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Deconfinement and Quarkonium Dissociation

Helmut Satz

Universität Bielefeld, Germany
and
Instituto Superior Técnico, Lisboa, Portugal

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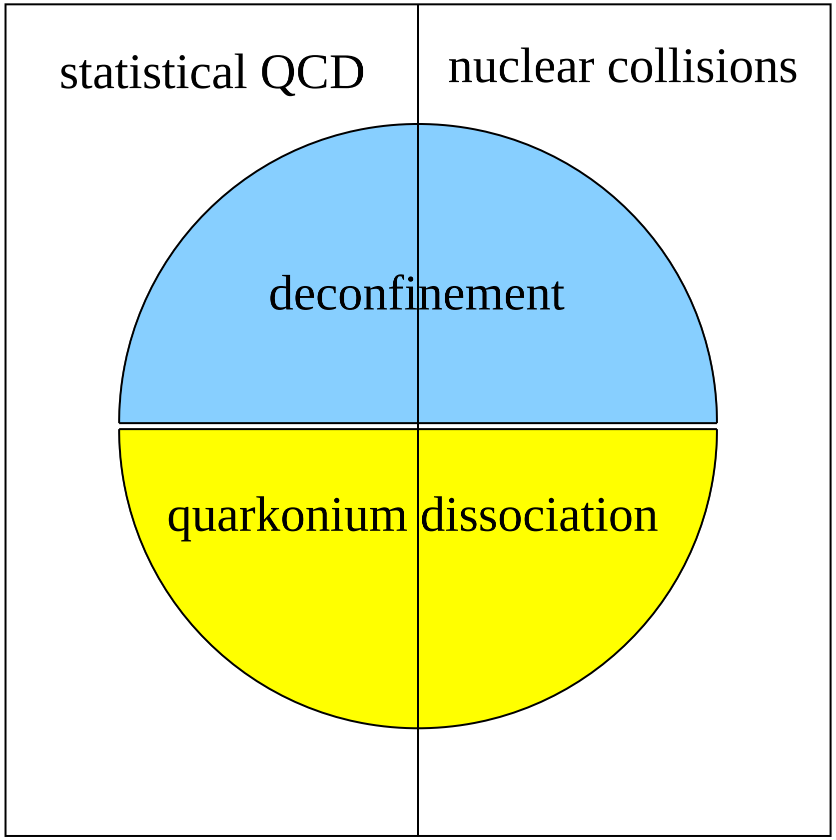

statistical QCD
nuclear collisions
deconfinement
quarkonium dissociation

1. Deconfinement

1.1 Phases of Strongly Interacting Matter

What happens to strongly interacting matter at high temperature and/or density?

- **hadrons have intrinsic size $r_h \simeq 1$ fm, need $V_h \simeq (4\pi/3)r_h^3$ to exist**

  ⇒ limiting density of hadronic matter

  $n_c = 1/V_h \simeq 1.5\ n_0$ **[Pomeranchuk 1951]**

- **resonances → exponential hadron spectrum $\rho(m) \sim \exp(bm)$**

  – statistical bootstrap model **[Hagedorn 1968]**

  – dual resonance model

  [Fubini & Veneziano 1969; Bardakçi &Mandelstam 1969]

  ⇒ limiting temperature of hadronic matter

  $T_c = 1/b \simeq 150 - 200$ **MeV**

$\Rightarrow$ **what lies beyond n_c, T_c?** $\Leftarrow$

- **quark liberation**

  hadronic matter: colorless constituents of hadronic dimension

  $\Downarrow$

  quark-gluon plasma: pointlike colored constituents

  $\Rightarrow$ **deconfinement: insulator-conductor transition in QCD**

- **quark mass shift**

  at $T = 0$, quarks 'dress' with gluons $\rightarrow$ constituent quarks

  bare quark mass $m_q \sim 0 \rightarrow$ constituent quark mass $M_q \sim 300$ MeV

  in hot medium, dressing 'melts' $M_q \rightarrow 0$

  for $m_q = 0$, $\mathcal{L}_{QCD}$ has chiral symmetry

  $M_q \neq 0 \rightarrow$ spontaneous chiral symmetry breaking

  $M_q \rightarrow 0 \Rightarrow$ chiral symmetry restoration

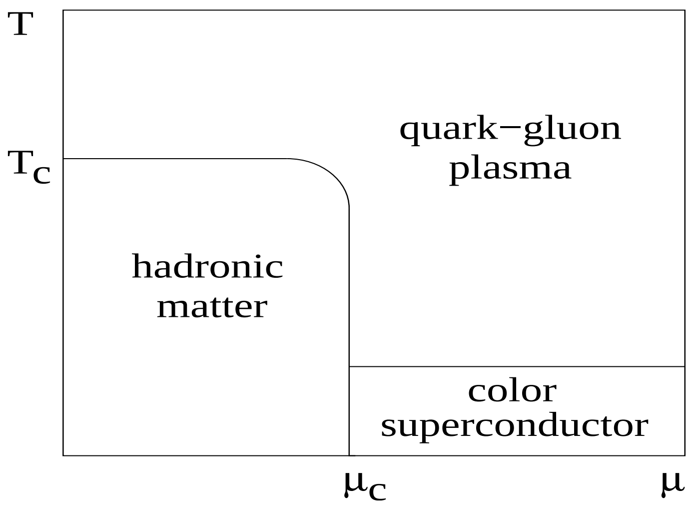
- diquark matter

  deconfined quarks ∼ attractive interaction

  can form colored bosonic 'diquark' pairs (QCD's Cooper pairs)

  form condensate ⇒ color superconductor

- expected phase diagram of QCD:



baryochemical potential μ ∼ baryon density.

1.2 From Hadrons to Quarks and Gluons

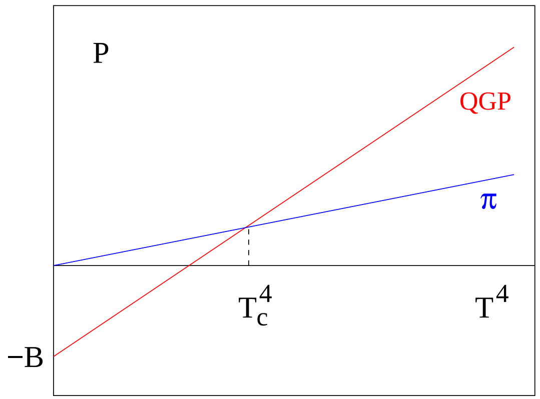
simplest confined matter: ideal pion gas $P_\pi = \frac{\pi^2}{90}\, 3\, T^4 \simeq \frac{1}{3}\, T^4$

simplest deconfined matter: ideal quark-gluon plasma

$$P_{QGP} = \frac{\pi^2}{90}\, \{\, 2 \times 8 + \frac{7}{8}\, [2 \times 2 \times 2 \times 3]\, \}\, T^4 - B \simeq 4\, T^4 - B$$

with bag pressure B **for outside/inside vacuum**

$\Rightarrow$ **compare** $P_\pi(T)$ **and** $P_{QGP}(T)$ **vs.** T



phase transition from hadronic matter at low T **to QGP at high** T

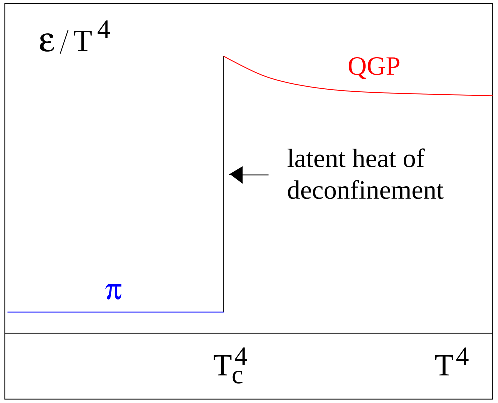
critical temperature:

$$P_\pi = P_{QGP} \rightarrow T_c^4 \simeq 0.3\ B \simeq 150\ \text{MeV}$$

with $B^{1/4} \simeq 200$ **MeV from quarkonium spectroscopy**

corresponding energy densities

$$\epsilon_\pi \simeq T^4 \rightarrow \epsilon_{QGP} \simeq 12\ T^4 + B$$



at T_c**, energy density changes abruptly by latent heat of deconfinement**

so far, simplistic model; real world?

1.3 Finite Temperature Lattice QCD

given QCD as dynamics input, calculate resulting thermodynamics, based on QCD partition function

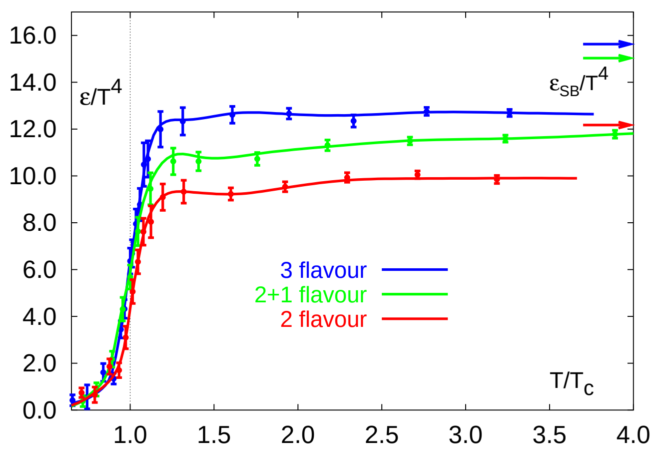
$\Rightarrow$ lattice regularization

- energy density

  $\Rightarrow$ latent heat of deconfinement

  For $N_f = 2, 2+1$:

  $T_c \simeq$ 175 MeV
  $\epsilon(T_c) \simeq 0.5 - 1.0$ GeV/fm^3



explicit relation to deconfinement, chiral symmetry restoration?

$\Rightarrow$ order parameters

- **deconfinement** $\Rightarrow m_q \to \infty$

  Polyakov loop $L(T) \sim \exp\{-F_{Q\bar{Q}}/T\}$

  $F_{Q\bar{Q}}$**: free energy of** $Q\bar{Q}$ **pair for** $r \to \infty$

$$L(T) \begin{cases} = 0 & T < T_L \text{ confinement} \\ \\ \neq 0 & T > T_L \text{ deconfinement} \end{cases}$$

  variation defines deconfinement temperature T_L

- **chiral symmetry restoration** $\Rightarrow m_q \to 0$

  chiral condensate $\chi(T) \equiv \langle\bar{\psi}\psi\rangle \sim M_q$

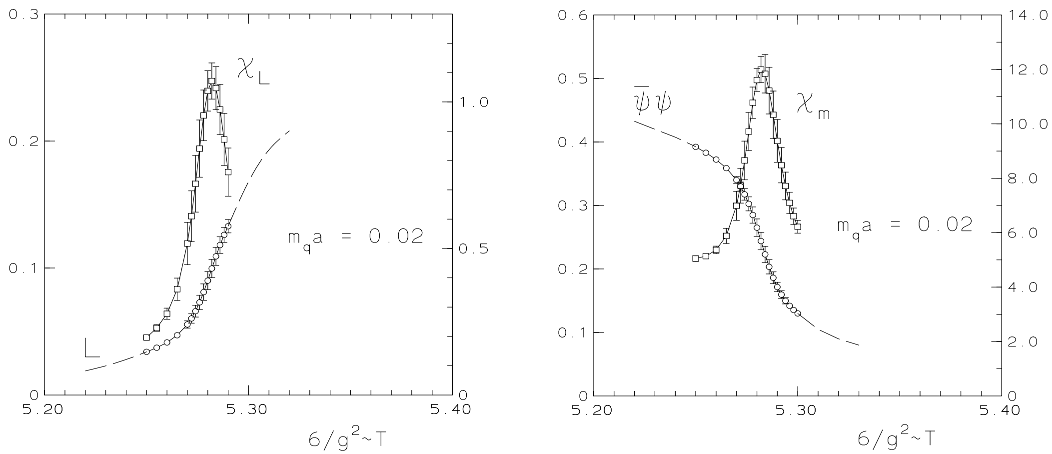
  measures dynamically generated ('constituent') quark mass

$$\chi(T) \begin{cases} \neq 0 & T < T_\chi \text{ chiral symmetry broken} \\ \\ = 0 & T > T_\chi \text{ chiral symmetry restored} \end{cases}$$

  variation defines chiral symmetry temperature T_χ

- **how are T_L and T_χ related?**

lattice results



Polyakov loop & chiral condensate vs. temperature

$\Rightarrow$ **deconfinement and chiral symmetry restoration coincide**

at $\mu = 0$

$\exists$ **one transition** **hadronic matter $\rightarrow$ QGP**

for $N_f = 2, m_q \rightarrow 0$ **at** $T_c = T_L = T_\chi \simeq 175$ MeV

2. Quarkonia

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

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

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

heavy quarks:

$\Rightarrow$ 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 determine average radii

$$< r_i^2 >= \int d^3r \ r^2|\Phi_i(r)|^2$$

Semi-classical solution: $< p^2 >< r^2 >\simeq 1$

$$E(r) = 2m + \frac{p^2}{m} + V(r) \simeq 2m + \frac{1}{mr^2} + V(r)$$

minimize re r**:** $dE/dr = 0$ **gives for generic charmonium**

$$r_0 \simeq 0.44 \text{ fm} \ \Rightarrow \ M_0 = E(r_0) \simeq 3.1 \text{ GeV}$$

and for generic bottomonium

$$r_0 \simeq 0.33 \text{ fm} \ \Rightarrow \ M_0 = E(r_0) \simeq 9.6 \text{ GeV}$$

Exact solution: good account of full 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**

Ground states:

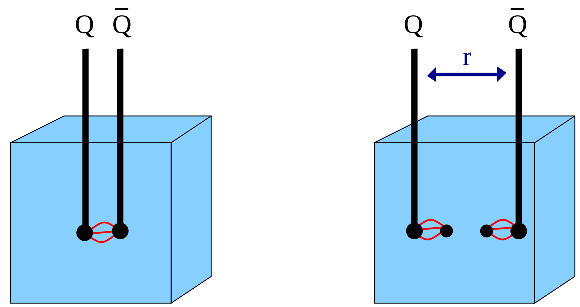
tightly bound $2M_{D,B} - M_0 \gg \Lambda_{QCD}$ **and small** $r_0 \ll r_h$

How can they be dissociated?

3. Quarkonium Dissociation in QCD Thermodynamics

3.1 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 $F(r) \geq F_0$

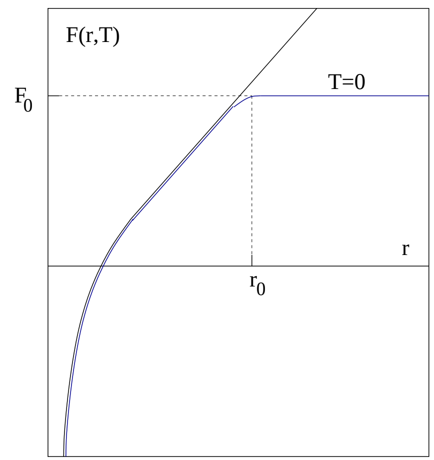
  $\Rightarrow$ **two light-heavy mesons** $(Q\bar{q})$, $(\bar{Q}q)$

  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

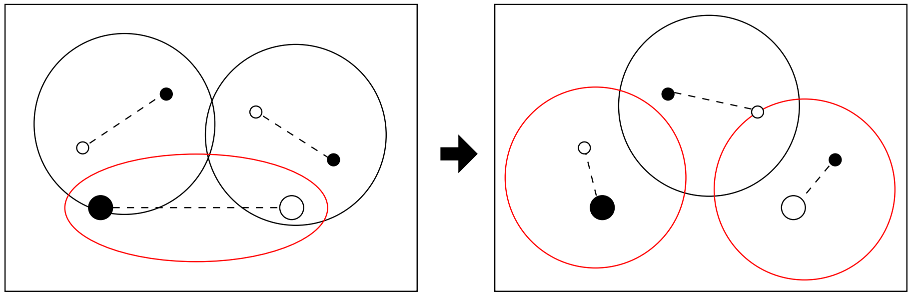
$$r_0 \simeq 1.2 \text{ GeV}/\sigma \simeq 1.5 \text{ fm}$$

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

- **in medium**, $0 < T < T_c$

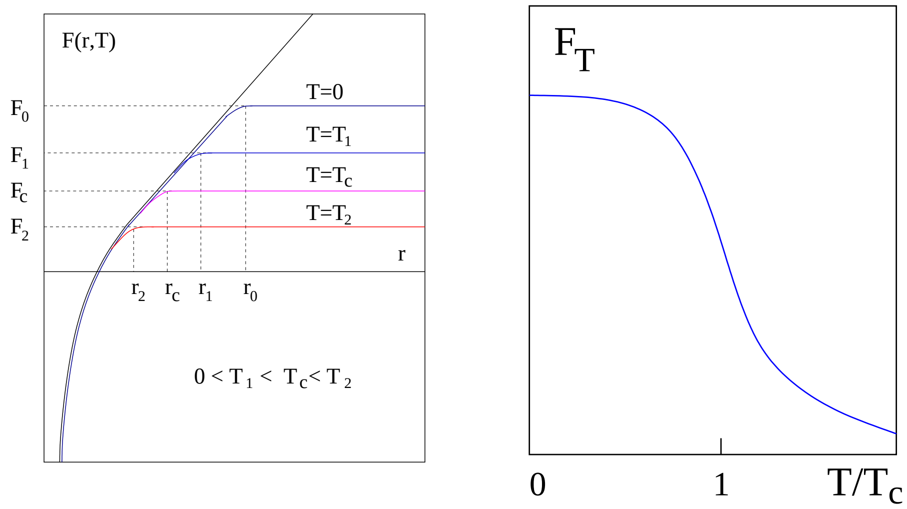
medium now contains normal hadrons (mesons)

overlap ⇒ dissociation via quark recombination



increasing T increases hadron density, lowers dissociation energy, shortens dissociation separation ⇒ effective screening

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



- **in medium, $T > T_c$**

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

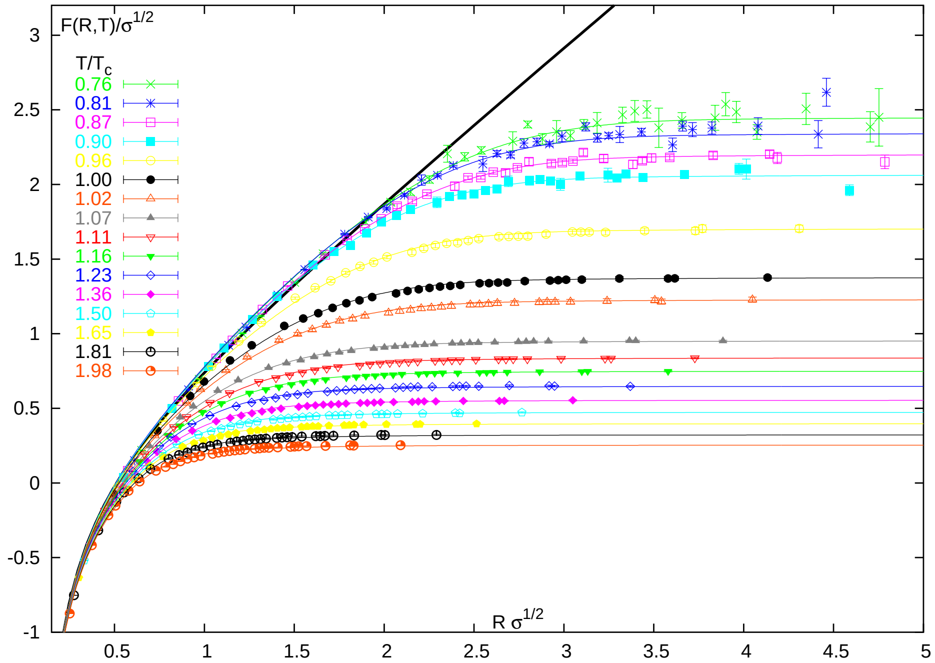
Conceptually clear: ∃ three types of separation mechanisms

- $T = 0$: **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?

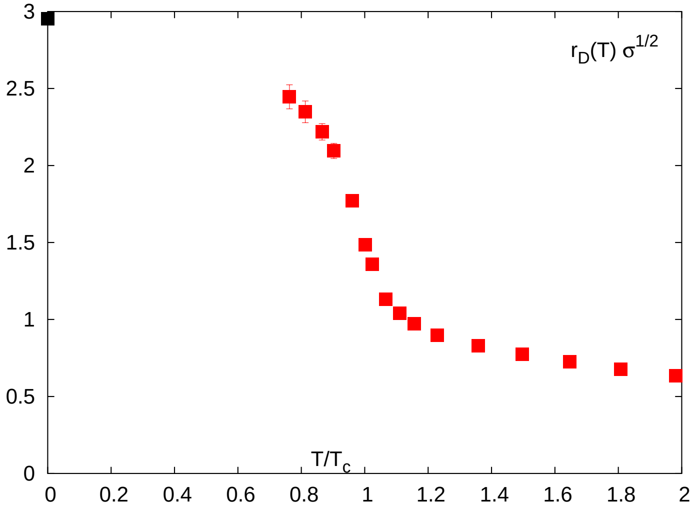
$N_f = 2$ **lattice QCD:**

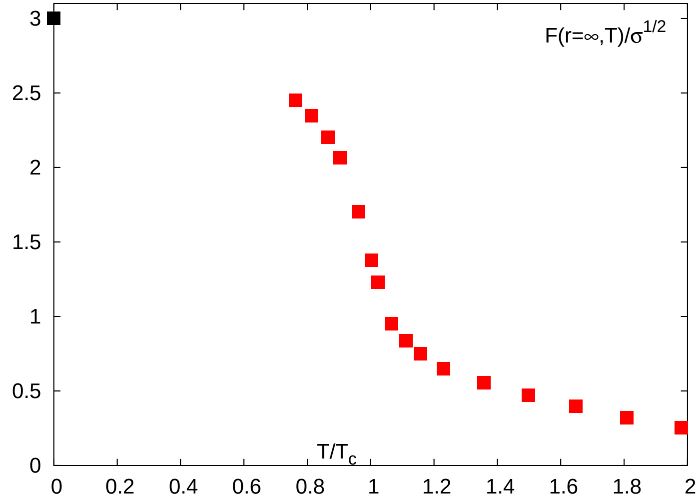
Bielefeld Lattice Group (2004)



Breaking point specifies <u>force range</u>,

large distance behaviour specifies <u>maximum binding energy</u>





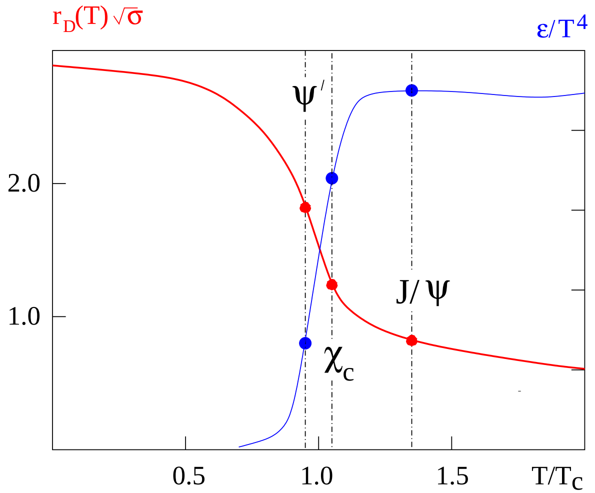
strong density increase near T_c causes strong decrease in both

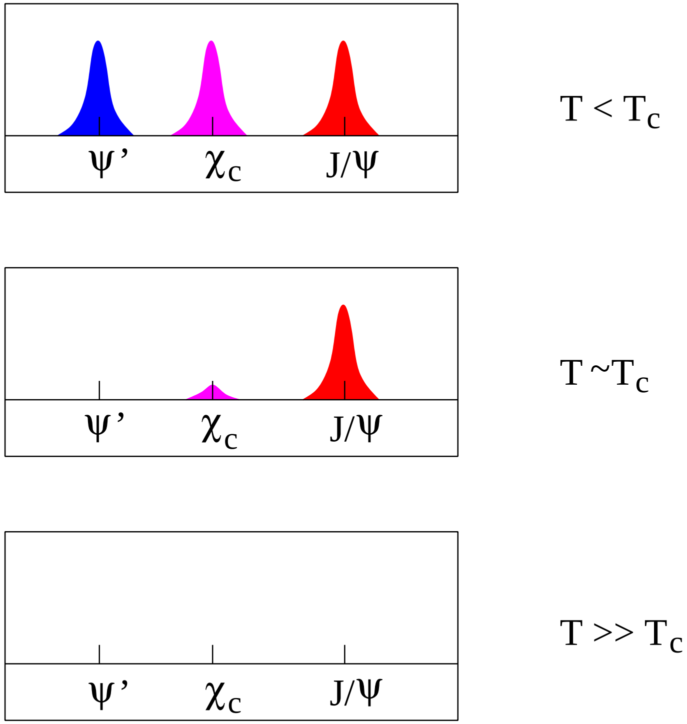
What happens when force range $<$ quarkonium radius?

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?

Three possibilities:

- **calculate quarkonium spectrum directly in finite T lattice QCD**
- **solve Schrödinger equation using heavy quark potential $V(r,T)$ obtained from lattice results for free energy $F(r,T)$, using the thermodynamic relation**

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

- **model $V(r,T)$ and solve Schrödinger equation**

Lattice results, direct and for $F(r,T)$, available only recently

– hence most work so far on third alternative

– conceptually OK, in detail and quantitatively NOT

– consider two examples as illustration

3.2. Potential Models for Quarkonium Dissociation

- **Schwinger model screening** — Karsch, Mehr, HS (1988)
  - separate string and gauge potentials, screen separately
  - screen string potential by 1-d form, gauge by Debye form:

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

    with screening mass $\mu(T) = 1/r_D(T)$
  - for $r \to \infty$, temperature-dependent string breaking form

$$V(r,T) = \frac{\sigma}{\mu(T)}$$

  - take screening mass from lattice estimates $\mu(T) \simeq 4\,T$ for $T > 0$
  - solve Schrödinger equation: with increasing T, bound state i disappears at some $\mu_i(T) = \mu(T_i)$

– **charmonia:**

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

Critique:

$*$ **screening of sum = sum of screening**

$*$ **1-d string screening form**

$*$ **very rough** $\mu(T)$ **does not include variation near** T_c

- **Free energy appproximation** — Digal, Petreczky, HS (2001)

  – **assume potential ∼ lattice free energy**

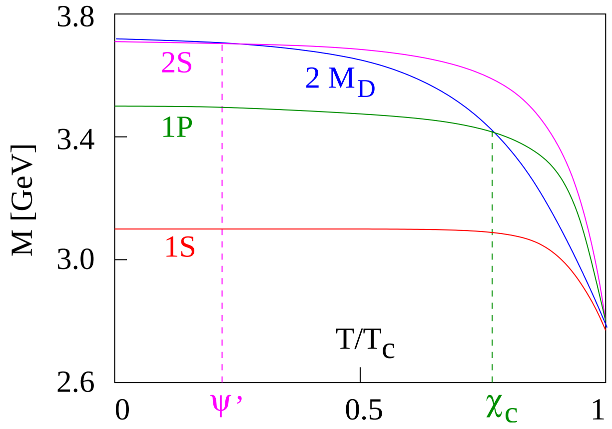
  $$V(r,T) = F(r,T) - T(\partial F/\partial T) \simeq F(r,T)$$

  with $N_f = 2$ **lattice results for** $F(r,T)$**,**
  i.e., neglect entropy term

  – $V(\infty, T)$ **determines open charm threshold**

  $$2M_D(T) \simeq 2m_c + V(\infty, T)$$

– obtain charmonium masses by solving Schrödinger eq'n with lattice $V(r,T) \simeq F(r,T)$



compare to $2M_D$:
dissociation for $M_i > 2M_D$

– charmonia:

ψ' dissociated at $T \simeq 0.2\ T_c$

χ_c dissociated at $T \simeq 0.8\ T_c$

J/ψ survives up to $T \gtrsim T_c$

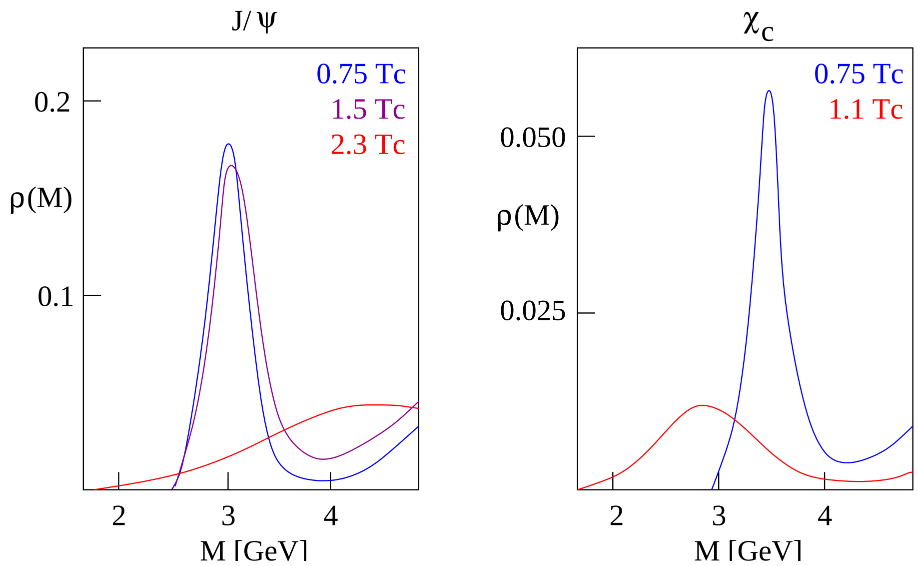
earlier dissociation: M_D mass drops faster than $M_{c\bar{c}}$

Critique:

* neglect of entropy term reduces $V(r,T)$, binding energy
* lattice data, parametrization applicable only for $T \leq T_c$
* no information about ground state dissociation in QGP

3.3 Direct Lattice Studies of Charmonia in Media

Determination of $c\bar{c}$ spectral functions from thermal hadron correlation functions in quenched QCD **Karsch et al., Hatsuda et al., (2003)**



charmonia:

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

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

Critique:

- **dynamical quarks (unquenching) can change results**
- **no physical widths calculated so far**
- **temperature scans needed to determine exact dissociation points**

3.4 Debye-Hückel Theory of Screening

Potential theory approach:
given $Q\bar{Q}$ free energy $F(r)$, what screening form in media?

Debye-Hückel theory: framework for general $F(r)$

solved for $F(r) \sim r^{\eta}$ with general η in d space dimensions

V. V. Dixit (1990)

apply to Cornell potential **S. Digal, O. Kaczmarek, F. Karsch, HS (2005)**

assumption: separate treatment of string and gauge contributions

$$F(r, T=0) = \sigma r - \frac{\alpha}{r}$$

becomes at finite T

$$F(r,T) = \sigma r f_s(r,T) - \frac{\alpha}{r} f_c(r,T)$$

with

$$\begin{aligned} f_s(r,T) &= f_c(r,T) = 1 \quad \text{for } r \longrightarrow 0 \\ f_s(r,T) &= f_c(r,T) = 1 \quad \text{for } T \longrightarrow 0 \end{aligned}$$

Result:

$$F_c(r,T) = -\frac{\alpha}{r}\left[e^{-\mu r} + \mu r\right]$$

for gauge (Coulomb) term, and

$$F_s(r,T) = \frac{\sigma}{\mu}\left[\frac{\Gamma\left(1/4\right)}{2^{3/2}\Gamma\left(3/4\right)} - \frac{\sqrt{\mu r}}{2^{3/4}\Gamma\left(3/4\right)} K_{1/4}[(\mu r)^2]\right]$$

for string term screening

NB: for $d = 3$ Gaussian, for $d = 1$ exponential cut-off in $x = \mu r$

Debye-Hückel theory correct for dilute medium of charges

dense media, quark recombination, string breaking: $\Rightarrow$ corrections

to include, assume $K_{1/4}(x^2) \rightarrow K_{1/4}(x^2 + \kappa x^4)$, $\kappa(T) \rightarrow 0$ for large T

$\Rightarrow$ **<u>temperature dependence of $Q\bar{Q}$ free energy</u>**

$$F(r,T) \;=\; \frac{\sigma}{\mu}\left[\frac{\Gamma(1/4)}{2^{3/2}\Gamma(3/4)} - \frac{\sqrt{x}}{2^{3/4}\Gamma(3/4)}K_{1/4}(x^2+\kappa x^4)\right] - \frac{\alpha}{r}\left[e^{-x}+x\right]$$

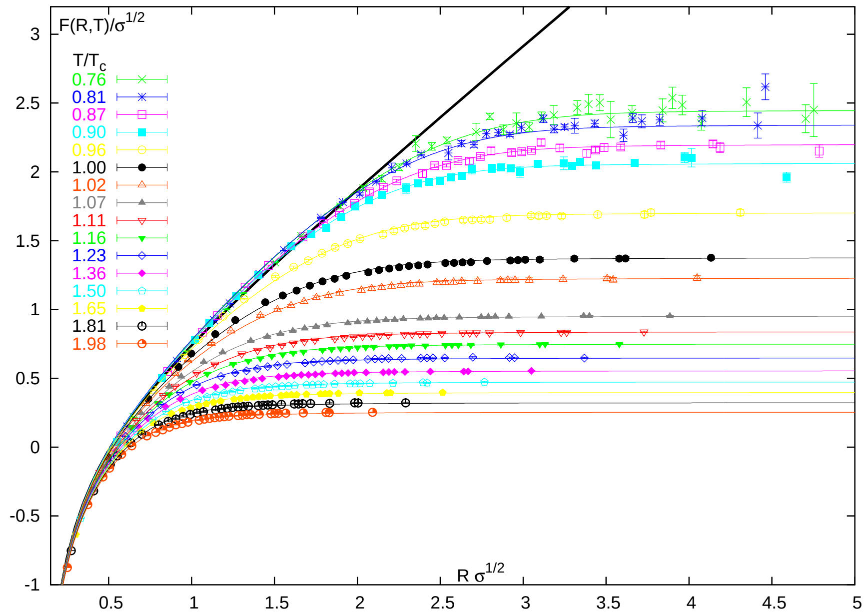
resulting $F(r \rightarrow \infty, T)$ depends only on $\mu(T)$:

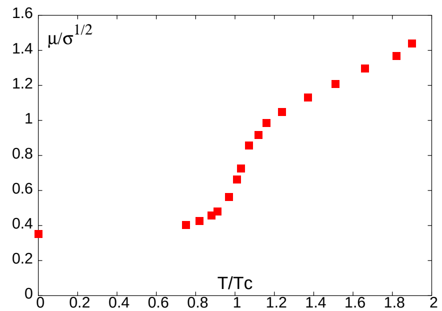
$$F(T) = \frac{\sigma}{\mu(T)}\frac{\Gamma\left(1/4\right)}{2^{3/2}\Gamma\left(3/4\right)} - \alpha\mu(T)$$

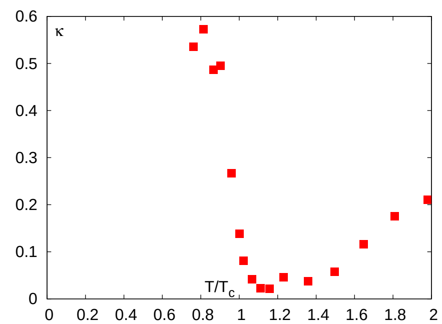
use lattice data for $F(\infty, T)$ determine $\mu(T)$

then one-parameter fit in $\kappa(T)$ for general $F(r,T)$

result: excellent parametrization of $F(r,T)$ for all r, $0 \leq T \leq 2\ T_c$


F(R,T)/σ^1/2
T/T_c
0.76
0.81
0.87
0.90
0.96
1.00
1.02
1.07
1.11
1.16
1.23
1.36
1.50
1.65
1.81
1.98
R σ^1/2


μ/σ^1/2
T/Tc


κ
T/T_c

With $F(r,T)$ given, use

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

to get $V(r,T)$, then Schrödinger equ'n $\rightarrow$ quarkonium spectroscopy.

3.5 Outlook

$\exists$ two viable methods to determine the in-medium behaviour of quarkonia and specify the respective dissociation points

- **direct lattice calculations of spectral functions**
- **lattice calculations of free energy $\rightarrow$ $V(r,T)$ for potential theory calculations**

Calculations with both methods in progress, excellent cross-check to get

precise determination of temperature (energy density) of thermal QCD medium in terms of quarkonium dissociation

4. Dynamics of Quarkonium Dissociation

Study of global medium effects on quarkonium probe $\Rightarrow$ only hot deconfined medium can dissociate ground state quarkonia

deconfinend medium: constituents are unbound partons
confined medium: constituents are hadronic "comovers"

why can collisions with hadrons not dissociate J/ψ, Υ, ... ?

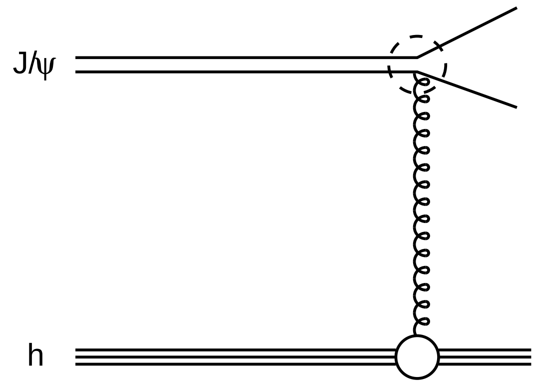
Collision Dissociation of Quarkonia

Bhanot & Peskin (1979), Kharzeev & HS (1994)

consider J/ψ dissociation:

- J/ψ **is small ($r_{J/\psi} \sim 0.2$ fm), can only be resolved by hard probes**
- J/ψ **is tightly bound ($2M_D - M_{J/\psi} \sim 0.6$ GeV), needs hard probe to dissociate**

consider hadron dissociation of 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, $g(x) \sim (1-x)^3$, leads to

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

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

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

$\Rightarrow$ hadron dissociation impossible

gluons in the hadronic constituents of confined matter are too soft to dissociate J/ψ

in deconfined medium,

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

so that for $T \geq 1.15\ T_c$**, enough energy to overcome** J/ψ **binding**

More quantitative:

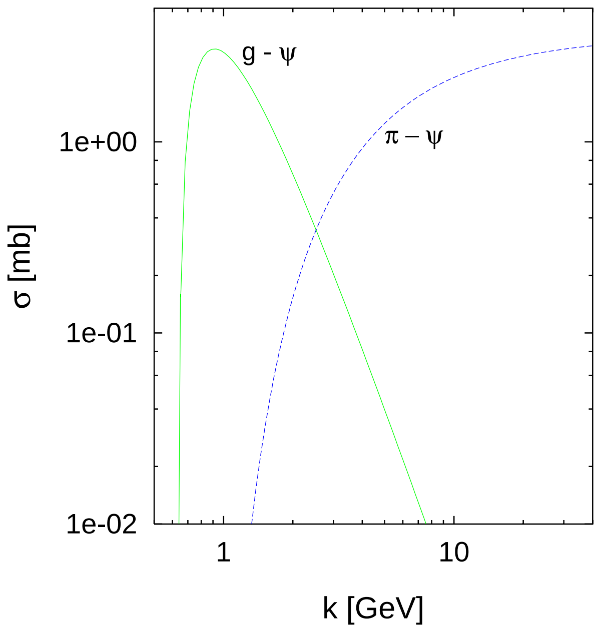
gluon dissociation (QCD photo effect)

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

with $\Delta E_{J/\psi} = 2M_D - M_{J/\psi}$
convolution with meson PDF gives

$$\sigma_{h-J/\psi} \simeq \sigma_{\text{geom}}(1 - \lambda_0/\lambda)^{n+3.5}$$

with $\lambda \simeq (s - M_\psi^2)/M_\psi$ **and**
$\lambda_0 \simeq (M_h + \Delta E_\psi)$



5. Quarkonium Dissociation in Nuclear Collisions

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

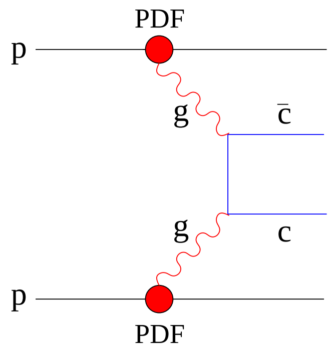
How to produce the charmonium to be put into the medium?

5.1 Quarkonium Production in Hadronic Collisions

$c\bar{c}$ **production:**

hard process calculated in perturbative QCD

with PDF determined from DIS



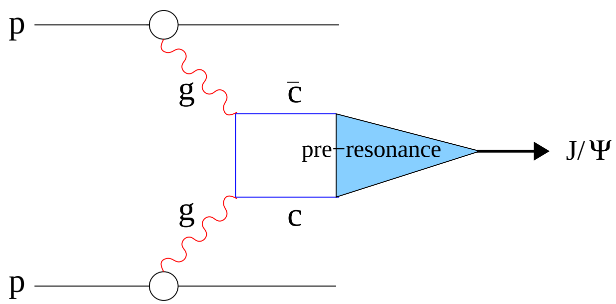
fixed fraction of subthreshold $c\bar{c}$ **production** $\Rightarrow$ **charmonium**

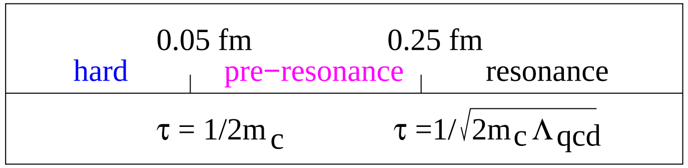
colour evaporation model (1975)

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

energy-independent fractions f_i for all charmonium states i (same for $b\bar{b}$ and bottomonium) $\Rightarrow$ correct quarkonium cross sections

J/ψ formation and time scales:





When is the medium formed (thermalization time) relative to the quarkonium evolution? Role of nuclear matter?

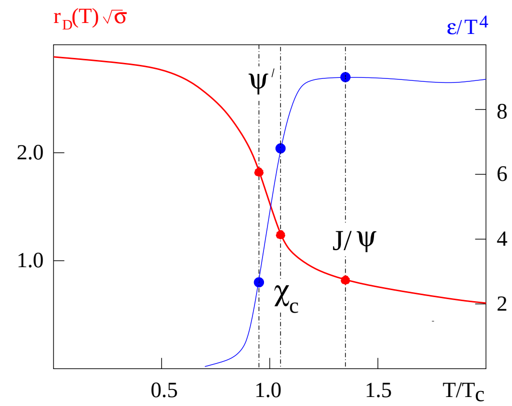
In any analysis, must consider the in-medium behaviour of both pre-resonance and resonance quarkonium states

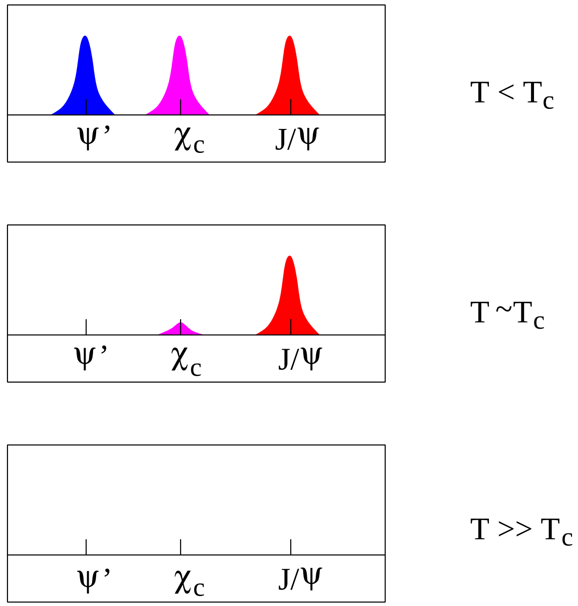
Assume: nuclear absorption, pre-resonance effects can be accounted for; what remains?

5.2 Sequential Quarkonium Suppression

J/ψ production in hadronic collisions:

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





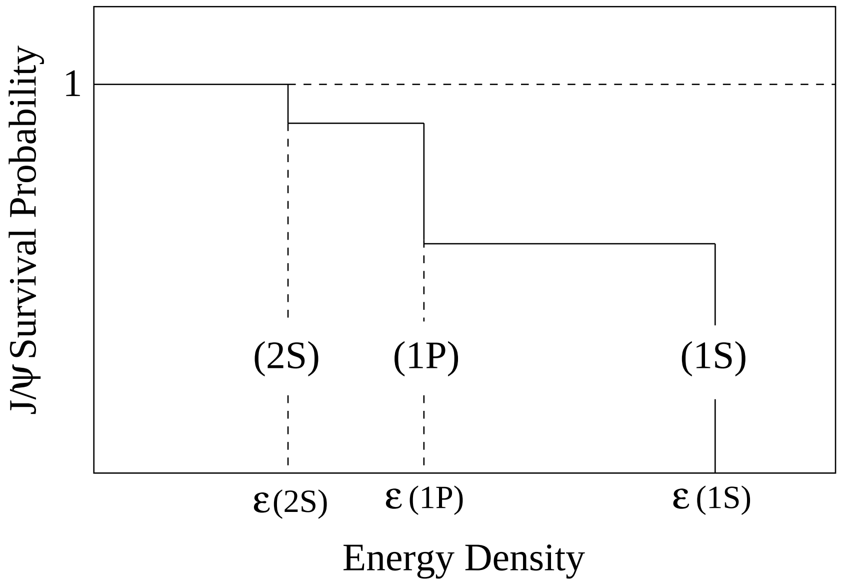
In a thermal QCD medium, higher excited states are absorbed at lower temperatures, energy densities: first ψ', then χ_c, last ψ'

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 onset values predicted by QCD

6. Conclusions

The study of quarkonium spectra provides in statistical QCD an unambiguous method to determine temperature or energy density of strongly interacting matter.

Whether it can also do that in nuclear collisions remains another matter.

We have not addressed here

- **whether nuclear collisions produce thermal media,**
- **possible initial state dissociation of quarkonia (parton percolation/saturation),**
- **the experimental results and their analyis, including the determination of pre-resonance nuclear absorption or the information obtained from transverse momentum spectra.**

There is much interesting work left to do...