Melting of Open Charm
and
Screening properties of Charmonia

Swagato Mukherjee

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Deconfined open charm in HIC?

partonic nature of charm degrees of freedom

✔ when do the open charm hadrons start to deconfine?

✔ role of chiral crossover?

✔ what are the open charm hadrons during the freeze-out?

Lattice QCD
Role of chiral crossover on charm deconfinement?

Chiral crossover:
\[ T_c = 154 \pm 9 \text{ MeV} \]


2nd order quark number fluctuations

4th order quark number fluctuations

liberation of quark DoF: \( N^0_c \rightarrow N_c \)

rise in quark number fluctuations
Proper observables: conserved number correlations

probe quantum numbers associated with the DoF

baryon(B)/charge(Q)/strangeness(S)/charm(C) correlations

\[
\chi_{mn}^{XY} = \left. \frac{\partial^{m+n} P}{\partial^m \hat{\mu}_X \partial^n \hat{\mu}_Y} \right|_{\mu_X = \mu_Y = 0}
\]

\[
\chi_0^n \equiv \chi^n_Y
\]

\[
P = \frac{p}{T^4}
\]

\[
\hat{\mu}_X = \frac{\mu_X}{T}
\]

\[
\hat{m} = \frac{m}{T}
\]

hadron gas:

\[
P_h \sim f(\hat{m}_h) \exp \left[ -B_h \hat{\mu}_B - Q_h \hat{\mu}_Q - S_h \hat{\mu}_S - C_h \hat{\mu}_C \right]
\]

\[
\chi_{nm}^{BX} = B^n \times F(\hat{m})
\]

\[
\chi_{nm}^{BX} - \chi_{km}^{BX} = (B^n - B^k) \times F(\hat{m})
\]

depends on hadron spectra

= 0 when B=1, DoF are hadronic

=\neq 0 when B=1/3, DoF are quark like

irrespective of the hadron spectra
Example: strangeness

\[ S_1 = \chi_{31}^{BS} - \chi_{11}^{BS} \]

if sDoF are hadrons with S=1,2,3 and B=0,1

\[ S_1 = \chi_{31}^{BS} - \chi_{11}^{BS} = (B^3 - B) \times f(m^\text{had}_S) \]

depends on the hadron spectrum

\[ S_1 = 0 \text{ for } B=0,1 \]

irrespective of the hadron spectrum

if sDoF are quarks then B=1/3: \( S_1 \neq 0 \)

similarly:

\[ \chi^B_4 - \chi^B_2 = (B^4 - B^2) \times f(m^\text{had}_{u,d,S}) \]
Example: strangeness

\[
\chi_{31}^{BS} - \chi_{11}^{BS} - (\chi_{S2}^{S} - \chi_{S4}^{S})/3 - 2\chi_{13}^{BS} - 4\chi_{22}^{BS} - 2\chi_{31}^{BS} - 2
\]

sDoF appears with fractional baryon number

deconfinement & chiral crossovers in same temperature range

Charm DoF

hadron gas: \( P^C = P^C_M \cosh[\hat{\mu}_C] + \sum_{k=1,2,3} P^C_B \cosh[B \hat{\mu}_B + k \hat{\mu}_C] \)

\[ P^C_M \] : partial pressure of \(|C| \neq 0\) mesons
\[ P^C_B \] : partial pressure of \(|C| = k\) baryons

\[
\chi^{BC}_{mn} = B^m P_B^{C=1} + B^m 2^n P_B^{C=2} + B^m 3^n P_B^{C=3} \sim B^m P_B^{C=1}
\]

\( \chi^{BC}_{mn} = B^m P_B^{C=1} \)

relative contribution of \( C=2,3\) baryons negligible: x1000 suppressed for \( T \sim 150 \text{ MeV} \)

weakly interacting charm quasi-quarks: \( P^C = F(m_c) \cosh[B \hat{\mu}_B + \hat{\mu}_C] \)

\[ \chi^{BC}_{mn} = B^m F(m_c) \]

\[
\frac{\chi^{BC}_{mn}}{\chi^{BC}_{m+1,n-1}} = B^{-1} \quad \frac{\chi^{BC}_{mn}}{\chi^{BC}_{m,n+2}} = 1
\]

independent of mass spectra
Deconfinement of open charm baryons

\[ \chi_{mn}^{BC} = B^{-1} \]

\[ \chi_{m+1,n-1}^{BC} = 1 \]

Chiral crossover:
\( T_c = 154 \pm 9 \text{ MeV} \)

Deconfinement & chiral crossovers in same temperature range

Deconfinement of open charm mesons

hadron gas: $P^C_P = P^C_M \cosh[\hat{u}_C] + \sum_{k=1,2,3} P^C_{B} \cosh[\hat{u}_B + k\hat{u}_C]$

$\chi_{mn}^{BC} = P^C_{B} + 2^n P^C_{B} + 3^n P^C_{B} \approx P^C_{B}$

$\chi^C_k = P^C_M + P^C_{B} + 2^n P^C_{B} + 3^n P^C_{B} \approx P^C_M + P^C_{B}$

$P^C_M = \chi^C_2 - \chi^{BC}_{22} = \chi^C_4 - \chi^{BC}_{13}$

deconfinement & chiral crossovers in same temperature range
Flavor blind deconfinement?

\[
\chi_{BX}^{nm}/\chi_{BX}^{km} = B^{n-k}
\]

= 0 when \( B=1 \), DoF are hadronic

\( \neq 0 \) when \( B=1/3 \), DoF are quark like

Flavor blind deconfinement?

Flavor correlations: \( \chi_{mn}^{f_1 f_2} / \chi_{m+n}^{f_2} \)

\[
\chi_{mn}^{f_1 f_2} = \frac{\partial^{m+n} P}{\partial \hat{u}_{f_1}^m \partial \hat{u}_{f_2}^n}
\]

in deconfined phase gluon dominated interactions:
flavor blind

strong flavor correlations, but almost flavor blind

\( T_c \lesssim T \lesssim 2T_c \)
Flavor blind deconfinement?

Flavor correlations: \( \chi_{mn}^{f_1 f_2} / \chi_{m+n}^{f_2} \)

\[
\chi_{mn}^{f_1 f_2} = \frac{\partial^{m+n} \mathbf{P}}{\partial \hat{u}_{f_1}^m \partial \hat{u}_{f_2}^n}
\]

in deconfined phase gluon dominated interactions:
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\( T_c \lesssim T \lesssim 2T_c \)

strong flavor correlations, but almost flavor blind
Probing open charm hadron spectrum

hadron gas: \( P^C = P_M^C \cosh[\hat{\mu}_C] + \sum_{k=1,2,3} P_B^{C=k} \cosh[\hat{\mu}_B + k\hat{\mu}_C] \)

- \( P^C_M \): partial pressure of \(|C| \neq 0\) mesons
- \( P^C_{B=k} \): partial pressure of \(|C|=k\) baryons

\[
\chi^{BC}_{mn} = P_B^{C=1} + 2^n P_B^{C=2} + 3^n P_B^{C=3} \approx P_B^{C=1}
\]

\[
\chi^C_k = P_M^C + P_B^{C=1} + 2^n P_B^{C=2} + 3^n P_B^{C=3} \approx P_M^C + P_B^{C=1}
\]

\[
\frac{\chi^{BC}_{13}}{(\chi^C_4 - \chi^{BC}_{13})} = \frac{P_B^{C=1}}{P_M^C}
\]
Probing open charm hadron spectrum

hadronic pressure: $P^C = \sum_{h \in \text{all hadrons}} P_h$

expt. observed hadrons + unobserved ones

Probing open charm hadron spectrum

hadronic pressure: \( P^C = \sum_{h \in \text{all hadrons}} P_h \)  

\[
\sum_{h \in \text{all hadrons}} P_h \quad \text{expt. observed hadrons + unobserved ones}
\]

Quark Model

LQCD


Padmanath et al.: arXiv:1311.4806 [hep-lat]
Probing open charm hadron spectrum

$P_{B}^{C=1} / P_{M}^{C}$

$P_{B}^{C=1}$: partial pressure of $|C|=1$ baryons

$P_{M}^{C}$: partial pressure of $C=/=0$ mesons
Signature of unobserved charm baryons

relative contributions:

- charm baryons to charmed mesons
\[ \chi_{13}^{BC} / (\chi_4^C - \chi_{13}^{BC}) = P_{B}^{C=1} / P_{M}^C \]

- charged charm baryons to charged charmed mesons

- strange charm baryons to strange charmed mesons

signatures of additional, unobserved charm baryons from QCD thermodynamics
Charmonia melting from LQCD via analytic continuation

temporal correlation function of charmonia
always limited to physical distance of $1/T$

$$C(\tau, T) = \int_0^\infty \frac{d\omega}{2\pi} \sigma(\omega, T) \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)}$$

reconstruct through analytic continuation: Euclidean $\rightarrow$ Minkowski

ill-posed: Bayesian (maximum entropy) method

require lattices with vary large temporal extents

complementary avenue: spatial correlation functions
Spatial correlations of charmonia

spatial (screening) correlation functions of charmonia

\[ C(z, T) = \int_0^\infty \frac{2\, d\omega}{\omega} \int_{-\infty}^{\infty} dp_z e^{izp_z} \sigma(\omega, p_z, T) \]

temporal correlation function: \[ C(\tau, T) = \int_0^\infty \frac{d\omega}{2\pi} \sigma(\omega, T) \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)} \]

spatial correlation function:

✔ is not limited to the physical distance of 1/T

✔ transport-type zero mode contribution: \( \sigma(\omega) \sim \omega \delta(\omega) \)

does not lead to a non-decaying constant at large distances, only generates a contact term

✔ the kernel is T independent \( \rightarrow \) direct comparison with T=0, thermal modification of spectral function itself
Charm meson spectra at $T=0$
In-medium charm mesons: $J/\Psi$ vs. $D_s^*$

Ratios of $T>0$ to $T=0$ spatial correlators

$G_{NO}(z,T)/G_{NO}(z,0)$, $c\bar{c}$, $1^-$

$G_{NO}(z,T)/G_{NO}(z,0)$, $s\bar{c}$, $1^-$

$T$ [MeV]
- 149
- 171
- 197
- 220
- 248

$z$ [fm]
- 0.0
- 0.5
- 1.0
- 1.5
- 2.0

$J/\Psi$

$D_s^*$

Ratios of $T>0$ to $T=0$ spatial correlators

$G_{NO}(z)/G_{NO}(z,0)$ $\neq=1$ $\leftarrow$ thermal modification of the spectral function
In-medium charm mesons: $J/\Psi$ vs. $D_s^*$

thermal modifications are already significant for $T \gtrsim T_c$?

remember: open charm mesons starts to deconfine at $T \simeq T_c$
In-medium charm mesons: $\eta_c$ vs. $D_s$
In-medium charm mesons: $\eta_c$ vs. $D_s$

Thermal modifications are already significant for $T \gtrsim T_c$?
Screening masses of charmonia

\[ C(z, T) = \int_0^\infty \frac{2d\omega}{\omega} \int_{-\infty}^{\infty} d\rho \, e^{iz\rho} \sigma(\omega, p_z, T) \]

high T, non-interacting quark–antiquark pair:

\[ C(z \to \infty, T) \sim e^{-Mz} \]

\[ M : \text{screening mass} \]

\[ M = 2 \sqrt{\left(\frac{\pi}{2} T\right)^2 + m_c^2} \]

low T, well-defined mesonic bound state:

\[ \sigma(\omega, p_z) \sim \delta\left(\omega^2 - p_z^2 - m_{\text{mes}}^2\right) \]

\[ M = m_{\text{mes}} \]

a trick: one can study the onset of T dependence of M more clearly by imposing a periodic temporal boundary conditions for the valence charm quarks along with the usual anti-periodic ones

high T, no minimal Matsubara mode:

\[ M = 2m_c \]

low T, bosonic meson bound states insensitive to fermionic b.c at the quark level:

\[ M = m_{\text{mes}} \]
Screening masses of 1S charmonia

\[ \Delta M(T) [\text{MeV}], \bar{c}\bar{c} \]

\[ \Delta M(T) = M_{\text{scr}}(T) - m_{\text{mes}}(0) \]

'proxy' for mass shift
Screening masses of 1S charmonia

\[ \frac{A(T)}{A(T=0)} \]

- \( s\bar{s} \)
- \( s\bar{c} \)
- \( c\bar{c} \)

\( \Phi \)

\( D_s^* \)

\( J/\Psi \)

ratio of amplitudes \( \sim |\psi(0, T)|^2 / |\psi(0,0)|^2 \)

'proxy' for broadening
In-medium 1P charmonia: $\chi_{c_0}$ vs. J/$\Psi$

thermal modifications are already significant for $T \lesssim T_c$?
In-medium 1P charmonia: $\chi_{c_1}$ vs. $J/\Psi$

thermal modifications are already significant for $T \approx T_c$?
open charm hadrons starts to deconfine at $T \approx T_c$

hits for additional, unobserved charmed baryons from QCD thermodynamics

thermal modifications of 1S charmonia may be significant already for $T \gtrsim T_c$

thermal modifications of 1P charmonia may be significant already for $T \lesssim T_c$