**J/ψ and Open Charm**

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**Motivation**

J/ψ (charmonium) as probe of nuclear medium/QGP in AA collisions
- Matsui and Satz prediction of J/ψ suppression
- NA50 confirmation (?)
- Alternative models arise and initial RHIC results
- Initial RHIC results and reaffirmation of interest in J/ψ

**Charm and J/ψ Production in pp, pA, dA collisions:**
- Charm provides important baseline to understanding J/ψ
- Do we understand the production mechanism of charm, J/ψ, nuclear modifications?
- Above critical to understanding if AA shows production outside bounds of expectations or not and interesting in its own right
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J/Ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION *

T. Matsui
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology,
Cambridge, MA 02139, USA

and

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Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents cc binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/Ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/Ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.
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R. L. Thews, M. Schroedter, J. Rafelski, Phys Rev C 63, 054905
Plasma Coalescence Model

Binary Scaling

Absorption (Nuclear + QGP) + final-state coalescence

Absorption (Nuclear + QGP)
L. Grandchamp, R. Rapp, Nucl Phys A709, 415; Phys Lett B 523, 60
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Recommendations of the Brookhaven High Energy and Nuclear Physics Program Advisory Committee: RHIC Run 4 September 2003
The highest priorities for Run-4 are an extended high luminosity full energy Au-Au run ensuring a significant measurement of quarkonia production, and a polarized proton-proton machine development run. Additional priorities are a 63 A-GeV energy Au-Au
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Outline of Talk

Theory of Charm and J/Ψ Production
  ➢ pQCD
  ➢ $c\bar{c}$ propagation and hadronization

Existing Measurements of Open Charm and J/Ψ Production
  ➢ pp collisions
  ➢ dA, pA production
  ➢ AA production

Future Prospects and Summary
Theoretical Models of Charm and $J/\Psi$ Production

Factorize calculations:
- $pQCD$ to calculate $c\bar{c}$ production
- $c\bar{c}$ propagation and Hadronization

Note: much of $J/\Psi$ production comes from feed-down from higher resonances

Input to $pQCD$ Calculations:
- Parton Distribution Functions $\rightarrow$ rapidity dependence, $\sqrt{s}$ dependence,
  - Modified in Nucleus? (sensitive to gluon polarization)
- LO, NLO, NNLO calculations change magnitude, shape of spectra
- Factorization, renormalization scales $\rightarrow$ total cross section
- Charm mass $\rightarrow$ total cross section
- $k_T \rightarrow p_T$ spectra

- Total cross sections and Differential vs. $y$, $p_T$, $\sqrt{s}$, etc. necessary to simultaneously constrain theoretical uncertainties
- Hadronization parameters can depend upon $pQCD$ portion of calculation
- $J/\Psi$ spectra dependence on $\Psi'$, $\chi$
Charm Production Uncertainties

- Gluon distribution functions uncertain
- Diagrams other than gluon-gluon fusion contribute, and relative fraction changes versus rapidity, $x_F$
- PDFs modified in a nucleus
- Measurements versus rapidity, etc. can help constrain PDFs, uncover nuclear modifications to PDFs

Nuclear dependence included
Open Charm Production Cross Sections—Theory vs. Data

• Charm hadro-production over a large energy range predicted reasonably well by theory
• Large error bands due to $m_c$, scale uncertainties; theoretical parameters that fit data not unique

Charm Production Asymmetries at large $X_F$

$\pi^+$ beam $(u\bar{d})$

$D^+(\bar{c}\bar{d})$ favored over $D^- (\bar{c}\bar{d})$


- At large $x_F$, $cc$ more likely to pair up with valence quarks of beam $\rightarrow D^+$ favored over $D^-$ when $\pi^+$ beam, for example
- Production in different kinematic regions often uncovers different physics
- Charm production spectra also sensitive to hadronization model
Hadronization into J/Ψ

Various J/Ψ hadronization models:

• Color-singlet model (CSM)
  • c ¯ c pair in color-singlet state, with same quantum numbers as J/Ψ forms into J/Ψ
  • Predicts no polarization

• Color-octet model (COM)
  • J/Ψ formed from c ¯ c color-octet state with one or more soft gluons emitted
  • Color octet matrix elements expected to be universal
  • Predicts transverse polarization at high pT of J/Ψ

• Color-evaporation model (CEM)
  • Assumes a certain fraction of c ¯ c (determined from experimental data) form J/Ψ by emission of several soft gluons
  • Predicts no polarization

• Would polarization measurements solidify COM?

CDF Data first uncovered shortcomings of CSM
Color Octet Model predicts $J/\Psi$ polarization at large $p_T$ NOT SEEN in data

- CDF and Fermilab E866 data show little polarization of $J/\Psi$ and opposite trend of predictions
- $\Upsilon$ polarized for (2S+3S) but not (1S)
- Is feed-down washing out polarization or something more?

\[ \cos \theta = A(1 + \alpha \cos^2 \theta) \]
Matrix Element Extraction for photo, hadro-production

Extracted values of matrix elements from photo-production and hadro-production $J/\Psi$ dependent upon pQCD calculation part

Is this agreement?

Is factorization picture not valid?

*Mizukoshi, hep-ph/99111384v2
Charm and J/Ψ Data from RHIC

Run I, 2001  Au-Au beams at $\sqrt{s}=130$ GeV
  • Open charm from PHENIX
Run II, 2002  Au-Au beams and p-p at $\sqrt{s}=200$ GeV
  • Open charm and J/Ψ from PHENIX
Run III, 2003  d-Au, p-p at $\sqrt{s}=200$ GeV
  • Open charm from PHENIX and STAR, J/Ψ from PHENIX
Run IV, 2004  Au-Au, $\sqrt{s}=200$ GeV
  • More measurements to come
Open Charm Production from Single Leptons from PHENIX

Electrons at Central Rapidity:
Cocktail = $\pi^0$ Dalitz + $\gamma$ Conversions, etc.
Excess over cocktail = charm + bottom

Muons at $|y|=$(1.2-2.4):
Cocktail = $\pi$, K decay muons and punch-through, etc.
**PHENIX: Charm at \(|y|\)=0 from pp**

**PHENIX single electron:**
- PYTHIA pp charm cross section agrees with data with:
  - PDF=CTEQ5L
  - \(m_c = 1.25 \text{ GeV}/c^2\)
  - \(K = 3.5\)
  - \(\langle k_T \rangle = 1.5 \text{ GeV}/c\)

- PYTHIA tuned for QM02 under predict data at \(p_T>1.5 \text{ GeV}/c\)

- Forward rapidity analysis underway

*S. Kelly "Charm Production in AuAu, dAu and pp Reactions at PHENIX"
STAR: Charm at $|y|<1.0$ from pp*

STAR D meson and single electron measurements:

- $D^0 \rightarrow K\pi$ \hspace{1cm} $p_T=(0.3)$ $|y|<1.0$
- $D^{*\pm} \rightarrow D^0\pi$ \hspace{1cm} $p_T=(1.3,6.0)$
- $D^+ \rightarrow K\pi p$ \hspace{1cm} $p_T=(6.7,11)$
- Single electrons \hspace{1cm} $p_T=(0.3)$

First direct open charm measurement at RHIC!

Results shown with dAu a little later

* A. Tai, “Measurements of high pt $D^*$ and $D^+$ production in d+Au collisions at 200 GeV”
* L. Ruan, “Open charm production and Cronin Effect of leptons and identified hadrons in p+p and d+Au collisions at 200 GeV at STAR”
**PHENIX: J/ψ → e+e- and µ+µ- from pp**

R. Granier "J/Psi Production and Nuclear Effects for dAu and pp Collisions at RHIC"

σ = 3.99 +/- 0.61(stat) +/- 0.58(sys) +/- 0.40(abs) µb

(\(BR^*\sigma_{tot} = 239\text{ nb}\))

Central and forward rapidity measurements from Central and Muon Arms:

- Rapidity shape consistent with various PDFs
- \(\sqrt{s}\) dependence consistent with various PDFs
  - with factorization and renormalization scales chosen to match data

Higher statistics needed to constrain PDFs
PHENIX: J/ψ→e+e- and μ+μ- from pp

- $p_T$ shape consistent with COM over our $p_T$ range
- Higher statistics needed to constrain models at high $p_T$
- Polarization measurement limited
Summary of Nucleon-Nucleon Charm and $J/\Psi$ Production

Our Understanding of Production:
- Cross sections from pQCD match open charm real data reasonably well but
- Difficult to simultaneously constrain PDFs, $m_C$, $k_T$, normalization and factorization scale. LARGE changes in parameters can still match data.
- CEM and COM can also match $J/\Psi$ data well but some resolution required between COM predictions and data
- More theoretical work to reconcile production calculations and data, more data covering large kinematic regions with smaller error bars desirable?

What we have coming, what we might like:
- Forward rapidity charm production to come
- Smaller error bars versus rapidity and at high $p_T$ might be nice to further constrain models
Nuclear Effects on Charm, $J/\Psi$ Production in dA

Initial state/final state interactions with medium
- Multiple scattering $\rightarrow$ broadening of $p_T$ spectra
- Energy loss $\rightarrow$ shift of $x_F$ distribution, reduction in cross section as partons effectively shifted to lower $\sqrt{s}$
  - Not expected to be significant effect at RHIC
- Absorption reduces $J/\Psi$ as $c\bar{c}$, $J/\Psi$ propagate through nucleus

Modification of the parton distribution functions:
- Gluon shadowing would lead to reduction of production at low $x$. Antishadowing would give enhancement at moderate $x$

Centrality Dependence

![Graph showing CTEQ5L Gluon PDF with and without EKS98 Shadowing Corrections (A=197) for $Q^2=4$ GeV^2.](Eskola, Kolhinen, Vogt hep-ph/0104124)
J/Ψ Production From Fermilab Experiment 866 at \( \sqrt{s}=39 \text{ GeV} \)

p-Be, Fe, W production of J/Ψ

\[ \sigma_A = \sigma_N \cdot A^\alpha \]

A plausible production scenario to explain data:
• Production at low \( x_F \) reduced by absorption of J/Ψ and enhanced by anti-shadowing (D not affected and Ψ' absorbed more)
• Some suppression increasing with \( x_F \) due to gluon shadowing
• \( dE/dx \) shifts \( x_F \) and reduces cross section at large \( x_F \)

*Kopeliovich, Tarasov, Hufner Nucl Phys A696 (2001) 669-714*
$\alpha(p_T)$ shape is independent of $x_F$ and approximately the same for NA3 at a lower energy

- DY shows no broadening
**NA50: J/ψ and Ψ’ from p-Be, Al, Cu, Ag, W, Pb**

G. Borges, "New Results on J/ψ and psiprime nuclear absorption in p-A and S-U collisions at the CERN/SPS"

\[
\sigma_{J/\psi, \psi'}^{p-A} = \sigma_{J/\psi, \psi'}^{0} \times A^{\alpha}
\]

\[
\alpha_{J/\psi} = 0.931 \pm 0.002 \pm 0.007 \quad (\chi^2/dof = 1.4)
\]

\[
\alpha_{\psi'} = 0.858 \pm 0.017 \pm 0.008 \quad (\chi^2/dof = 2.2)
\]

\[
\sigma_{\psi}^{\text{abs}} = 4.2 \pm 0.5 \text{ mb} \quad (\chi^2/dof = 0.9)
\]

\[
\sigma_{\psi'}^{\text{abs}} = 9.6 \pm 1.6 \text{ mb} \quad (\chi^2/dof = 2.9)
\]
PHENIX: $J/\Psi$ in $dA$

- PHENIX measurements cover expected shadowing, anti-shadowing range
- All expected to see $p_T$ broadening
- $dE/dx$ not expected to be significant effect at RHIC energies
- Overall absorption expected
**J/ψ dA from PHENIX**

R. Granier "J/Psi Production and Nuclear Effects for dAu and pp Collisions at RHIC"

- Suppression in deuteron direction consistent with some shadowing but can’t distinguish among various models
- Anti-shadowing in Au direction
- Overall absorption
  *Centrality dependence unique measurement from RHIC
PHENIX: Open Charm in dA at y=0

- Similar $p_T$ shape compared to pp data
- No significant centrality dependence seen
- Seems little net nuclear effect on charm production at central rapidity
• Single electron and D results consistent

• RdAu for charm consistent with 1 but large error bars:

• RdAu(e) = 1.23 ± 0.26 (stat)

• p_T spectrum harder than PYTHIA
Summary of pA, dA J/Ψ and Open Charm Production

What have we learned
• Ψ, Ψ’ nuclear dependence mapped out at CERN
• Gluon shadowing and anti-shadowing, absorption at RHIC
• New centrality dependence information from RHIC
• Open charm measurements from RHIC at central rapidity
• Very important baseline measurements to understand AA at RHIC and CERN

What would we might like:
• Forward rapidity open charm (coming)
• Higher statistics desirable to better delineate various shadowing models and other nuclear effects on J/Ψ production
• Ψ’
Charm and J/Ψ in Heavy Ion Collisions

pA effects scaled up PLUS
• Hot hadron gas, comovers
• QGP/dense matter modifications to production:
  • Debye screening,
  • Enhancement in coalescence models, balancing of D+D↔J/Ψ+X
  • Thermal production of charm
  • Energy loss and dead cone effect

Must fully understand pp, dAu production to see suppression/enhancement beyond “normal nuclear suppression”; measure over large kinematic regions best
Excess Open Charm in NA50, m=(1.6-2.5) GeV

- Charm extracted by fitting dimuon spectra in range 1.6<M_{\mu\mu}<8 GeV/c^2 and looking at m=(1.6-2.5)
- Open charm cross section from p-N, p-N data show no deviation from scaling with A
- Charm cross section from Pb-Pb shows enhancement which increases with N_{part}
- Enhanced charm or thermal production of dimuons?
**J/Ψ Suppression in Pb-Pb at NA50**

H. Santos, "Psi' production in nucleus-nucleus collisions at the CERN/SPS".

- Suppression with respect to normal nuclear suppression expectations
- Detailed data collection to measure “normal nuclear suppression” → updated results
- Theorists have produced various alternative models which also reproduce data:
  - Statistical coalescence model (also needs enhanced open charm)
  - Comovers

- RHIC data on J/Ψ highly desired to give another data point(s) to compare to PbPb results and implied expectations

A. Capella, D. Sousa, nucl-th/0303055


Melynda Brooks
\[ \Psi' \] Suppression in Pb-Pb at NA50

H. Santos, "Psi' production in nucleus-nucleus collisions at the CERN/SPS".

\[ \sigma_0 e^{-<\rho L>\sigma_{abs}} \]

- \( \Psi' \) suppression seen with respect to DY and J/\( \Psi \), increasing with centrality
- Different apparent behavior between pA and AA collisions
- S-U and Pb-Pb collisions behave similarly
AuAu data compared to pp data at 200 GeV
Spectral shapes the same? Can’t say definitively with these error bars.
No significant dependence with \( N_{\text{coll}} \), within error bars
PHENIX: Charm Flow in AuAu?

Why might we care?
• Does charm agree with binary scaling because little interaction with the medium or does charm flow result in no net change in $p_T$ spectrum (within our measurement)?

How do we attempt to measure it?
• Calculate flow of single electrons (remember cocktail: photon conversion, … and charm)
• Calculate flow of photonic sources and compare to model with and without charm flow
PHENIX: $J/\Psi$ in AuAu from Run 2

- 49.3 million minimum bias events analyzed in Central Arm, Run 2
- 8, 5, 0 “most likely signal” for 3 centrality bins
- Not enough statistical significance to distinguish various models but strong enhancement seems to be disfavored.
Near Future Measurements

RHIC – 200 GeV AuAu running in Run 4, CERN Runs

• PHENIX AuAu at 200 GeV: (assume 123 µb⁻¹ and A²α)
  • ~1600 J/Ψ into each muon arm
  • ~400 J/Ψ into central arm
• Open charm at central and forward rapidities via single leptons
• Higher statistics highly desireable to allow kinematic binning, possible large suppression, etc.

• STAR AuAu at 200 GeV:
  • Open charm via single electrons and reconstructed D mesons

• NA60 at CERN
  • χ_c from pA (Important to understand feed-down contribution to J/Ψ)
  • Tagged charm production with vertex detector (is enhancement in dimuons charm or something else?) Indium-Indium data being analyzed

more
Summary

• Many data sets now available on open charm and J/Ψ production over large kinematic ranges to constrain pp production models

• Important pA, dA data from CERN and RHIC taken to establish suppression/enhancement in cold nuclear environment

• First data versus centrality in dA collisions available

• Production in heavy ion collisions not clear: enhancement of charm or not? abnormal suppression of J/Ψ? Difference between CERN and RHIC energies…?

• AuAu data should provide critical insights. The more statistics the better.