The Analysis of Matter in QCD

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Lecture 0: The Thermodynamics of Quarks and Gluons

Lecture 1: The States of Matter in QCD

Lecture 2: The Spectral Analysis of the QGP

Lecture 3: The Origin of Thermal Hadron Production

The Spectral Analysis of the QGP

Contents

1. Quarkonia

heavy quark ($Q\bar{Q} = c\bar{c}, b\bar{b}$) bound states stable under strong decay

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

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

$M_{D,B}$ open charm/beauty mesons $(c\bar{u})/(b\bar{u})$...

heavy quarks:

⇒ quarkonium spectroscopy via non-relativistic potential theory

confining ("Cornell") potential for $Q\bar{Q}$ at separation distance r,

$$V(r) = \sigma\, r - \frac{\alpha}{r}$$

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

Schrödinger equation

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

determines bound state masses M_i and wave functions $\Phi_i(r)$

wave functions $\longrightarrow$ average radii $\quad < r_i^2 >= \int d^3r\ r^2|\Phi_i(r)|^2$

binding energies $\quad \Delta E \equiv 2\, M_{D,B} - M_i$

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

- **N-R potential theory provides excellent account of quarkonium spectroscopy**

Ground states J/ψ, Υ

tightly bound $2\,M_{D,B} - M_{J/\psi,\Upsilon} \gg \Lambda_{QCD}$

small size $r_{J/\psi,\Upsilon} \ll r_h$

How can they be dissociated?

2. Quarkonium Dissociation in QCD Thermodynamics

2.1 Heavy Quark Binding in Media

What happens if we separate Q and $\bar{Q}$?

- in vacuum

  confining string energy

  $$F(r) \sim \sigma\, r$$

  string breaking for $F(r) \geq F_0$

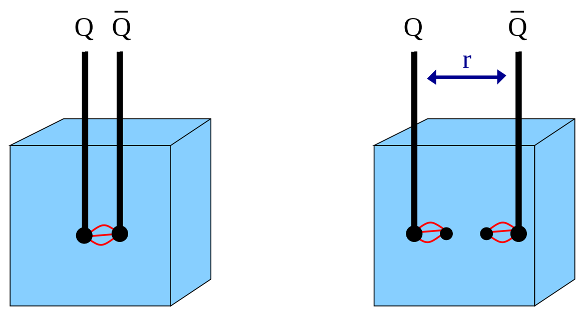
  $\Rightarrow$ light-heavy mesons $(Q\bar{q})$, $(\bar{Q}q)$

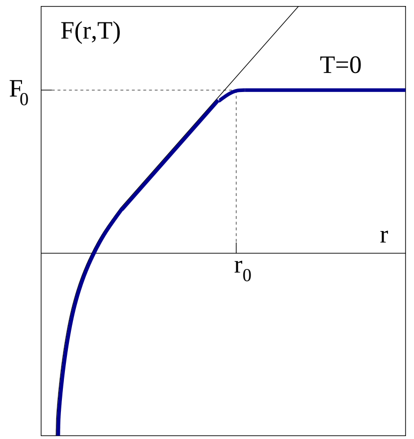
  String breaking energy for charm

  $$F_0 = 2(M_D - m_c) \simeq 1.2 \text{ GeV}$$

  and for bottom

  $$F_0 = 2(M_B - m_b) \simeq 1.2 \text{ GeV}$$





String breaking occurs when charges are separated by

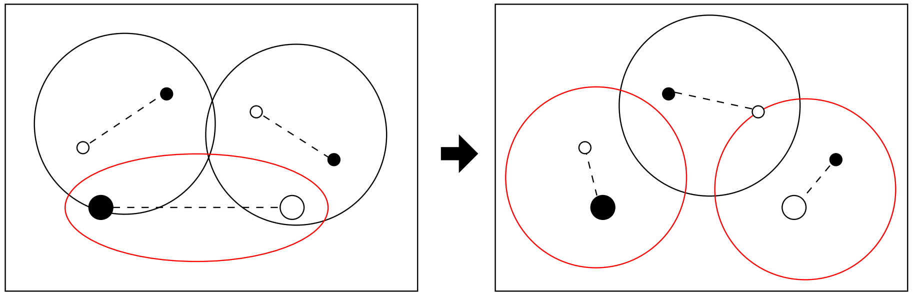
$$r_0 \simeq 1.2 \text{ GeV}/\sigma \simeq 1.5 \text{ fm}$$

property of "vacuum as medium at $T = 0$"

- in medium, $0 < T < T_c$

medium now contains normal hadrons (mesons)

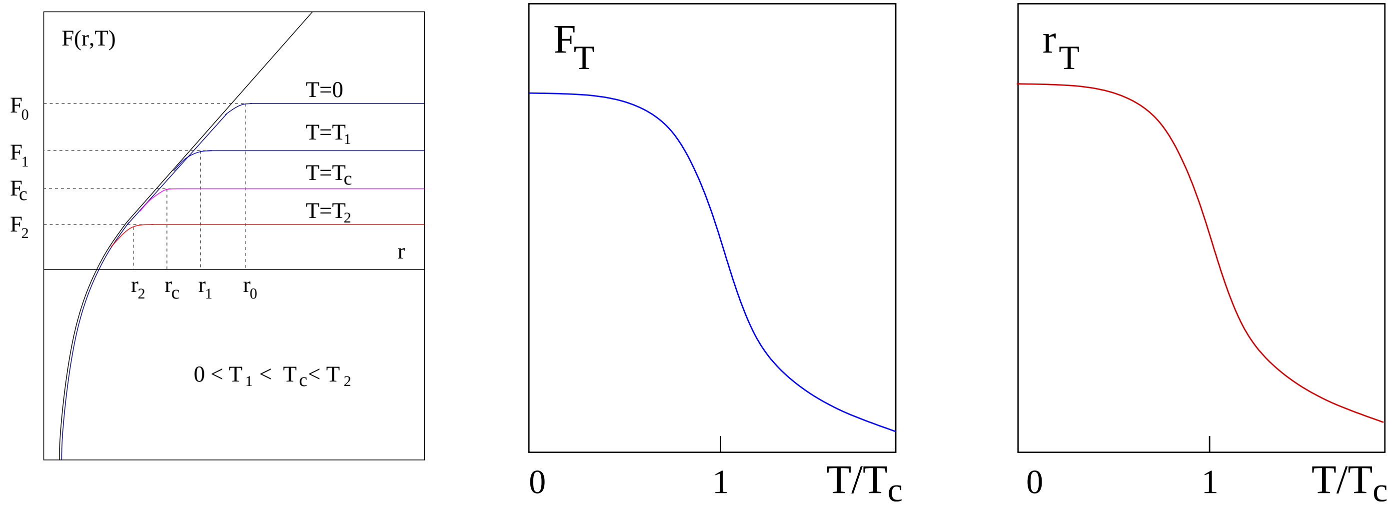
overlap $\Rightarrow$ dissociation via quark recombination



increasing T increases hadron density, lowers dissociation energy,

shortens dissociation separation $\Rightarrow$ effective screening

Near deconfinement point $T = T_c$, strong density increase and consequences



- <u>in medium</u>, <u>$T > T_c$</u>

medium now consists of unbound colour charges

polarization around Q and $\bar{Q}$: $\exists$ colour screening

$\Rightarrow$ screening radius $r_D(T)$ determines range of force

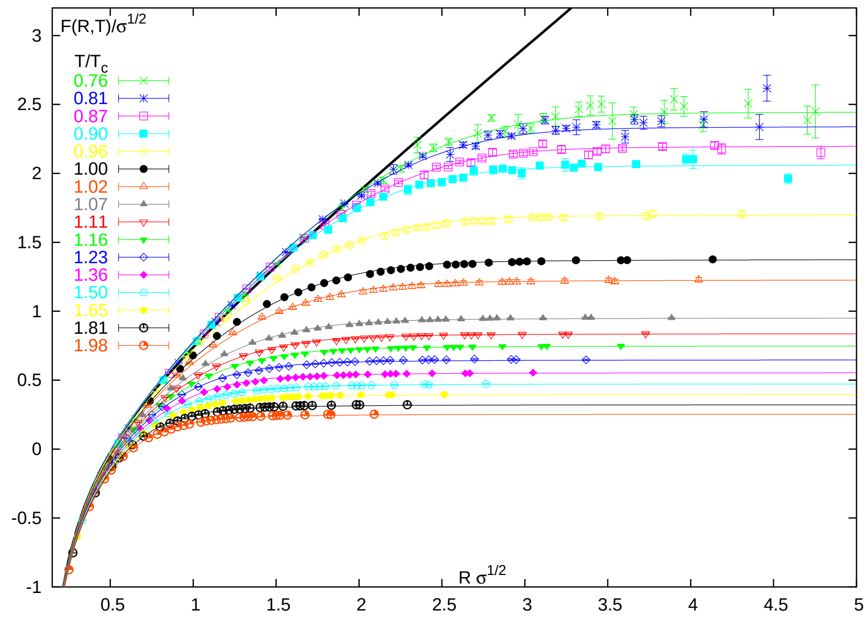
dissociation distance r_T and energy F_T decrease further with T

Conceptually clear: ∃ three types of separation mechanisms

- $T = 0$: string breaking
- $0 < T < T_c$: quark recombination ∼ effective screening
- $T_c < T$: colour screening

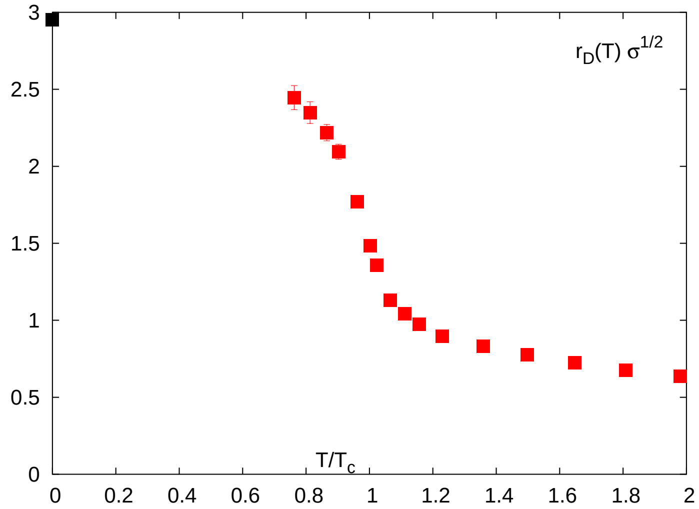
What is the <u>quantitative</u> effect of these mechanisms?

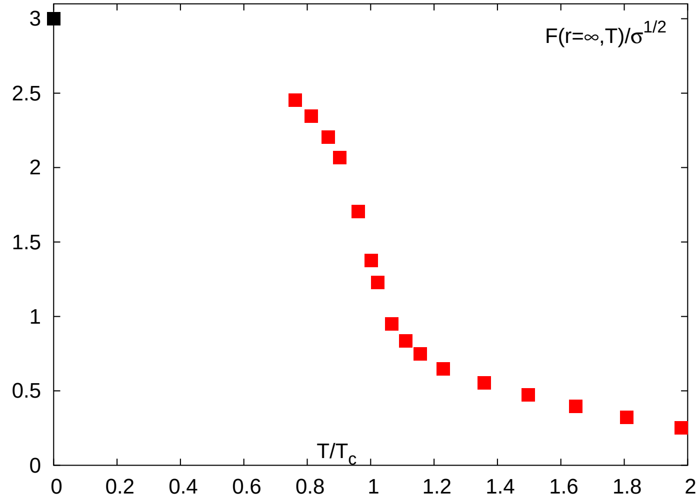
$N_f = 2$ lattice QCD:



Breaking point specifies force range,

large distance behaviour specifies maximum binding energy





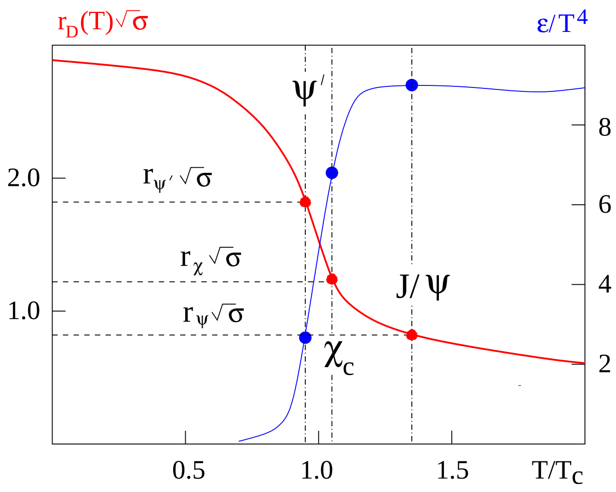
strong density increase near T_c causes strong decrease in both

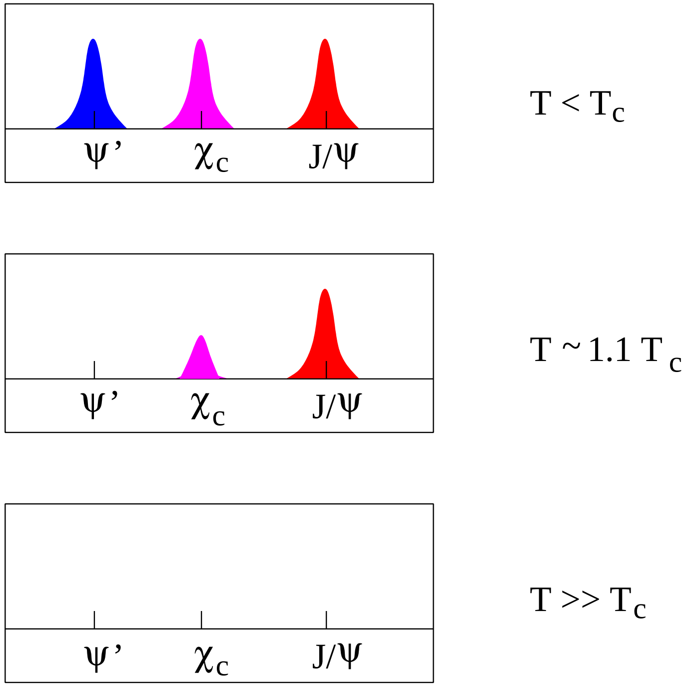
What happens when force range < quarkonium radius?

Q and $\bar{Q}$ inside quarkonium cannot "see" each other any more:

$\Rightarrow$ quarkonium dissociates

⇒ **dissociation points of quarkonia determine temperature, energy density of medium**





How can one calculate quarkonium dissociation points?

Two possibilities:

- solve Schrödinger equation using a temperature-dependent heavy quark potential $V(r,T)$
- calculate quarkonium spectrum directly in finite T lattice QCD

2.2. Potential Models for Quarkonium Dissociation

- model heavy quark potential (Schwinger model)

$$V(r,T) = \sigma r \left\{ \frac{1 - e^{-\mu r}}{\mu r} \right\} - \frac{\alpha}{r} e^{-\mu r}$$

with screening mass $\mu(T) = 1/r_D(T)$

solve Schrödinger equation: with increasing T, bound state i disappears at some $\mu_i(T) = \mu(T_i)$

use screening mass from lattice estimates $\mu(T) \simeq 4\,T$ for $T > 0$ to determine dissociation temperature T_i

charmonia:

ψ' and χ_c dissociated at $T \simeq T_c$
J/ψ at $T \simeq 1.2\ T_c$

- determine potential $V(r,T)$ from lattice studies of heavy quark free energy: [Karsch, Kaczmarek, HS 2008]

Consider free energy with and without color singlet $Q\bar{Q}$ pair

Hamiltonian $\mathcal{H}_0$ for QGP with $Q\bar{Q}$:

$$F_Q(r,T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_Q/T\}$$

Hamiltonian $\mathcal{H}_Q$ for QGP without $Q\bar{Q}$:

$$F_0(T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_0/T\}$$

lattice QCD: free energy difference $F(r,T) = F_Q(r,T) - F_0(T)$

internal energy difference $U(r,T)$ & entropy difference $S(r,T)$

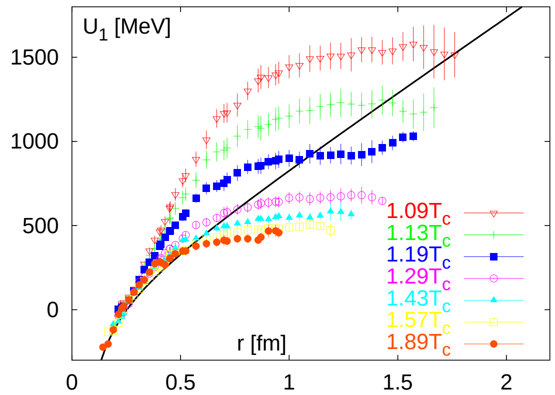
$$U(r,T) = -T^2 \left(\frac{\partial [F(r,t)/T]}{\partial T} \right) = F(r,T) + TS(r,T)$$

Internal energy difference $\quad U(r,T) = \langle \mathcal{H}_Q(r,T) \rangle - \langle \mathcal{H}_0(T) \rangle$

for static heavy quarks, H_Q contains no kinetic term, so $U(r,T)$ gives change in potential energy due to presence of $Q\bar{Q}$ pair

at $T = 0$: $\quad U(r, T=0) = F(r, T=0) = \sigma r - \dfrac{\alpha}{r}$

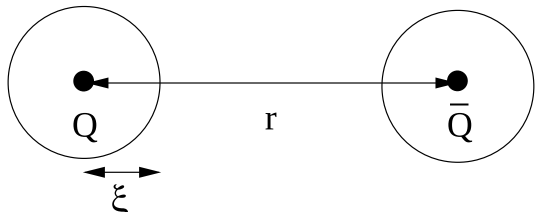
for $T > T_c$ & two flavor QCD, very much stronger interaction potential in the region $0.3 \le r \le 1.5$ fm



consider $Q\bar{Q}$ in QGP (above T_c)

– <u>large distance limit</u>

for $r \longrightarrow \infty$, $\exists$ polarization clouds, of radius correlation length $\xi(T)$



– <u>short distance limit</u>

for $r \longrightarrow 0$ (so that $r \ll T^{-1}$):

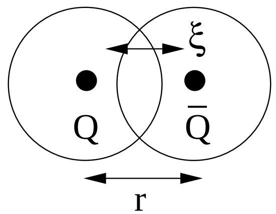
– $Q\bar{Q}$ neutralizes itself & does not see medium

– medium does not see color-neutral $Q\bar{Q}$;

– hence effectively $T = 0$ and $\quad U(r,T) = -\frac{4}{3}\frac{\alpha(r)}{r}$

– <u>intermediate separation regime</u>

at small r, polarization clouds overlap



how does this affect binding?

$U(r,T)$ is sum of $Q\bar{Q}$ interaction and "cloud" energy

concentrate on binding (remove constant $U(r \to \infty, T)$),

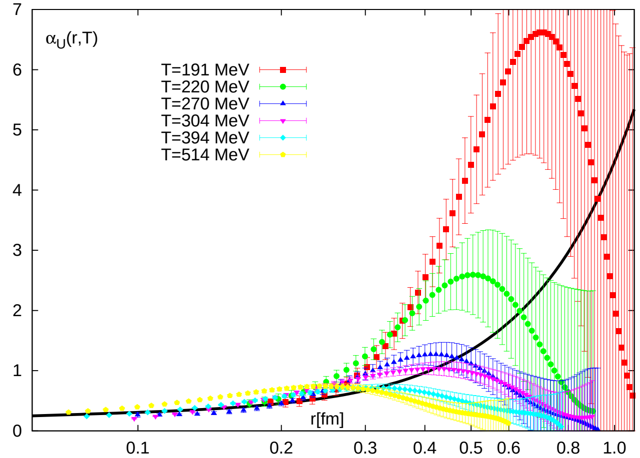
consider effective coupling $$\alpha(r,T) = \frac{3}{4} r^2 \left(\frac{\partial U(r,T)}{\partial r} \right)$$

at $T=0$: $$\alpha(r, T=0) = -\alpha + \sigma r^2$$

result for QGP:

strong enhancement
when $T_c < T < 2\ T_c$

effective binding in medium
is stronger than in vacuum



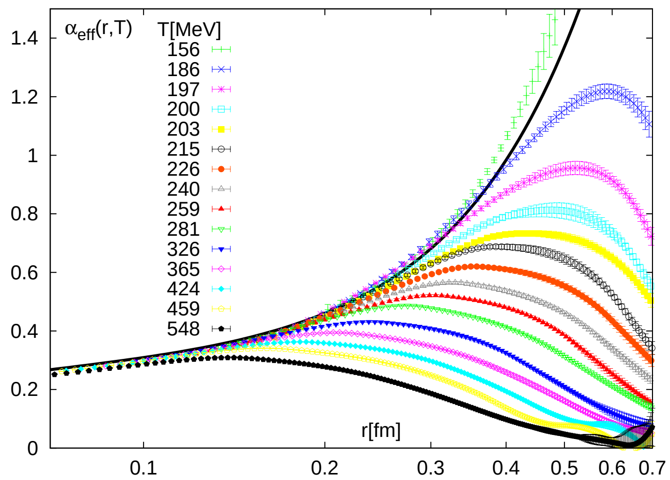
$\exists$ addditional binding mechanism in medium

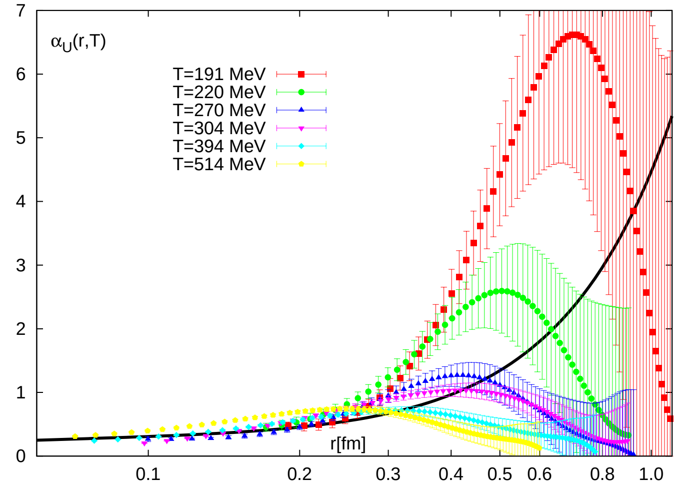
when polarization clouds overlap

∃ "cloud-cloud" binding

in addition to direct $Q\bar{Q}$ binding

to include cloud-cloud binding, must use $U(r,T) = V(r,T)$ in Schrödinger equation; compare to $F(r,T)$:





illustrate: dissociation in semi-classical approximation

$$2m_c + \frac{p^2}{m_c} + V(r,T) = M$$

uncertainty relation $\Rightarrow p^2 \simeq c/r^2$,

$$2m_c + \frac{c}{m_c r^2} + V(r,T) = M$$

minimize

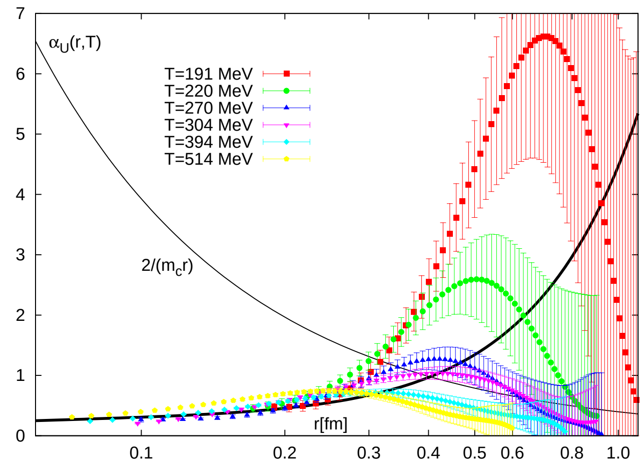
$$E(r,T) = \frac{c}{m_c r^2} + V(r,T)$$

to get

$$\frac{2c}{m_c r} = r^2 \left(\frac{\partial V(r,T)}{\partial T} \right) = \frac{4}{3}\alpha(r,T)$$

fix c by $M = M_{J/\psi}$,

compare kinetic term $2c/m_c r$ to potential term $\alpha_U(r,T)$



$\Rightarrow$ J/ψ dissociation at about 1.5 - 2 T_c

more general: solve Schrödinger equation

ψ' dissociated at $T \simeq 1.1\ T_c$

χ_c dissociated at $T \simeq 1.2\ T_c$

J/ψ survives up to $T \gtrsim 2\ T_c$

- reason for later dissociation: $U(r, T)$ provides stronger binding than Schwinger model potential

  ambiguity in specifying "lattice" potential: $U(r, T)$ or $F(r, T)$

  $F(r, T)$ results $\sim$ Schwinger model

  various alternatives: $V(r, T) = a \; F(r, T) + b \; U(r, T)$ reduce binding, lower dissociation temperatures

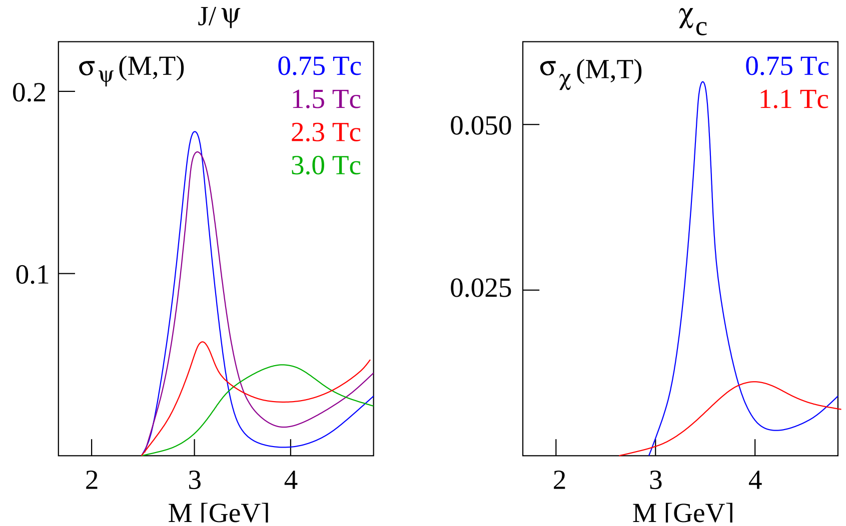
  resolution: determine dissociation points <u>directly</u> in finite T lattice QCD

2.3 Lattice Studies of In-Medium Charmonium Survival

determine $c\bar{c}$ spectrum $\sigma(\omega, T)$ in specific quantum number channel as function of $c\bar{c}$ energy ω

results for quenched and unquenched ($N_f = 2$) QCD agree schematic pattern

lattice resolution limits precision; reliable only for resonance peak strength, position, not width, not continuum ($\omega > 4$ GeV)



charmonia

χ_c is dissociated for $T \geq 1.1\ T_c$

J/ψ persists up to $1.5\ T_c < T < 2.3\ T_c$

preliminary conclusion:
– higher excited states melt near T_c
– J/ψ melts around $2\,T_c$

in accord with direct lattice calculation and potential model studies

- caveat: physical widths

3. Dynamics of Quarkonium Dissociation

Study of global medium effects on quarkonia

$\Rightarrow$ only hot deconfined medium can dissociate ground state

deconfinend medium: constituents are unbound partons

confined medium: constituents are hadronic "comovers"

why cannot collisions with hadrons dissociate J/ψ?

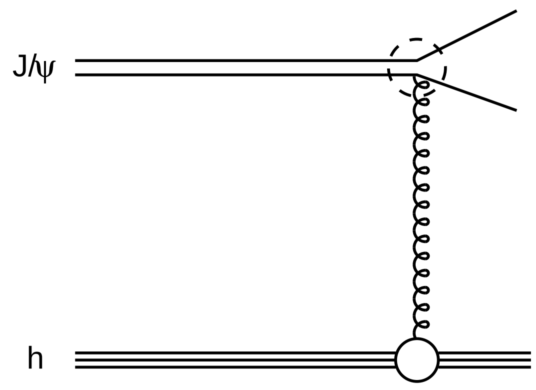
Collision Dissociation of Quarkonia

consider J/ψ dissociation:

- J/ψ is small ($r_{J/\psi} \sim 0.2$ fm), resolved only by hard probes
- J/ψ is tightly bound ($2M_D - M_{J/\psi} \sim 0.6$ GeV), dissociated only by hard probes

how could hadrons interact with J/ψ?

J/ψ interacts with gluon in hadron



gluon momentum distribution (PDF) in hadron, $g(x)$, with $x = 2k/\sqrt{s}$, as determined in DIS

for pions, $g(x) \sim (1-x)^3$, hence

$$< k_g >_h \simeq \frac{1}{5} < p_h >$$

in confined matter, $< p_h > \sim 3T$, with $T < 175$ MeV:

$$< k_g >_h \simeq \frac{3}{5} T \leq 0.1 \text{ GeV} \ll \text{binding energy } 0.6 \text{ GeV}$$

$\Rightarrow$ dissociation in hadronic matter impossible: gluons in hadronic constituents of confined matter are too soft to dissociate J/ψ

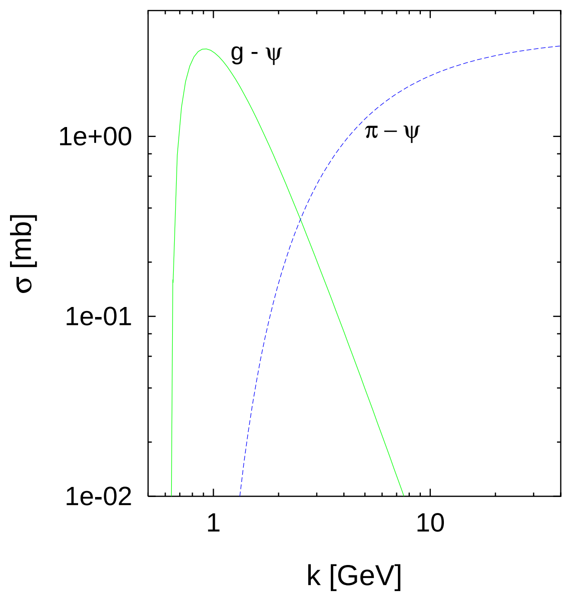
in deconfined medium,

$$< k_g > \simeq 3\ T$$

so that for $T \geq 1.2\ T_c$,
enough energy to
overcome J/ψ binding

More quantitative:

gluon dissociation (QCD photo effect)



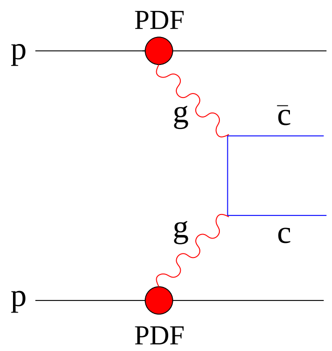
4. Quarkonium Production in Nuclear Collisions

Aim: probe medium produced in nuclear collisions by studying the fate of quarkonia

How to produce the charmonium to be put into the medium?

<u>4.1 Quarkonium Production in Hadronic Collisions</u>

$c\bar{c}$ production:



<u>hard</u> process calculated in <u>perturbative</u> QCD

with PDF determined from DIS

fixed fraction of subthreshold $c\bar{c}$ production $\Rightarrow$ charmonium

colour evaporation model

$$\sigma_{hh\to J/\psi}(s) = f_{J/\psi}\ \sigma_{hh\to c\bar{c}}(M_{c\bar{c}} \leq 2M_D; s)$$

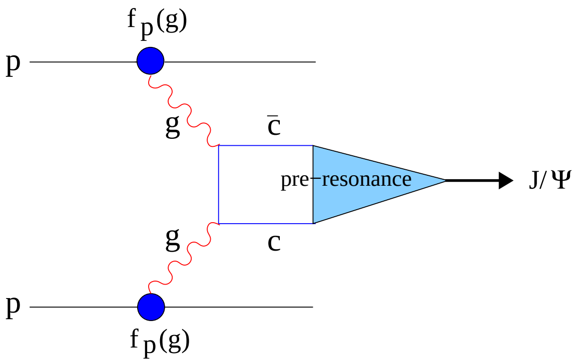
with $\sqrt{s} \sim$ cms collision energy

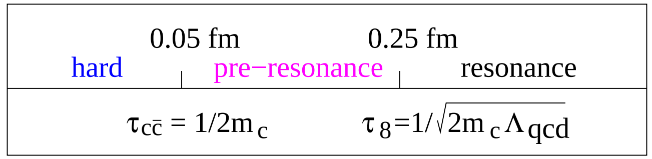
energy-independent fractions f_i for all charmonium states i

(similarly for $b\bar{b}$ and bottomonium)

$\Rightarrow$ correct size & energy dependence of all quarkonium cross sections

J/ψ formation and time scales:





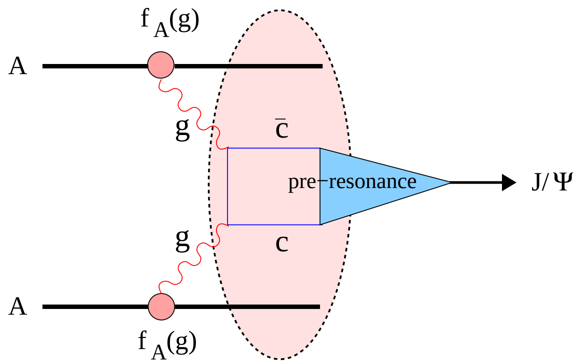
in hadronic collisions, hadron PDF's and $c\bar{c}$ formation in vacuum

4.2 Quarkonium Production in Nuclear Collisions

nuclear collisions:

– modified PDF's
    shadowing/antishadowing

– evolution in nuclear matter
    pre-resonance absorption



hence J/ψ production is modified in nuclear medium,
independent of/before any QGP formation and QGP effects

$\Rightarrow$ must take that into account before looking for QGP effects

How?

both in theory and in experiment:

dilepton, open charm and charmonium production
in pA/dA collisions

essential for any understanding of quarkonium production in nuclear collisions

Procedure:

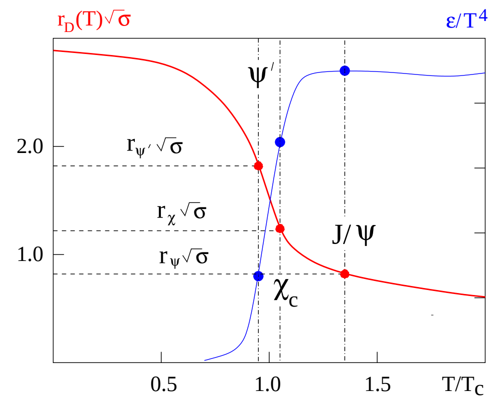
- **determine PDF's in nuclear matter by open charm & dilepton production in pA/dA in the relevant kinematic regions;**
- **predict production of the different charmonium states via colour evaporation model;**
- **determine pre-resonance absorption by J/ψ & ψ' production in pA/dA in the relevant kinematic regions (Glauber analysis).**

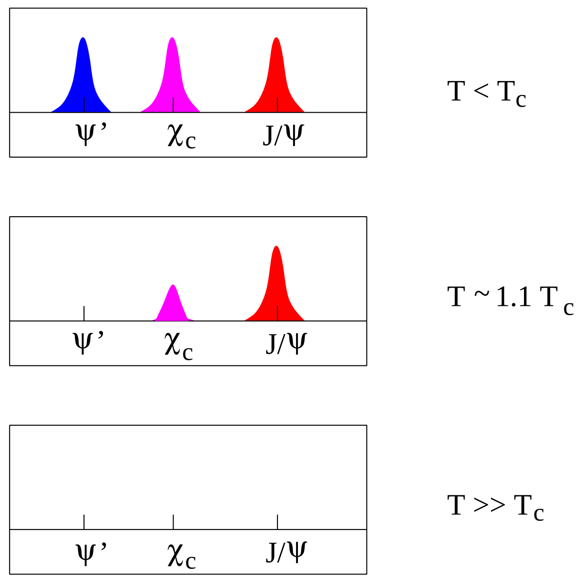
Assume: PDF modifications, nuclear absorption, pre-resonance effects are accounted for; what remains?

4.3 Sequential Quarkonium Suppression

J/ψ production in hadronic collisions:

- $\sim$ 60 % direct $J/\psi(1S)$ production
- $\sim$ 30 % decay $\chi_c(1P) \rightarrow J/\psi + x$
- $\sim$ 10 % decay $\psi'(2S) \rightarrow J/\psi + x$





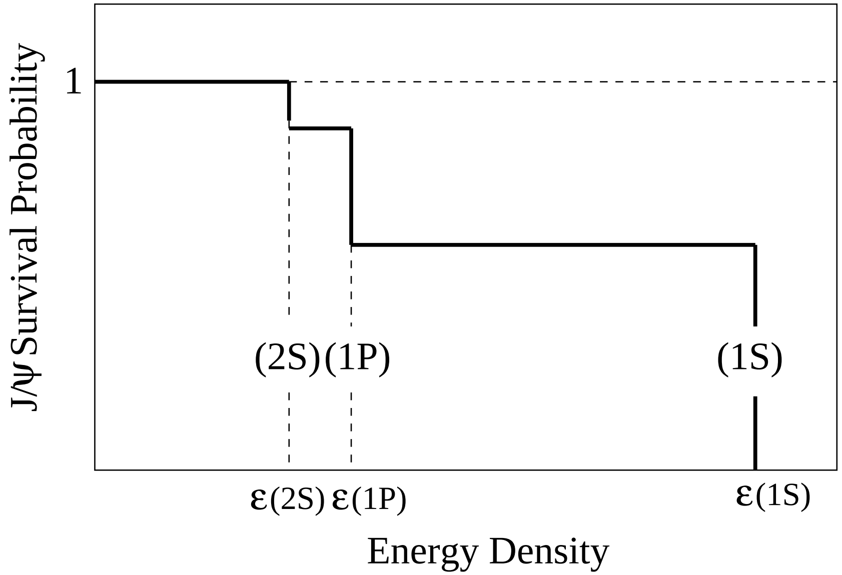
In a thermal QCD medium, higher excited states are absorbed at lower temperatures, energy densities: first ψ', then χ_c, last ψ'

Hence: if

– nuclear collisions produce a thermal QCD medium, and

– nuclear/pre-resonance effects on charmonium production can be accounted for

then J/ψ suppression should be observed in sequential form



with suppression onsets and amounts predicted by QCD

4.4 Charmonium Regeneration

so far: charmonia as “outside” probes, pre-QGP production

no thermal charmonium production in QGP:

$$\exp\{-M_{J/\psi}/T_c\} \sim 10^{-8}$$

but what if initial QGP contains more than thermal amount of charm quarks?

- $c\bar{c}$ production is hard process $\sim N_{coll}$, in contrast to soft hadron (u, d, s) production $\sim N_{part}$
  [breaks down at high energy, parton saturation]

- increase collision energy $\longrightarrow$ increase charm content in produced system

- c or $\bar{c}$ from a given nucleon-nucleon collision can at hadronization bind with charm constituents from different collisions

  ∃ new exogamous charmonium production mechanism;

  c and $\bar{c}$ in such charmonia have different parents,

  in contrast to introgamous production in pp

Predict:

High energy ⇒ enhanced J/ψ production in AA re pp

Scenario:

- at sufficiently high energy, charmonia from primary production (introgamous) melt in QGP;
- QGP is over-saturated in charm (higher charm abundance than in thermal equilibrium), due to charm production $\sim$ number of collisions;
- at hadronization, statistical combination (regeneration) of $c\bar{c}$ pairs from the set of all (exogamous) charm quarks in QGP more than compensates the removal of primary production;
- at high energy, J/ψ enhancement, not suppression

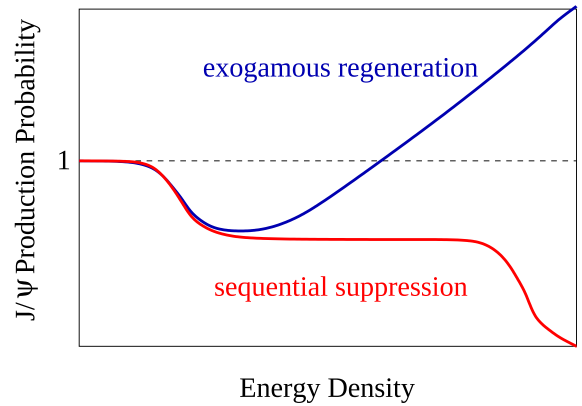
How to distinguish between

– J/ψ suppression in equilibrium QGP

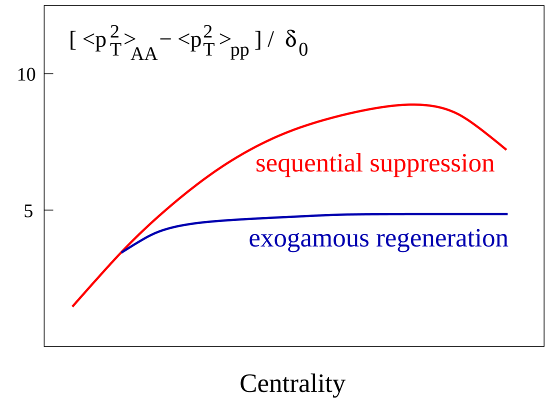
– J/ψ enhancement by charm over-abundance?

Remove nuclear matter & (at high energy) beauty decay effects

- overall J/ψ survival: suppression vs. enhancement at high energy densities



- p_T behaviour: initial state parton scattering vs. final state charm production



- in general, regeneration → quarkonium momentum distributions as convolution of open charm momenta

5. Conclusions

In statistical QCD, quarkonium spectra provide an unambiguous tool to determine temperature/energy density of QGP.

In nuclear collisions?

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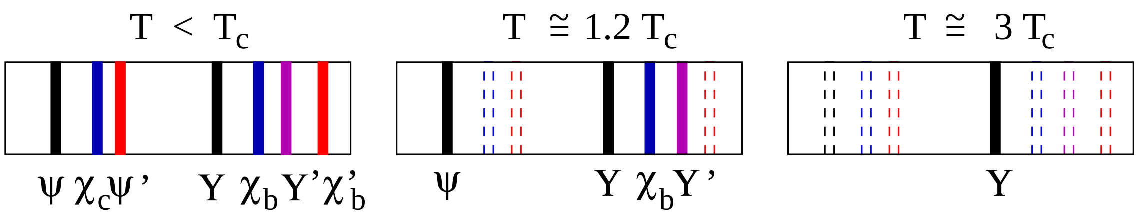
In nuclear collisions?

- **If J/ψ production remains "external" probe (no regeneration), sequential suppression leads to a quantitative QCD prediction**



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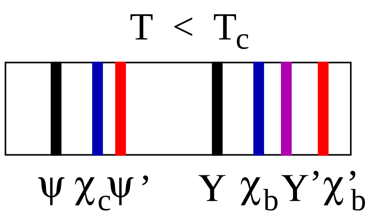

- **If there is regeneration & J/ψ enhancement: clear evidence of thermalization on a pre-hadronic level, but no thermometer.**

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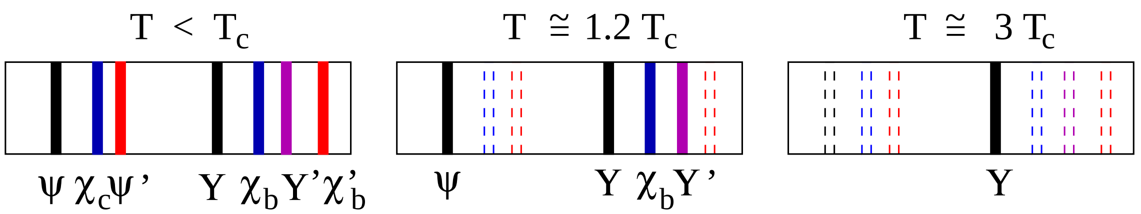

- If there is regeneration & J/ψ enhancement: clear evidence of thermalization on a pre-hadronic level, but no thermometer.

- In that case, bottomonium production remains as the QGP thermometer.

There is much interesting work left to do...