Quarkonia and B_c Mesons at Finite Temperature and in Heavy Ion Collisions

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June 9, 2015

The experimental status of J/ψ in heavy ion collisions

Dynamics of heavy quarks and quarkonium

Quarkonium as an open quantum system

What evidence exists concerning $Q\bar{Q}$ dynamics?

1980s: After perturbative calculations of QCD at high temperatures sparked interest in quark-gluon plasma, lattice QCD was studied at finite temperature.

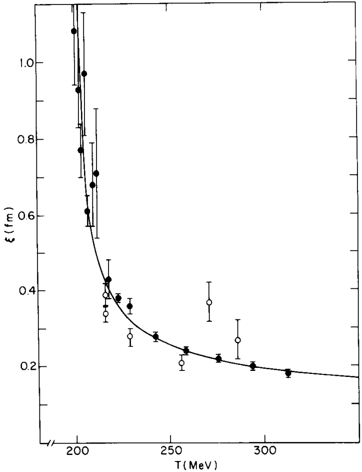
Kanaya and Satz: The Polyakov loop correlation function

$$\begin{aligned} \Gamma(r,T) &= \langle L(0)L(r)\rangle - \langle L(r)\rangle^2 \\ &\sim \exp(-r/\xi(T)) \text{ at high T and large r.} \end{aligned}$$

Usual physical interpretation: what is the free energy of two infinitely heavy quarks in pure gauge theory?

Lattice gauge theory at high temperatures

ξ at high temperatures:



Matsui and Satz, 1986

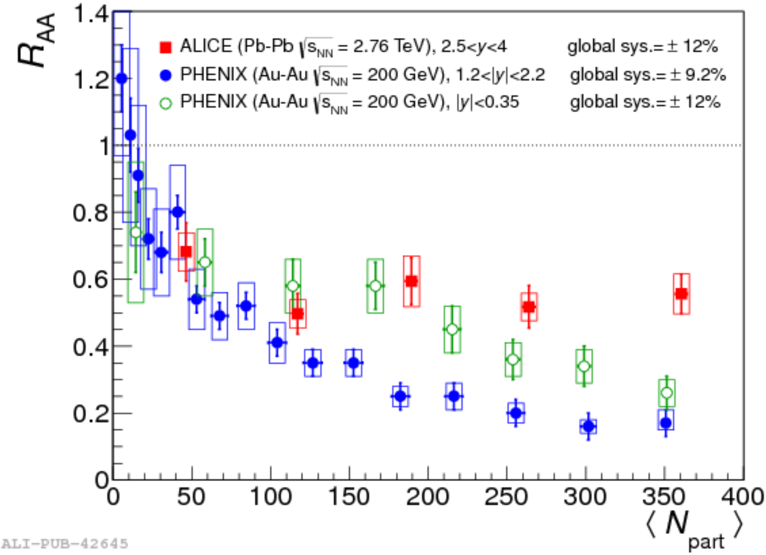
The J/ψ particle is *quarkonium*: a $c\bar{c}$ bound state described phenomenologically with the Cornell potential:

$$V_C(r) = -\alpha/r + \sigma r.$$

$\Gamma(r)$ at zero T behaves roughly like $\exp(-V_C(r)/T)$.
$\xi(T) \to 0$: $c\bar{c}$ bound states change with T and above some T_c, no longer exist.

Pure gauge theory suggests no J/ψ states can exist above $1.2T_c$; theories with dynamical quarks should not allow quarkonia even at lower temperatures.

The experimental status of J/ψ in HICs



A single heavy quark above deconfinement

When $M \gg T, p$, the dynamics described by $3\kappa = \int d^3q |\mathbf{q}|^2 \frac{d\Gamma}{dq^3}$.

How to determine?

- HTL effective theory (poor convergence from LO to NLO for realistic α_s) (Moore and Teaney, Caron-Huot and Moore).
- Lattice QCD (analytic continuation of Euclidean correlators difficult).
- AdS/CFT for strongly-coupled gauge theories (not QCD) (Gubser, Casalderrey-Solana and Teaney).

Current phenomenology of heavy quark elliptic flow gives $3\kappa \approx 4T^3$, larger than LO HTL estimates but smaller than in strongly-coupled $\mathcal{N} = 4$ SYM theory.

A single heavy quark above deconfinement

When $M \gg T$ and $\gamma v \lesssim 1$, dynamics described by the relativistic Langevin equation:

$$\frac{dp^i}{dt} = -\eta p^i + \xi^i(t), \quad \left\langle \xi^i(t)\xi^j(t')\right\rangle = \kappa\delta^{ij}\delta(t-t').$$

Requiring $\langle p^2(t)\rangle$ to approach the thermal value gives the Einstein relation:

$$\eta = \kappa/2MT$$

Modelling *quarkonium* with Langevin dynamics

Loosely bound quarkonium can also be described with a relativistic Langevin equation. For each quark J in a pair forming quarkonium,

$$\frac{dp_J^i}{dt} = -\eta p_J^i + \xi_J^i(t) - \frac{\partial V(\mathbf{x}_K)}{\partial x_J^i},$$

$$\left\langle \xi_J^i(t) \xi_K^j(t') \right\rangle = \kappa \delta^{ij} \delta^{JK} \delta(t - t').$$

Disassociation of J/ψ now dynamical, includes the physics of potentials with both real and imaginary parts. A satisfactory description at strong coupling.

Heavy quark hadronization at freeze-out

In elementary collisions, *color evaporation model*: if $M < 2M_D$, where $M = \sqrt{(p_1 + p_2)^2}$, the heavy quarks form a quarkonium state. Simple, successful across experiments (color singlet model underpredicts, color octet (NRQCD) model has many parameters).

However, in AA collisions, how to take into account non-trivial evolution in momentum *and position*?

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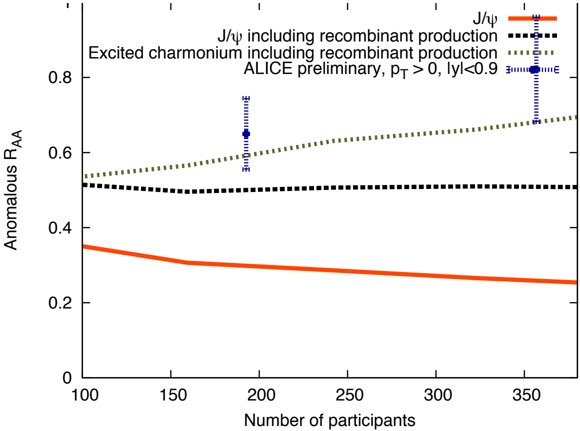
However, in AA collisions, how to take into account non-trivial evolution in momentum *and position*?

Modified color evaporation model: $M = \sqrt{(p_1 + p_2)^2} + V_{\mathrm{Cornell}}(r_{\mathrm{CM}})$.

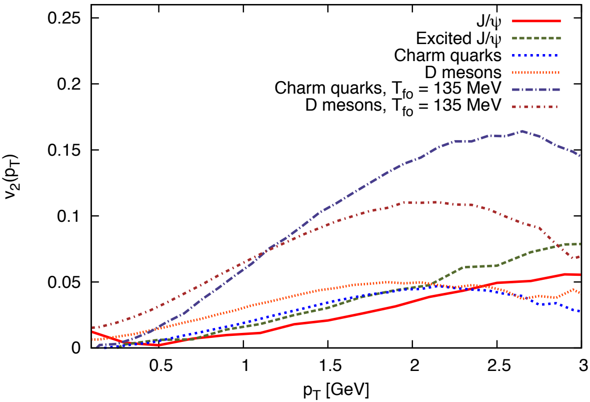
Useful for calculating recombinant production (Q and $\bar{Q}$ from separate perturbative processes) and B_c yields.

R_{AA} for J/ψ and MARTINI



The surviving component of the J/ψ yield not enough to explain the total yield. Including recombinant production is needed.

D and J/ψ $v_2(p_T)$ with MARTINI

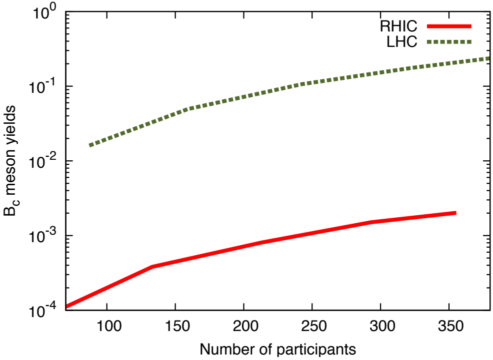


Flow of J/ψ and D mesons explained with different kinetic freeze-out temperatures for the different mesons (sequential freeze-out).
$T_{\mathrm{kin}} = 190\ \mathrm{MeV}$ consistent with Euclidean quarkonium correlators.

B_c meson production

B_c mesons are predicted for heavy ion collisions (Schroedter et al. 2000); the yields for these states in elementary collisions are small.

- Mostly produced recombinantly, testing models for in-medium hadronization.
- Sensitive to heavy quark densities at hadronization; an indirect probe of T_{ch} for quarkonia.
- Measurements at RHIC and the LHC *complementary*.



J/ψ properties from quarkonium spectral functions

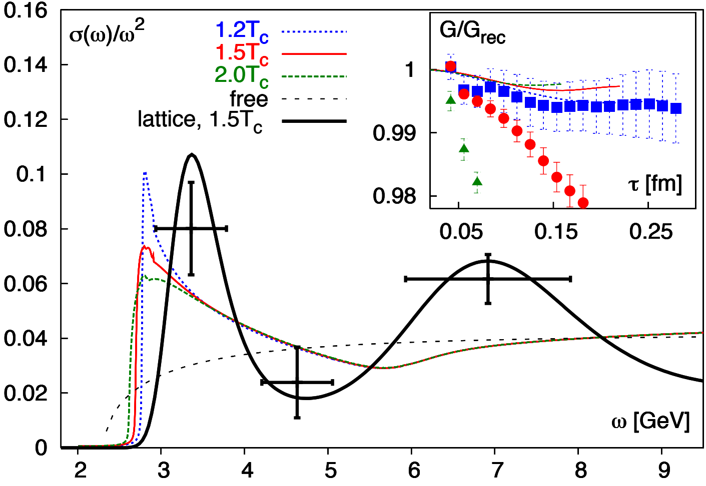
It is possible to use lattice QCD to probe quarkonium melting more directly that with $\Gamma(r, T)$, by examining correlation functions of $J^\mu = \bar{\psi}(x)\gamma^\mu\psi(x)$.

Mocsy and Petreczky: This current's autocorrelation function at finite temperature is related to the spectral function for quarkonium in the vector channel:

$$G(\tau) = \int d^3x \, \langle J^\mu(\mathbf{x}, \tau) J_\mu(\mathbf{0}, 0)\rangle = \int d\omega \, \frac{\cos(\omega(\tau - \beta/2))}{\sin(\omega\beta/2)} \sigma(\omega);$$

and through this, to the existence of bound states and resonances. Are changes in $G(\tau)$ with decreasing β caused by changes in the spectral function? If yes, how?

J/ψ properties from quarkonium spectral functions



Quarkonium as an open quantum system

What dynamics can explain these changes in the quarkonium spectral functions, specifically, resonances persisting with a decreased lifetime above T_c?

Brownian motion for single heavy quarks successful for describing flow of D mesons: the relativistic Langevin equation

$$\frac{dp^i}{dt} = -\eta p^i + \xi^i, \langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$$

describes heavy quarks at high temperature as a stochastic process.

The spatial diffusion $2\pi TD \sim 3$ in order to explain the significant flow of charm at the RHIC: much smaller than perturbative estimates.

A unified phenomenological description of heavy quark flow, J/ψ suppression, and quarkonium spectral functions is better than a phenomenological description of only one of these.

Quarkonium as an open quantum system

How can Brownian motion be quantized? Feynman's reduced density matrix: suppose a heavy particle interacts with a light degree of freedom we don't care about:

$$\begin{aligned} L &= L_S + L_I; \\ L_S &= \frac{1}{2}M\dot{x}^2 - V(x), \\ L_I &= \frac{1}{2}m\dot{r}^2 - \frac{1}{2}m\omega^2 r^2 - Cxr. \end{aligned}$$

Taking the trace over the light degree of freedom gives

$$\rho_{red}(x_i, x_f, \beta) \equiv \int dr \rho(x_i, r; x_f, r; \beta) = \int_{x(0)=x_i}^{x(\beta)=x_f} \mathcal{D}x$$

$$\exp(-S_S^E[x] + \sum_k \frac{C_k^2}{2m\omega_k \sinh(\frac{\omega_k \beta}{2})} \int_0^\beta d\tau \int_0^\tau ds\, x(\tau)x(s) \cosh\left[\omega_k \left(\tau - s - \beta/2\right)\right]).$$

Quarkonium as an open quantum system

Caldeira and Leggett: A continuous density of states

$$C^2(\omega)\rho_D(\omega) = \begin{cases} \frac{2m\eta\omega^2}{\pi} & \text{if } \omega < \Omega \\ 0 & \text{if } \omega > \Omega \end{cases}$$

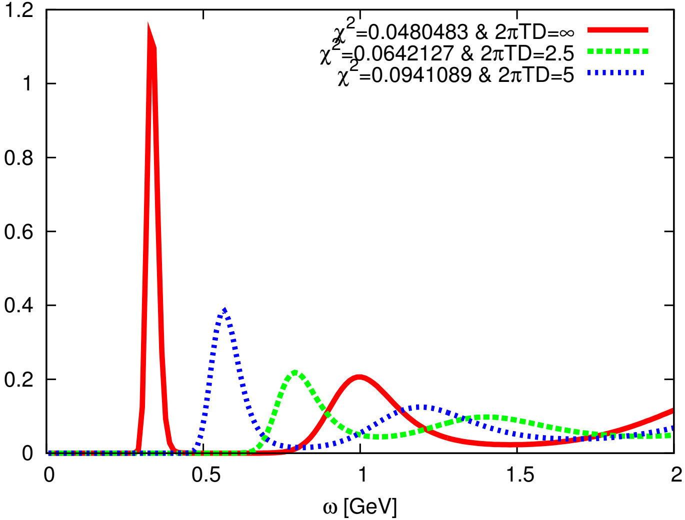
leads to the Langevin equation with drag coefficient η in the classical limit.
CY and Dusling: The reduced imaginary-time Green function

$$G_{\mathrm{red}}(x_f, x_i, \tau, \beta) = \sum_{n=-\infty}^{\infty} \langle x_f, |\tau + n\beta| | x_i, 0\rangle_{\mathrm{red}}$$

$$= \sum_{n=-\infty}^{\infty} \int_{x(0)=x_i}^{x(|\tau+n\beta|)=x_f} \mathcal{D}x \ \exp\left(- \int_0^{|\tau+n\beta|} d\tau' \left[\frac{1}{2}M\dot{x}(\tau')^2 + V_R(x(\tau'))\right.\right.$$

$$\left.\left. - \frac{\eta}{2\pi} \int_0^{\tau'} ds \ \dot{x}(\tau')\dot{x}(s) \log\left[\frac{\sin(\frac{\pi}{2}\frac{\tau'-s}{|\tau+n\beta|})}{\sin(\frac{\pi}{2}\frac{\tau'+s}{|\tau+n\beta|})}\right]\right]\right).$$

Is Langevin dynamics consistent with changes to the charmonium spectral functions?



Back to the main question: what evidence exists concerning $Q\bar{Q}$ dynamics?

It remains unclear:

- Lattice QCD reliable for correlation functions (indirectly interesting physically), difficult to extract spectral functions
- Experimental results are of fundamental importance but include multiple effects (modified initial production, early time dynamics, recombination,...)
- Perturbative QCD (NRQCD) reliable in limits of dubious significance for HICs
- AdS/CFT of questionable significance in *any* limit

Conclusions

- In ~ 10 years, the J/ψ went from being an important clue in the development of the Standard Model to a probe for temperature in heavy-ion collisions.
- Langevin dynamics makes predictions about quarkonium spectral functions above deconfinement and will help untangle the roles of changing potentials and interaction with the medium.

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