Charmonium Production in Nuclear Matter

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Why study charmonium production in nuclear matter?

- <u>Charmonium interactions</u>:

  Normal hadrons (u,d,s): large ($\sim$ 1 fm), all of same size

  Charmonia ($c\bar{c}$) : small, different sizes, different binding

  Effect of size and binding on interaction with normal hadrons?

- <u>Charmonium formation</u>:

  Charmonia formed in medium, evolution from $c\bar{c}$ to physical resonance

  In-medium behavior of charmonia of different momenta probes different evolution stages

Quarkonium Structure: Phenomenology

Quarkonia: heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV), beauty ($m_b \simeq 4.7$ GeV)

stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks ⇒ quarkonium spectroscopy via non-relativistic potential theory

Schrödinger equation

$$\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$$

confining (“Cornell”) potential $V(r) = \sigma\, r - \dfrac{\alpha}{r}$

string tension $\sigma \simeq 0.2$ GeV^2, gauge coupling $\alpha \simeq \pi/12$

⇒ good account of quarkonium spectroscopy

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	**3.10**	**3.53**	**3.68**	**9.46**	**9.99**	**10.02**	**10.26**	**10.36**
ΔE [GeV]	**0.64**	**0.20**	**0.05**	**1.10**	**0.67**	**0.54**	**0.31**	**0.20**
ΔM [GeV]	**0.02**	**-0.03**	**0.03**	**0.06**	**-0.06**	**-0.06**	**-0.08**	**-0.07**
radius [fm]	**0.25**	**0.36**	**0.45**	**0.14**	**0.22**	**0.28**	**0.34**	**0.39**

NB: error in mass determination ΔM is less than 1 %

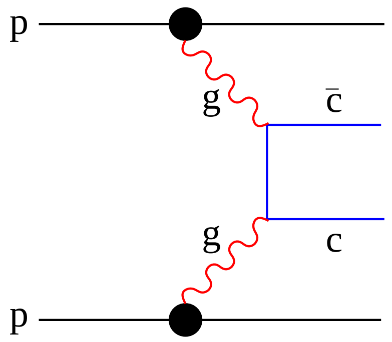
Ground states:

tighly bound $\Delta E = 2M_{D,B} - M_0 \gg \Lambda_{QCD}$, small $r_0 \ll r_h$

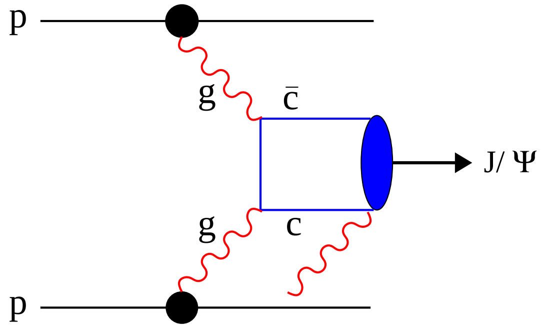
NB: confirmed by QCD theory – lattice, NRQCD, pNRQCD...

1. How to make a J/ψ

step 1: hard production process of $c\bar{c}$



step 2: binding of $c\bar{c}$ to J/ψ



total number of produced $c\bar{c}$ pairs distributed into open charm, different charmonium states J/ψ, χ_c, ψ'

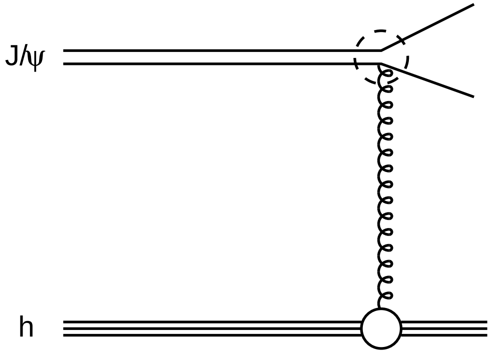
in p-p collisions (no medium), experimentally determined:

95 % open charm, 1.2 % J/ψ, 3.5 % χ_c, 0.3 % ψ'

Feed-down: measured J/ψ are

60 % direct $J/\psi(1S)$, 30 % $\chi_c(1P)$ decay, 10 % $\psi'(2S)$ decay

2. How to break a J/ψ



gluo-effect: sufficiently hard gluon (k) from hadron can dissociate $c\bar{c}$ bound state

$$\sigma_{\rm diss}(g - J/\psi) \sim (k - \Delta E_\psi)^{3/2} k^{-5}$$

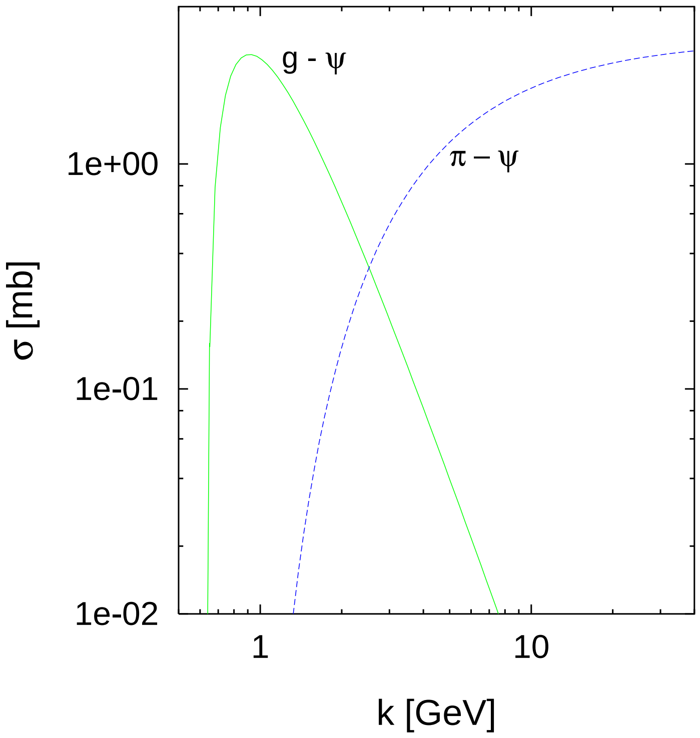
convolute with hadron PDF, for pions $xg(x) \sim (1-x)^3$, $x = k/p$

$$\sigma_{\rm diss}(h - J/\psi) \simeq \sigma_{\rm geom}(1-\lambda)^{11/2} \qquad \lambda = \frac{(M_h + \Delta E_\psi)M_\psi}{(s - M_\psi^2)}$$

hadronic dissociation cross section
$\sigma_{\rm diss}(h - J/\psi)$ shows
strong threshold damping,

attains asymptotic value
$\sigma_{\rm geom} \simeq \pi r^2_{J/\psi} \simeq 2 - 3$ mb
only for large collision energy

reason:
slow hadrons don't contain
sufficiently hard gluons

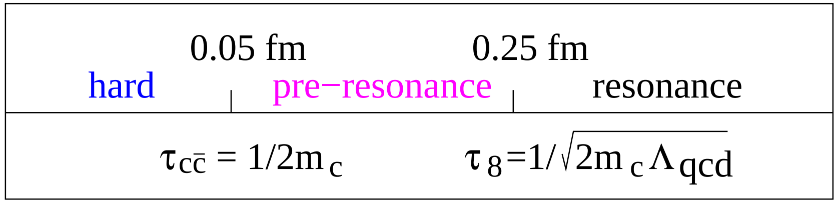


Conclusion:

slow hadrons cannot break up $J/\psi \Rightarrow$ slow J/ψ's in nuclear matter are not dissociated

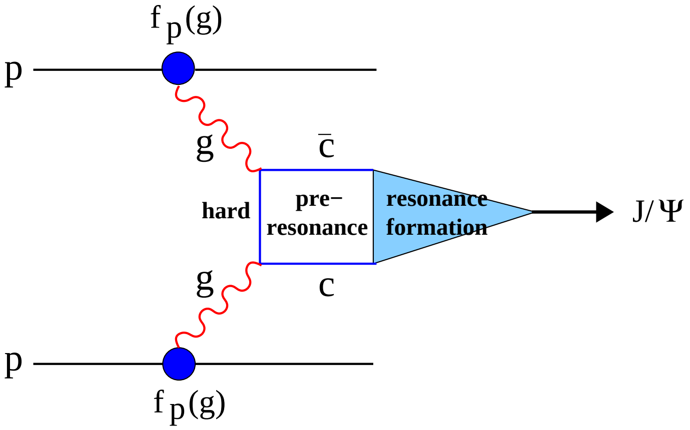
3. Effect of nuclear matter on J/ψ production

time evolution of J/ψ formation



hard — 0.05 fm — pre−resonance — 0.25 fm — resonance

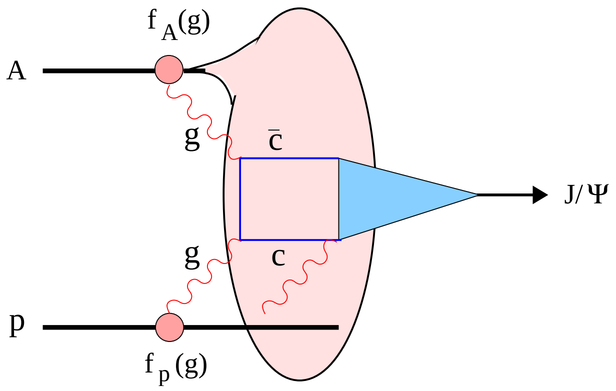
$\tau_{c\bar{c}} = 1/2m_c$ $\tau_8 = 1/\sqrt{2m_c \Lambda_{qcd}}$



similar for excited states, but longer resonance formation time

Consider charmonium production in pA collision:

charmonia are produced in part inside nuclear medium, hence their momentum dependence reflects their state during the passage



very fast in nuclear rest frame: nucleus sees color octet state, same for all charmonium states

very slow in nuclear rest frame: nucleus sees fully formed charmonium, different for different states

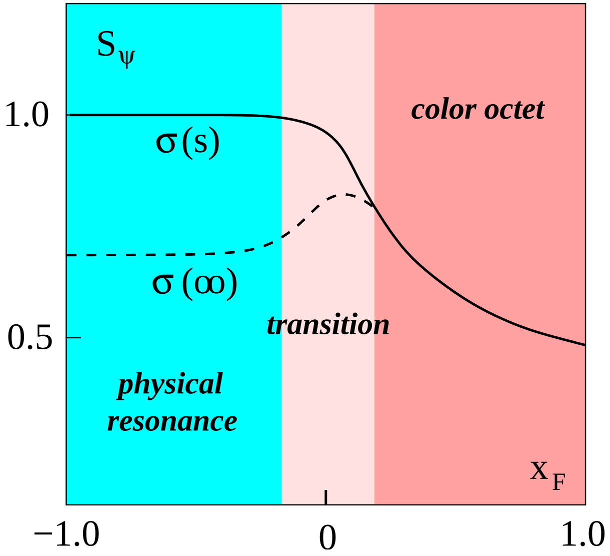
detailed study: [Kharzeev & HS, 1995]

$p - Pb$ at 160 GeV lab energy protons

$$S_{\psi} = \exp\{-n_0 \sigma_{J/\psi} L\}$$

$$L = (3/4) R_A = (3/4) 1.15 A^{1/3}$$

color octet region:
experimentally well studied,
theoretically not clear



resonance region: experimentally terra incognita, not at all investigated

- **why no experiments?** *[no di-muon studies at AGS]*

detect J/ψ via muon decay: $J/\psi \rightarrow \mu^+ + \mu^-$

can only measure relatively hard muons ($k \geq 2-3$ GeV)

$p - A$ experiments: proton beam on nuclear target;
cannot measure slow muons in nuclear rest frame

solution: A-beam on hydrogen/deuterium target –
"inverse kinematics experiment"

investigated by NA38/NA60 at CERN:
needs complete restructure of set-up

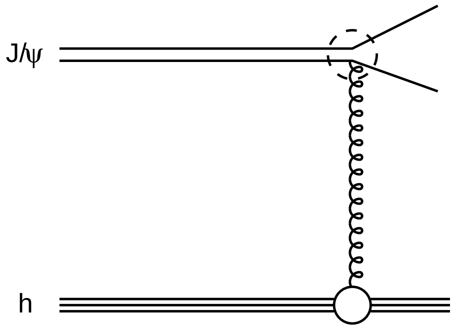
Challenge to FAIR-CBM:

measure for the first time the behavior of physical J/ψ and excited charmonium states in normal nuclear matter

More on Theory

- Gluo-effect: short-distance QCD, OPE, correct for $m_c \to \infty$

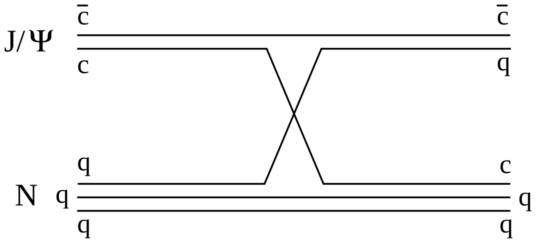
  [Bhanot & Peskin 1979; Kaidalov 1993; Kharzeev & HS, 1995]



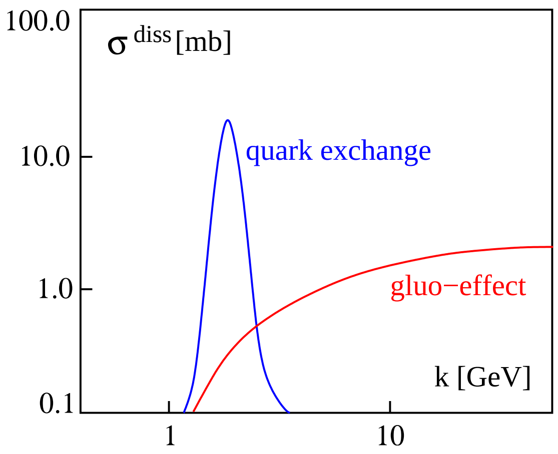
only hard gluons can break up J/ψ
$\longrightarrow$ strong threshold damping
$\longrightarrow$ slow J/ψ's do not interact
in nuclear matter.

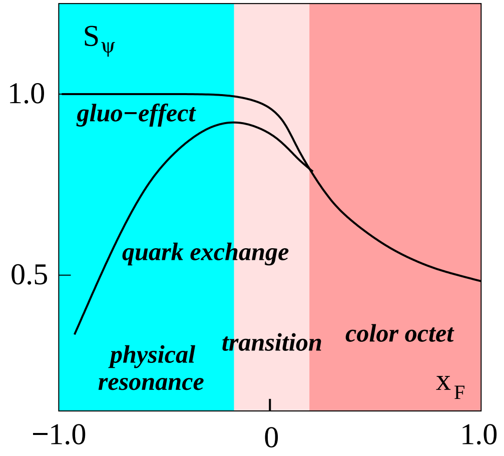
- Quark exchange, comover coalescence

  [Brodsky & Mueller 1988;
  Martins, Blaschke & Quack 1994;
  Matinyan & Muller 1998]



string flip between quarks
$\longrightarrow$ strong threshold enhancement





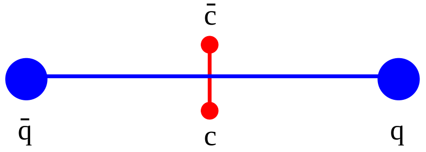
Basic physics question:

- do slow quarkonia interact with normal hadrons
- or does the tight binding/small size make them invisible?

open issues:

gluo-effect: role of finite m_c?

quark-exchange: role of different scales?
spin flip possible?

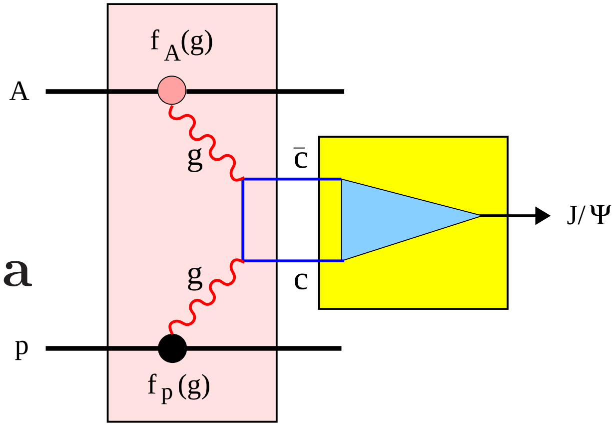


More on Experiment

Want to study the effect of medium on charmonia, $c\bar{c}$ binding;
BUT: the medium also affects overall $c\bar{c}$ production

Two issues:

1. How is the overall $c\bar{c}$ production rate modified in nuclear matter? Is the open charm rate changed?
2. How is the binding of $c\bar{c}$ to charmonia modified in nuclear matter? Is the J/ψ to open charm ratio changed?



The measured J/ψ rate includes both effects;
it is therefore absolutely crucial to measure also open charm.

To illustrate:
if the medium reduces the overall $c\bar{c}$ rate by a factor two,
then also the J/ψ rate will be reduced by this factor,
provided the medium has no effect on the J/ψ binding.

However, if we simply compare
J/ψ production in pA with scaled pp production,
we wrongly claim "J/ψ suppression" by nuclear matter.

So the crucial first step must be

measure open charm in pp and in pA/AA.

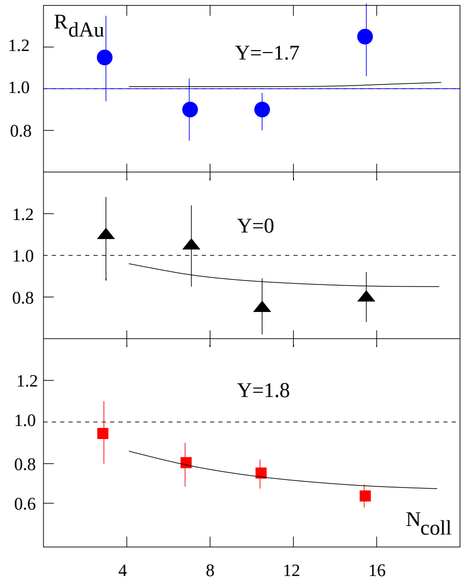
This provides the basis for determining what happens to
- charm production in nuclear matter,
- charmonium formation in nuclear matter.

Example:

J/ψ production in $d - Au$ at RHIC

Puzzle:

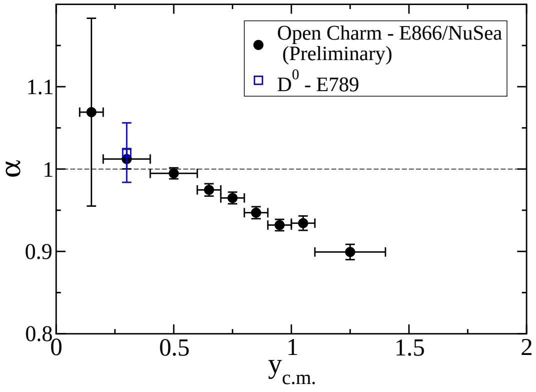
why more J/ψ suppression
at forward than at central
or backward rapidity?



Preliminary data from Fermilab
for open charm production in
800 GeV $p - A$ collisions;

$\sigma_{pA} = A^{\alpha}\sigma_{pp}$

reduced charm forward production



Conclusions

CBM can provide unique opportunity for pioneering studies of

- **charm production**
- **charmonium formation**

in normal $[p - A]$ and compressed $[A - A]$ nuclear matter.

In all cases, need $p - p$ as reference, and all reactions should be studied at the same collision energy.