Sequential Charmonium Suppression

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1. Charmonium Binding and Dissociation

Charmonia: $c\bar{c}$ **bound states stable under strong decay**

Binding energy $\Delta E = 2\ M_D - M_i$

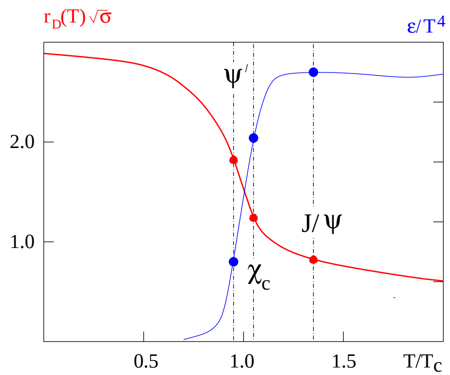
ground state J/ψ**: tightly bound** $\Delta E \gg \Lambda_{QCD}$**, very small** $r_{J/\psi} \ll r_h$

What happens to binding in QGP?

Colour screening $\Rightarrow$ **binding becomes weaker and of shorter range**

What happens when
force range $<$ **charmonium radius?**

Q **and** $\bar{Q}$ **cannot "see" each other**
$\Rightarrow$ **charmonium dissociates**



$\Rightarrow$ **charmonium dissociation points determine temperature, energy density of medium**

How to calculate? Three possibilities:

1. **model heavy quark potential $V(r,T)$, solve Schrödinger equation:**

   Karsch et al. 1988, Digal et al. 2001 $T_{J/\psi} \gtrsim T_c$, T_χ & $T_{\psi'} \lesssim T_c$

2. **determine heavy quark potential $V(r,T)$ in lattice QCD, solve Schrödinger equation**

   Wong 2004, 2005

   Alberico et al. 2005

   Digal et al. 2005

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

3. **calculate quarkonium spectrum directly in finite T lattice QCD**

   quenched: Umeda et al. 2001, Asakawa & Hatsuda 2004, Datta et al. 2004, Iida et al. 2005

   unquenched: Morrin et al. 2005

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	> 2.0	< 1.1	**?**

Conclude:

- J/ψ **survives up to** $T \geq 2\ T_c \Rightarrow \epsilon_{J/\psi} \geq 15$ **GeV/fm**^{3}
- χ_c **and** ψ' **dissociated near** $T_c \Rightarrow \epsilon_{\psi',\chi} \simeq 0.5 - 2$ **GeV/fm**^{3}
- **caveats: thermal activation, widths as** $f(T)$

Schematic Approach:

- ψ' **and** χ_c **melt at same point** $T \simeq T_c$**,**
  same suppression pattern $S_{\psi'}(T) \simeq S_{\chi}(T)$
- J/ψ **survives up to much higher** $T_{J/\psi} \gg T_c$**,**
  so that for $T \leq 2\,T_c$**,** $S_{J/\psi}(T) = 1$**.**
- **in hadronic collisions, 60%** J/ψ **are directly produced** $1S$ **states,**
  30% come from χ_c **decay, 10% from** ψ' **decay.**
- **hence**

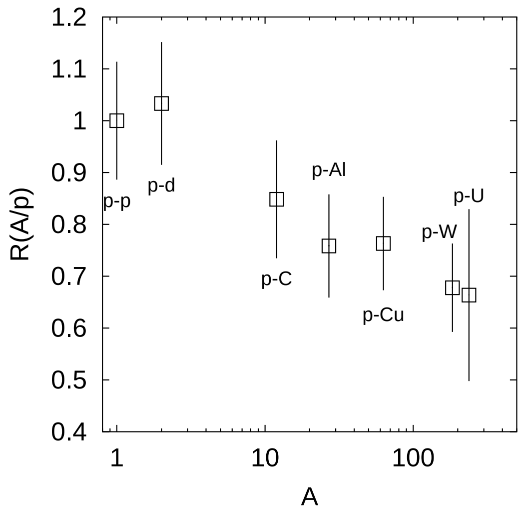
$$S_{J/\psi}(T) = 0.4\ S_{\psi'}(T) + 0.6 \quad \forall \quad T \leq 2\,T_c$$

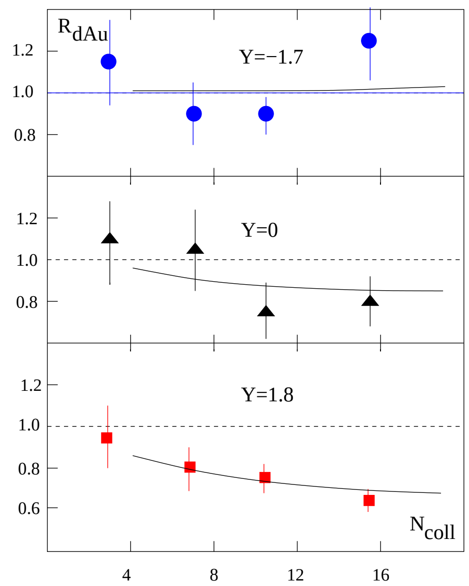
$\Rightarrow$ **scaling relation for data.**

2. Charmonium Production in Nuclear Collisions

To probe produced medium, account for effects of nuclear medium

determine normal nuclear absorption through $p-A$ or $d-A$ studies





nuclear suppression at SPS ($p-A$) **at RHIC ($d-Au$)**

specify dissociation cross sections $S \sim \exp\{-n_0\, \sigma_i\, L\}$

(SPS full Glauber analysis)

SPS	**RHIC**
$\sigma_{J/\psi} = 4.18 \pm 0.35$ mb	$\sigma_{J/\psi}(y = 1.8) = 3.1 \pm 0.2$ mb
$\sigma_{\psi'} = 7.3 \pm 1.6$ mb	$\sigma_{J/\psi}(y = 0) = 1.2 \pm 0.4$ mb
	$\sigma_{J/\psi}(y = -1.7) = -0.1 \pm 0.2$ mb

use to account for normal nuclear absorption in AA collisions

- **SPS:**

calculate $(d\sigma_i/dy)_{Gl}$ as function of centrality, then define

survival probability $$S_i = \frac{(d\sigma_i/dy)_{ex}}{(d\sigma_i/dy)_{Gl}}$$

for $i = J/\psi,\ \psi'$ in AA collisions as function of centrality

- **RHIC:**

experiment provides J/ψ production rates in $AuAu$ collisions relative

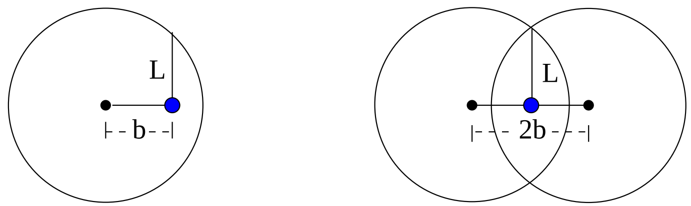
to pp collisions $R_{AuAu}(y, N_{part})$

as function of rapidity y and centrality N_{part}

define survival probility

$$S(y, N_{part}) = \frac{R_{AuAu}(y, N_{part})}{\{exp\{-n_0[\sigma_{\rm diss}(y) + \sigma_{\rm diss}(-y)]L\}}$$

centrality measures $b,\ L,\ N_{part},\ \epsilon$
related by Glauber



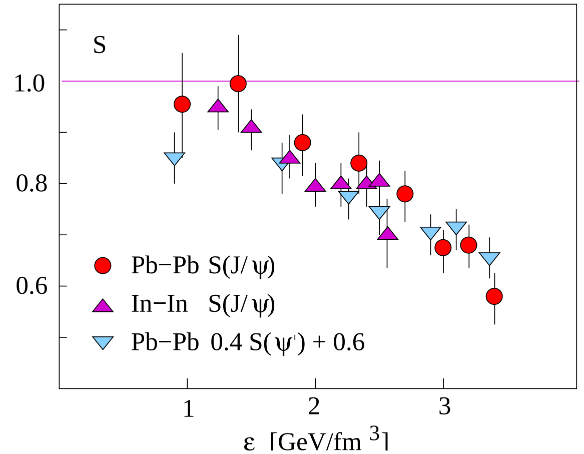
p−A A−A

3. Analysis of Nuclear Collision Results

- **scaling relation for ψ' and J/ψ**

  $$S_{J/\psi}(T) = 0.4\ S_{\psi'}(T) + 0.6 \quad \forall \quad T \leq 2\,T_c$$

  in reasonable accord with SPS data

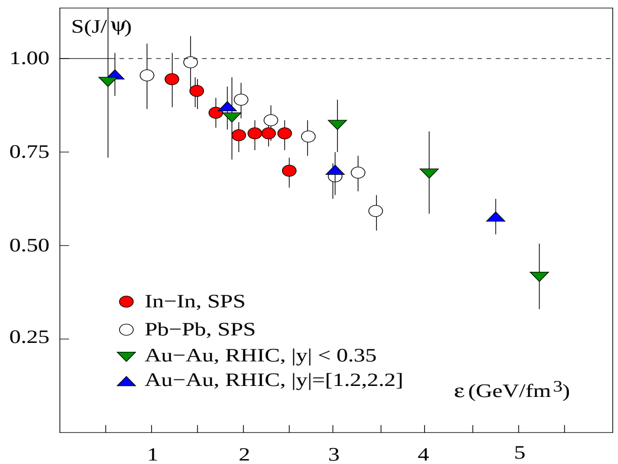


- **constant J/ψ rate $S_{J/\psi} \simeq 0.6$**

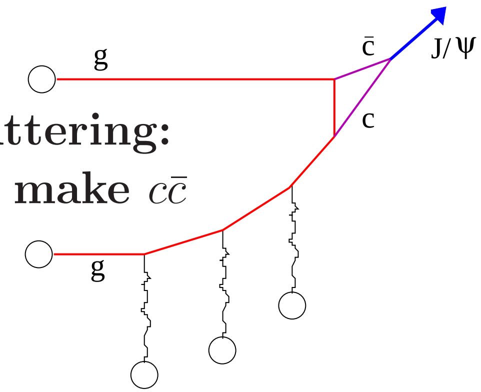
  beyond ψ', χ_c suppression region

  in reasonable accord with

  combined RHIC/SPS data

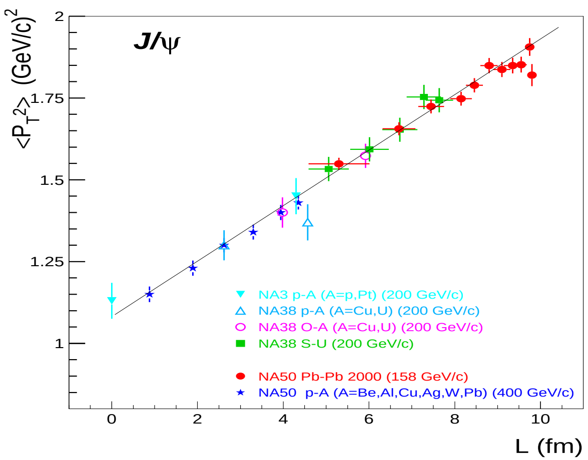


- J/ψ **transverse momentum behaviour**

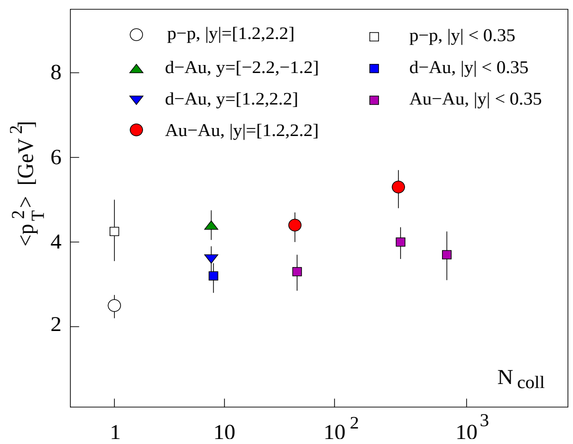


p_T**-broadening due to initial state parton scattering: gluons scatter several times before fusing to make** $c\bar{c}$

$\Rightarrow \langle p_T^2 \rangle$ **increases with** A **in** $p{-}A$**, with centrality in** $A - A$



SPS



RHIC

random walk of projectile gluon $\Rightarrow$ $p-A$:

$$\langle p_T^2 \rangle_{pA} = \langle p_T^2 \rangle_{pp} + N_c^A \delta_0$$

$\exists$ $N_c^A + 1$ **pre-fusion collisions of incident projectile gluon in target and each subsequent collision gives "kick"** $\delta(s)$

random walk of pre-fusion projectile and target gluons $\Rightarrow$ $A-A$:

$$\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + N_c^{AA} \delta_0$$

with N_c^{AA} **sum of subsequent collisions of projectile gluon in target plus those of target gluon in projectile**

calculate N_c^A **via Glauber, determine** $\delta(s)$ **from** $p-A$
calculate N_c^{AA} **via Glauber, predict** $\langle p_T^2 \rangle_{AA}$**, IF no new** $A-A$ **effects**

Calculation of N_c^A

number of collisions of projectile nucleon in target

$$N_c = (3/4)\, 2\, R_A\, n_0\, \sigma$$

with $\sigma(s) \sim$ **nucleon-nucleon cross section**

if average fusion at center of target, $N_c^A \simeq (N_c - 1)/2$

normal nuclear absorption shifts fusion point "down-stream",

up to maximum $N_c^A \simeq (N_c - 1)$**; estimate (K-N-S) gives** $N_c^A \simeq 3 \pm 1$

SPS:

$$\langle p_T^2 \rangle_{pU} = 1.49{\pm}0.05 \text{ GeV}^2 - \langle p_T^2 \rangle_{pp} = 1.25{\pm}0.05 \text{ GeV}^2 \ \Rightarrow \delta \simeq 0.05 \text{ GeV}^2$$

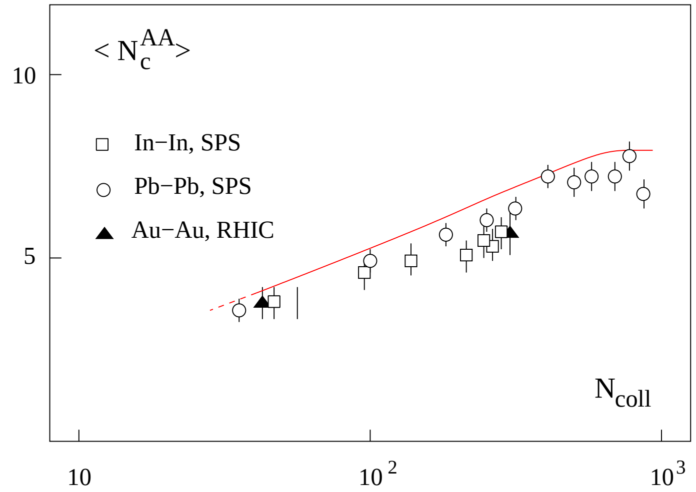
RHIC:

$$\langle p_T^2 \rangle_{pp} = 2.51{\pm}0.21 \text{ GeV}^2 - \langle p_T^2 \rangle_{dAu} = 3.96{\pm}0.28 \text{ GeV}^2 \ \Rightarrow \delta \simeq 0.3 \text{ GeV}^2$$

- with N_c^A and $\delta(s)$ given*, further scaling relation

$$N_c^{AA}(SPS) \simeq N_c^{AA}(RHIC)$$

as function of centrality



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* different value of N_c^A only shifts scale of N_c^{AA}

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transverse momentum dynamics same at RHIC and SPS,
only kick $\delta(s)$ differs

broadening correctly reproduced by Glauber based on
- initial state parton scattering
- normal nuclear absorption

no evidence for new behaviour
(direct J/ψ suppression, J/ψ formation by recombination)

Conclusions

SPS (Pb-Pb, In-In) and RHIC (Au-Au) data indicate

- **onset of ψ'~χ_c suppression around $\epsilon \simeq 1 - 1.5$ GeV/fm^3**
- **approximately constant $S_{J/\psi} \simeq 0.6$ above that (no significant direct J/ψ suppression)**

Agrees with present knowledge of in-medium J/ψ behaviour in finite temperature QCD

Further Tests:

more precise ψ' data (NA60)

direct χ_c data (?)

onset of direct J/ψ suppression (LHC)

NB: recombination $\rightarrow$ onset of J/ψ enhancement