. The transition temperature \(T_m\) can be used to determine the temperature of the QGP. If the melting is observed, it can be used as an indicator of the QGP formation.

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Melting temperature?
(large effort from theoretical side to calibrate thermometer)

Compilation of expectations

bottom line: the most loosely bound states disappears first, the ground state last i.e. $J/\psi$ should survive $\psi'$

To do: Implant quarkonia into the QGP and observed their modification, suppression or enhancement, with and without plasma formation in respect to reference

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... but quarkonia production is rather complex (many entangled effects):

Cold nuclear effects (CNM): pdf modification in nucleus (gluon saturation, Color Glass Condensate), initial state energy loss, nuclear absorption, Cronin effect, ....

Hot/dense medium effects: color screening, gluon dissociation, regeneration, feed-down, ...

→ requires several measurements (systems, energies, centralities) to isolate different effects.

at RHIC:

\[ \Upsilon / J/\Psi \]

\begin{align*}
  & \text{p+p, } \sqrt{s} = 62, 200, 500 \text{ GeV, and } \Psi(2S) \\
  & \text{d+Au, } \sqrt{s} = 200 \text{ GeV} \\
  & \text{Au+Au, } \sqrt{s_{NN}} = 200, 62.4, 39 \text{ GeV} \\
  & \text{U+U, } \sqrt{s_{NN}} = 193 \text{ GeV}
\end{align*}

U+U - higher energy density
- test sequential melting
- constrain models

Upsilon - a cleaner probe
- negligible regeneration at RHIC energy
- less CNM effects

\[ G. \text{Odyniec, IS 2014, Napa, Dec. 3-7, 2014 \quad 4} \]
Anomalous $J/\psi$ suppression in In+In (circles) and Pb+Pb collisions (triangles) as a function of $N_{\text{part}}$

Up to $N_{\text{part}} \sim 200$ : $J/\psi$ (measured) is compatible with extrapolation from p+A
For $N_{\text{part}} > 200$ – anomalous suppression at the level of 20-30% and only in central Pb+Pb

Expectations from lattice calculations,
e.g. M.Asakawa, T.Hatsuda Phys.Rev.Lett.92 (2004) 012001. that $J/\psi$ suppression does not occur until $T \sim 2T_c$ is compatible with this observation

$p+Pb$ data at 158 GeV was used to calculate the expected size of CNM effects on $J/\psi$ production

arXiv:0907.3682, QM 2009
Quarkonia at RHIC: STAR and PHENIX experiments

\[ J/\psi / \Upsilon \rightarrow e^+ e^- (\mu^+ \mu^-) \]

**STAR**

**TPC + TOF + BEMC**

- Central Arms measure electrons (RICH, EMCal, PC, DC, VTX)
- Forward arms measure muons (MuID, MuTr, FVTX)

\[ |\eta| < 1, \ 0 < \phi < 2\pi \]

**PHENIX**

- Central Arms measure electrons (RICH, EMCal, PC, DC, VTX)
- Forward arms measure muons (MuID, MuTr, FVTX)

TPC: \( dE/dx \) PID, large acceptance, uniform in a wide energy range

TOF: PID using flight time (extends PID to low momenta)

BEMC: PID with \( E/p \) ratio, high \( p_t \) trigger

\[ 1.2 < |y| < 2.2 \]

\[ y = |0.35| \]

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$J/\psi$

$p+p$

$Au+Au$

$U+U$
J/ψ in p+p at 200 GeV

Inclusive J/ψ spectra:

Data:
Reach: 0<p_t<14 GeV
Agreement between STAR and PHENIX

Models:
Prompt NLO CS+CO describes data for p_t>4 GeV/c
Prompt CEM describes data at high p_t
(over-predicts data at p_t ~ 3 GeV/c)
Direct NNLO*CS under-predicts high p_t part


J.P.Lansberg private communication
J/ψ in p+p 500 GeV

High precision measurement at new beam energy, up to $p_T = 20$ GeV/c
Constrain model parameters
(ψ(2S) / J/ψ) ratio in p+p at 500 GeV

First measurement at p+p at 500 GeV
No collision energy dependence observed
Consistent with previous measurements from other experiments
Constrain feed-down contribution to J/ψ production
Additional test for production mechanisms of charmonium

ψ(2S) in p+p 500 GeV

Also ψ′!
J/ψ and ψ’ suppression in d + Au

Suppression increases with increasing N_{coll}
ψ’ production is heavily suppressed in central d+Au collisions relative to J/ψ → ψ’ is more sensitive to the final state effects
(ψ’ binding energy is 12x smaller than J/ψ)

Nuclear crossing time at RHIC ~ 0.05 fm at mid-y while c̅c formation time ~ 0.15 fm → bound c̅c may cross nucleus as a pre-resonant state → J/ψ and ψ’ should have the same level of suppression → data shows something else!
(similar result seen at LHC)

Other process occurring on the time scale of c̅c formation that differently suppresses J/ψ and ψ’?
$R_{dAu}^{J/\psi}$ vs $p_t$

$R_{dAu} \sim 1$ at high $p_t$ – CNM effects are small at high $p_t$

High $p_t$ $J/\psi$ carry cleaner signal with less CNM influence

$R_{dAu}$ consistent with model calculations

shadowing from EPS09 nPDF, nuclear absorption $\sigma_{abs}^{J/\psi} \sim 3$mb

High-$p_T$ $J/\psi$ suppression in central collision

Suppression increases with collision centrality

$R_{AA}^{J/\psi}$ for high $p_t$ is systematically higher than for low $p_t$

may indicate color screening

presence of QGP

low $p_t$ - both models agree with data (green lines)

high $p_t$ - good agreement with Liu et al.,

Zhao and Rapp model underpredicts measured $R_{AA}$ (blue lines)

$R_{AA}^{J/\psi} \text{ in } Au+Au \text{ 200 GeV (high } p_t \text{ } J/\psi)$

- i.e. almost NOT effected by recombination and CNM effects

J/ψ in Au+Au at 200 GeV: two surprises

1: \( R_{\text{AA}}^{\text{RHIC}}(\text{mid-y}) \approx R_{\text{SPS}}^{\text{PbPb}} \)

![Graph showing comparison between RHIC and SPS data](image)

At mid-y \( R_{\text{AA}} \) looks similar, while there are obvious differences:
- at a given \( N_{\text{part}} \), at RHIC much higher energy densities…
- cold nuclear matter effects should be drastically different (\( x_{\text{Bjorken}}, \sigma_{\text{abs}} \)…)
- …

2: \( R_{\text{AA}}^{\text{forward}} < R_{\text{AA}}^{\text{mid-y}} \)

![Graph showing forward vs mid-y comparison](image)

Expectation from color screening:
\( R_{\text{AA}}(\text{mid-y}) < R_{\text{AA}}(\text{forward y}) \)

clearly data shows something else! 
\( R_{\text{AA}}(\text{mid-y}) > R_{\text{AA}}(\text{forward y}) \)
Possible explanations …

- Regeneration models
  - give enhancement that compensate screening, initially uncorrelated c and \( \bar{c} \) can recombine (\( N_{cc} \sim 12 \) in most central collisions)
  - qualitative explanation: less suppression in y-mid because there is more c and \( \bar{c} \) to recombine

- Cold nuclear matter effects (CNM)
  - in any case are always present

- Sequential suppression
  - QGP screening only of \( \chi_c \) and \( \psi' \) removing their feed-down contributions to \( J/\psi \)

Presently one can not exclude/favor one or other of the above scenarios!

\[ \bar{c} \text{ and } c \text{ to recombine} \]

\[ J/\psi \]

\[ L. \text{Grandchamp and R. Rapp, } \]
\[ \text{Nucl. Phys. A 709, 415 (2002)} \]
Significant suppression of J/ψ production observed for all energies (200, 62.4 and 39 GeV) in respect to $N_{\text{coll}}$ scaled with p+p yields. Consistent with suppression of directly produced J/ψ.

No significant energy dependence for $R_{AA}$

Two-component model (color screening, direct suppression + statistical regeneration) calculations consistent with data

$R_{AA}$ increases from low $p_t$ to high $p_t$, similar trend in 39, 62.4 and 200 GeV data
the “same” in the forward direction:

$$R_{\text{CP}}, R_{\text{AA}} \quad J/\psi \rightarrow \mu\mu, \quad 1.2 < |y| < 2.2$$

**Similarity of $J/\psi$ nuclear modifications**

$R_{\text{CP}}$ and $R_{\text{AA}}$ from 39 to 200 GeV is a challenge for models

Model includes CNM effects, regeneration and QGP suppression for $J/\psi$ forward rapidity is consistent with data

**Does coalescence compensate for melting?**

**Needs reference p+p data!**

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**p+p reference data determine taken from ISR, Fermilab and CEM**

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\( J/\psi \) does not flow

\( J/\psi \) does not flow consistent with 0 in \( p_t \) range of 2 to 8 GeV/c for all centralities

Disfavors \( J/\psi \) coalescence from thermalized charm quarks at RHIC

\( J/\psi \) is the ONLY hadron so far that does not flow!
Why $J/\psi$ in U+U 193 GeV so interesting?

1. **Higher energy density** in U+U collisions (~ 20%)

   - Tip-to-tip collision provides the highest energy density

   - Oblate vs. Prolate collisions

   - Higher energy density in U+U collisions


2. **Higher $N_{\text{part}}$**

   - It should be a good test for sequential suppression model …
   - greater suppression due to color screening
   - $N_{\text{coll}}$ increases $\rightarrow$ $N_{\text{charm}}$ increases $\rightarrow$ greater probability for regeneration

Kikola, Odyniec, Vogt, Phys. Rev. C 84, 054907
J/ψ in U+U 193 GeV

Similar suppression pattern in U+U as that in Au+Au 200 GeV

Baseline: J/ψ measurements in p+p 200 GeV

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System size?

Not much net effect from system size increase.
Upsilon

a cleaner (compare to $J/\psi$) probe:
- co-mover absorption negligible
- recombination negligible
- $\sim 12 \text{ cc}$ and $\sim 0.07 \text{ bb}$ pairs per central Au+Au collision at 200 GeV

but, rare probe, low rate …
Upsilon in \( p+p \) and \( d+Au \) 200 GeV

**STAR**

**PHENIX**

**Upsilon suppression in \( d+Au \) !**

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Upsilon rapidity dependence in $p+p$ and $d+Au$ 200 GeV

$\Upsilon$ cross section in $p+p$ vs rapidity consistent with NLO pQCD CEM predictions across all $y$ in $d+Au$ also, except $y\sim 0$


$R_{dAu}$ consistent with predictions except mid-rapidity -> indication of additional suppression at $y \sim 0$ beyond that of current models (i.e. in addition to shadowing and initial state parton energy loss)

- requires further studies $\rightarrow p+A$ run
Upsilon in U+U 193 GeV

Consistent increase of suppression with centrality in both Au+Au and U+U

Strong suppression in central collisions. Trend in U+U follows and extends trend in Au+Au

Agreement with models that include presence of QGP. Strickland model predicts temperature range:

\[ 428 \text{ MeV} < T < 442 \text{ MeV} \]
Suppression of \( \Upsilon(1S) \) in central collisions consistent with model calculations

- **Liu et al. Model** – suppression mostly due to dissociation of the excited states (CNM effects not included)

- **Strickland-Bazow Model** – hot and cold nuclear effects

No suppression: \( R_{AA}^{\Upsilon(1S)} \approx 1 \) in dAu, in peripheral and mid-central AuAu collisions

Indication of complete melting of \( \Upsilon(2S) \) and \( \Upsilon(3S) \) suppression in central collisions, consistent with predictions for central Au+Au

Suppression of \( \Upsilon(1S) \) similar to high-\( p_T \) \( J/\psi \)

\( \Upsilon \) suppression pattern supports sequential melting

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$\Upsilon R_{AA}$ at RHIC and LHC

Agreement between RHIC experiments
Larger suppression at CERN LHC energies, however at most central collisions comparable $\Upsilon$ suppression indicates color deconfinement
however, uncertainties are substantial
Where we are:

- Significant suppression of $J/\psi$ production in central Au+Au from 39 to 200 GeV with respect to $N_{\text{coll}}$ scaled p+p yields

- This $J/\psi$ suppression similar in Au+Au at 200, 62.4 and 39 GeV

  Does recombination compensate fully for melting?

- Indications of no system size dependence of $J/\psi$ suppression (similar in Au+Au and U+U)

- No collective behavior of $J/\psi$ observed – thermalizes $c\bar{c}$ coalescence unlikely

- d+Au – hint of “additional” suppression (beyond model calculations)

  Some final state effects (even in such a small system) ?

- $\Upsilon(2S)$ and $\Upsilon(3S)$ suppression stronger than $\Upsilon(1S)$ in central collisions

  Signal of deconfined medium ?

- first $\psi'$ measurements
Near future

Very soon – detailed quarkonium measurements

In STAR (fully installed and taking data in 2014):

HFT – separation of prompt and non-prompt $J/\psi$

MTD - $J/\psi$, $\Upsilon \rightarrow \mu^+\mu^-$ (compliment to e+e-)

In PHENIX:

VTX, FVTX –

nuclear modification and collective flow

of charm and bottom separately using DCA

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Thank you!
Suppression increases with increasing $N_{\text{coll}}$.

$\psi'$ production is heavily suppressed in central $d+Au$ collisions relative to $J/\psi$. $\psi'$ is more sensitive to the final state effects ($\psi'$ binding energy is 12x smaller than $J/\psi$).
CNM effects, $\Upsilon$ in d+Au 200 GeV,

Similar suppression seen at E772

Suppression increases with the size of the system

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Energy dependence of $J/\psi$ $R_{cp}$

RHIC BES program – a unique tool to study the interplay of $J/\psi$ direct production (with color screening), CNM effects and recombination with changing energy.

Nuclear modification factor $R_{cp}$ shows significant suppression in central Au + Au collisions at 62.4 GeV, similar as at 200 GeV.

Note, at 39 GeV large error bars.

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