Review of EFT Treatment of Quarkonium at Finite Temperature

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in collaboration with
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Confinement X, Garching, 08.10.2012
The QGP and heavy-ion collisions

- Heavy-ion collisions: experimental investigation of the deconfined phase of the diagram

- Characterization of the medium through 2 classes of observables:
  - Bulk properties (hydro, flow, etc...)
  - Hard probes (jets, e/m probes, quarkonia...)

[Diagram showing the QGP transitions and phases, including critical points and hadronization processes.]
Quarkonium as a hard probe

\section*{J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION} \footnote{MATSUI}

T. MATSUI  
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

\and

H. SATZ  
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany
\and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

\begin{itemize}
  \item Colour screening leads to the disappearance of the bound state
  \item A suppressed J/ψ yield is observed in the dilepton channel
\end{itemize}

Matsui Satz \textbf{PLB178} (1986)
Quarkonium suppression in experiments

• Typical observable: the nuclear modification factor

\[ R_{AA} = \frac{Yield_{AA}}{Yield_{pp} \times N_{bin}} \]

• \( R_{AA} \neq 1 \Rightarrow \) deviations from binary scaling. Causes:
  
  • Cold Nuclear Matter effects (affect production and early stages). Talk by R. Vogt on Thursday
  
  • Hot Medium effects, such as screening. Reduce \( R_{AA} \)
  
  • Recombination effects. Increase \( R_{AA} \)
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Charmonium suppression in experiments

- $J/\psi$ suppression has been measured at SPS, RHIC and now LHC. SPS~RHIC

![Graphs showing $R_{AA}$ vs $N_{part}$ and $p_T$ for $J/\psi$ suppression]

Scomparin QM2012

CMS-HIN-12-014
Bottomonium at the LHC: the new frontier

- First quality data on the $\Upsilon$ family from CMS

Sequential suppression of $\Upsilon(1S)$ and $\Upsilon(2S)$

CMS, 1208.2826
Overview of dissociation
Overview of dissociation

- Matsui/Satz: dissociation induced by colour screening of the interaction
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\[ V(r) \sim -\alpha_s \frac{e^{-m_D r}}{r} \]

\[ r \sim \frac{1}{m_D} \quad \text{Bound state dissolves} \]
Overview of dissociation

- Matsui/Satz: dissociation induced by colour screening of the interaction

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\[ r \sim \frac{1}{m_D} \rightarrow \text{Bound state dissolves} \]

- Since then, dissociation has been studied with potential models, lattice spectral functions, AdS/CFT and now with EFTs
• **Assume** Schrödinger equation, all medium effects in a $T$-dependent potential

$$i\partial_t\psi(r, T) = \left(-\frac{\nabla^2}{m} + V(r, T)\right)\psi(r, T)$$

• **Assume**

$$V = F_1 \equiv \langle \text{Tr} L(r) L^\dagger(0) \rangle$$

potential corresponding to a free energy or

$$V = U = F - TS$$

internal energy measured on the lattice.
Potential models

• Assume Schrödinger equation, all medium effects in a $T$-dependent potential

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potential corresponding to a free energy or

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• Issues:

• No clear relation to QCD and ab-initio derivation of the potential
• Gauge-dependent correlators
• Are all effects incorporated?

• Qualitative agreement on a picture of sequential dissociation
The complex potential

- Laine Philipsen Romatschke Tassler JHEP0703 (2007): analytical continuation of Wilson loop to large real time yields a complex potential in HTL-resummed PT

\[ V_{HTL} = -C_F \alpha_s \left( \frac{e^{-m_D r}}{r} + m_D - i \frac{2T}{m_D r} f(m_D r) \right) \]

- Re \( V \) ⇒ screening. Im \( V \) ⇒ width induced by collisions with the medium. Im \( V \gg\) Re \( V \)
The complex potential

- Phenomenological applications show the importance of the imaginary part

- Solving the Schrödinger equation for $V_{HTL}$: Laine JHEP0705, Burnier Laine Vepsäläinen JHEP0801 (2007)

- Hybrid potential model + Im $V$: Miao Mocsy Petreczky 1012.4443

Why EFTs?

- We have a system characterized by many scales and degrees of freedom
- With EFTs we can
  - Have a clear counting
  - Integrate out unnecessary DOFs
  - Obtain an effective description with potentials rigorously obtained from QCD, including all relevant effects for the desired accuracy
Why EFTs?

- An EFT is constructed by integrating out modes of energy and momentum larger than the cut-off ($\mu \ll \Lambda$)

$$\mathcal{L}_{\text{EFT}} = \sum_n c_n(\mu/\Lambda) \frac{O_n}{\Lambda^{d_n-4}}$$

- Low-energy operator/large scale

- Wilson coefficient
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Wilson coefficient

Low-energy operator/large scale

• The Wilson coefficient are obtained by matching Green’s functions in the two theories

• The procedure can be iterated \( \ldots \ll \mu_2 \ll \Lambda_2 \ll \mu_1 \ll \Lambda_1 \)
At zero temperature
Non-relativistic $Q\bar{Q}$ bound states are characterized by the hierarchy of the mass, momentum transfer and kinetic/binding energy scales.

At zero temperature:

$m \sim \langle \frac{1}{r} \rangle$

$m v \sim \langle \frac{1}{r} \rangle$

$m v^2 \sim E$
At zero temperature

- Non-relativistic $Q\bar{Q}$ bound states are characterized by the hierarchy of the mass, momentum transfer and kinetic/binding energy scales.

- Expand observables in terms of the ratio of the scales, $\nu$.

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\]

\[
mv^2 \sim E
\]
Non-relativistic $\bar{Q}Q$ bound states are characterized by the hierarchy of the mass, momentum transfer and kinetic/binding energy scales.

Expand observables in terms of the ratio of the scales, $\nu$.

Construct a hierarchy of EFTs. Equivalent to QCD order-by-order in the expansion parameter.
Integrating out the mass scale: 
Non-Relativistic QCD (NRQCD)

- The mass is integrated out and the theory becomes non-relativistic
- Factorization between contributions from the scale $m$ and from lower-energies
- Ideal for production and decay studies

$$m v \sim \left\langle \frac{1}{r} \right\rangle$$

$$m v^2 \sim E$$

$$\mathcal{L}_{NRQCD} = \sum_n c_n(\mu/m) \frac{O_n}{m^{d_n-4}}$$

Caswell Lepage **PLB167** (1986)
Bodwin Braaten Lepage **PRD51** (1995)
The scale $m v$: potential NRQCD (pNRQCD)

- Modes with momentum $m v$ are integrated out.
- This gives rise to non-local four-fermion operators. Their Wilson coefficients are the potentials, rigorously defined.
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- At weak coupling, $Q \bar{Q}$ DOFs are cast into colour-singlet and octet

$$\mathcal{L} = \mathcal{L}_{\text{light}} + \text{Tr} \left\{ S^\dagger \left[ i \partial_0 + \frac{\nabla^2}{m} - V_s \right] S + O^\dagger \left[ i D_0 + \frac{\nabla^2}{m} - V_o \right] O \right\}$$

$$+ \text{Tr} \left\{ O^\dagger r \cdot g E S + S^\dagger r \cdot g E O \right\} + \frac{1}{2} \text{Tr} \left\{ O^\dagger r \cdot g E O + O^\dagger O r \cdot g E \right\} + \ldots$$

Pineda Soto **NPPS64** (1998)
Brambilla Pineda Soto Vairo **NPB566** (2000)
The scale $mv$: potential NRQCD (pNRQCD)

- Modes with momentum $mv$ are integrated out
- This gives rise to non-local four-fermion operators. Their Wilson coefficients are the potentials, rigorously defined
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$$mv \sim \left\langle \frac{1}{r} \right\rangle$$

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The scale $mv$:

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$$m v \sim \langle \frac{1}{r} \rangle$$

$$m v^2 \sim E$$

$$\frac{1}{E - p^2/m - V(r)}$$
Bring in the medium

- The thermal medium introduces new scales in the physical problem
  - The temperature
  - The electric screening scale (Debye mass)
  - The magnetic screening scale (magnetic mass)
- In the weak coupling assumption these scales develop a hierarchy
The thermal medium introduces new scales in the physical problem:

- The temperature
- The electric screening scale (Debye mass) \( gT \sim m_D \)
- The magnetic screening scale (magnetic mass) \( g^2T \sim m_m \)
- In the weak coupling assumption these scales develop a hierarchy.
**Finite-temperature NR EFT how-to**

\[ m \gg m v \sim m \alpha_s \sim \langle 1/r \rangle \gg m v^2 \sim m \alpha_s^2 \sim E \]

? \[ T \gg m_D \sim g T \gg m_m \sim g^2 T \]

- Assume a global hierarchy between the bound-state and thermodynamical scales

- Many different possibilities have been considered in the relevant macroregions \( T \ll m v, T \sim m v \) and \( T \gg m v \) (with \( T \ll m \))

- Proceed from the top to systematically integrate out each scale, creating a tower of EFTs. Make use of existing EFTs (\( T=0 \) NR EFTs, finite \( T \) EFTs such as HTL)

- Once the scale \( m v \) has been integrated out the colour singlet and octet potentials appear
The screening region: $T \gg m_v$

- For $T \gg 1/r \sim m_D$ the potential first obtained by Laine et al. is rigorously derived when matching NRQCD to a modified version of pNRQCD.
The screening region: $T \gg m_v$

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- Advantages of the real-time calculation
The screening region: $T \gg m v$

- For $T>>1/r \sim m_D$ the potential first obtained by Laine et al. is rigorously derived when matching NRQCD to a modified version of pNRQCD.

- Advantages of the real-time calculation

- For $T >> 1/r >> m_D$ we obtain new results:

$$V_s(r) = -C_F \frac{\alpha_s}{r} - \frac{C_F}{2} \alpha_s r m^2_D - i \frac{C_F}{6} \alpha_s r^2 T m^2_D \left(-2\gamma_E - \ln(r m_D)^2 + \frac{8}{3}\right) + \ldots$$

Brambilla JG Petreczky Vairo PRD78 (2008)
The dissociation temperature

- Given the potential for $T \gg 1/r \gg m_D$

$$V_s(r) = -C_F \frac{\alpha_s}{r} - \frac{C_F}{2} \alpha_s r m_D^2 - i \frac{C_F}{6} \alpha_s r^2 T m_D^2 \left(-2\gamma_E - \ln(rm_D)^2 + \frac{8}{3}\right) + \ldots$$

- When $T \sim m \alpha_s^{2/3}$  $\Rightarrow$  $\text{Im}V \sim \text{Re}V$  

Dissociation temperature  
The dissociation temperature

- Given the potential for $T \gg 1/r \gg m_D$

  $$V_s(r) = -C_F \frac{\alpha_s}{r} - \frac{C_F}{2} \alpha_s r m_D^2 - i \frac{C_F}{6} \alpha_s r^2 T m_D^2 \left(-2\gamma_E - \ln(r m_D)^2 + \frac{8}{3}\right) + \ldots$$

- When $T \sim m_\alpha^{2/3} \Rightarrow \text{Im}V \sim \text{Re}V$ \textit{Dissociation temperature}


- Quantitatively, for the $\Upsilon(1S)$

  \begin{center}
  \renewcommand{\arraystretch}{1.2}
  \begin{tabular}{|c|c|}
  \hline
  $m_c$ (MeV) & $T_d$ (MeV) \\
  \hline
  $\infty$ & 480 \\
  5000 & 480 \\
  2500 & 460 \\
  1200 & 440 \\
  0 & 420 \\
  \hline
  \end{tabular}
  \end{center}

  Escobedo Soto \textbf{PRA82} (2010)
The perturbation region: $mv \gg T$

- When $mv >> T >> mv^2$ the thermal medium acts as a perturbation to the potential. Relevant for the ground states of bottomonium: $m_\alpha_s \sim 1.5\text{GeV, } T < 1\text{GeV}$

- The EFT obtained by integrating out the temperature from pNRQCD is called pNRQCD$_{HTL}$

$$\mathcal{L}_{pNRQCD_{HTL}} = \mathcal{L}_{HTL} + \text{Tr} \left\{ S^\dagger [i\partial_0 - h_s - \delta V_s] S + O^\dagger [iD_0 - h_o - \delta V_o] O \right\}$$

$$+ \text{Tr} \left\{ O^\dagger \mathbf{r} \cdot gE S + S^\dagger \mathbf{r} \cdot gE O \right\} + \frac{1}{2} \text{Tr} \left\{ O^\dagger \mathbf{r} \cdot gE O + O^\dagger O \mathbf{r} \cdot gE \right\} + \ldots$$

Brambilla Escobedo JG Soto Vairo JHEP1009 (2010)
Brambilla Escobedo JG Vairo JHEP1107 (2011)
The perturbation region: $mv \gg T$

- Within this theory we computed the spectrum and the thermal width of the $\Upsilon(1S)$ to order $ma_s^5$ in the power counting of the EFT
- We must evaluate loop diagrams in the EFTs

\[ T, mv^2, m_D \]
The perturbation region: $mv \gg T$

- For the spectrum (mass shift) we obtain

$$\delta E_{1S} = \frac{34}{27} \pi \alpha_s^2 T^2 a_0$$

$$+ \frac{E_1}{\pi} \alpha_s^3 \left[ \frac{7225}{324} \left( \log \left( \frac{2\pi T}{E_1} \right) \right)^2 - 2\gamma_E \right] + \frac{128}{81} L_{1S}$$

$$+ 3a_0^2 \left\{ - \left[ \frac{3}{2\pi} \zeta(3) + \frac{\pi}{3} \right] \frac{4}{3} \alpha_s T m_D^2 + \frac{8}{3} \zeta(3) \alpha_s^2 T^3 \right\},$$

$$E_1 = -\frac{4}{9} m\alpha_s^2, \quad a_0 = \frac{3}{2m\alpha_s}$$

- In the potential and spectrum, terms at order $1/m$ and $1/m^2$ turn out to be as large as static ($1/m^0$) terms.
The perturbation region: $mv \gg T$

- The width reads

$$
\Gamma_{1S} = \frac{1156}{27} \alpha_s^3 T + \frac{7225}{162} E_1 \alpha_s^3 \\
- \frac{4}{3} \alpha_s a_0^2 T m_D^2 \left( \ln \frac{E_1^2}{T^2} + 2 \gamma_E - 3 - \log 4 - 2 \frac{\zeta'(2)}{\zeta(2)} - \frac{8}{3} I_{1S} \right) \\
- \frac{32\pi}{3} \ln 2 \ a_0^2 \alpha_s^2 T^3
$$

$E_1 = -\frac{4}{9} m \alpha_s^2$, \quad $a_0 = \frac{3}{2m \alpha_s}$
The perturbation region: \( m v \gg T \)

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$$E_1 = -\frac{4}{9} m \alpha_s^2, \quad a_0 = \frac{3}{2m \alpha_s}$$

- The leading contribution is linear in the temperature
- Two mechanisms: singlet-to-octet thermal breakup and Landau damping
The perturbation region:

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Bottomonium on the lattice

- Extraction of the $b\bar{b}$ spectral function from lattice NRQCD with MEM. Mass shifts and widths are obtained by fitting

- Consistent with our LO predictions for $\alpha_s = 0.4$, $m_b = 5$ GeV

Aarts et al. JHEP1111 (2011). Talk by S. Ryan on Thursday

- See also Rothkopf Hatsuda Sasaki PRL108 (2012), Burnier Rothkopf 1208.1899
The thermal width in the literature
The thermal width in the literature

- Two processes have been considered in the literature:
  - gluo-dissociation \((g + \Psi \rightarrow (Q\bar{Q})_8)\)
  - quasi-free dissociation \(((g, q, \bar{q}) + \Psi \rightarrow (Q\bar{Q})_8 + (g, q, \bar{q}))\)

\[
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The thermal width in the literature

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  gluo-dissociation \((g + \Psi \rightarrow (Q\bar{Q})_8)\) and quasi-free dissociation \(((g, q, \bar{q}) + \Psi \rightarrow (Q\bar{Q})_8 + (g, q, \bar{q}))\)

- In both cases the width is obtained by convoluting the (zero-temperature) dissociation cross section with a thermal distribution for the incoming light particle

\[
\Gamma = \sum_i \int \frac{d^3q}{(2\pi)^3} f_i(q, T) \sigma(q) \nu_{\text{rel}}
\]

Grandchamp Rapp PLB523 (2001)
The thermal width in the EFT

Singlet-to-octet corresponds to gluodissociation. The old Bhanot-Peskin cross section is a limiting case of ours. The factorization formula works where it is applicable.

Bhanot Peskin **NPB156** (1979)
Brambilla Escobedo JG Vairo **JHEP1112** (2011)
Brezinski Wolschin **PLB707** (2011)
Talks by G. Wolschin on **Tuesday**, M. Escobedo on **Thursday**
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\[(g, q, \bar{q}) + \Psi \rightarrow (Q\bar{Q})_8 + (g, q, \bar{q})\]

- Landau damping and quasi-free dissociation are the same process.
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- Landau damping and quasi-free dissociation are the same process.

- The EFT analysis finds that the factorization formula is not correct:
  \[\Gamma = \sum_i \int \frac{d^3 q}{(2\pi)^3} f_i(q, T) 2\sigma_{HQ}(q) v_{rel}\]
The thermal width in the EFT

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- Fails to account for stimulated emission
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  \[\Gamma = \sum_i \int \frac{d^3q}{(2\pi)^3} f_i(q, T) 2\sigma_{HQ}(q) v_{rel} (1 \pm f_i(q, T))\]

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  \]
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Brambilla Escobedo JG Vairo, in preparation. Talk by M. Escobedo, Thursday
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Landau damping and quasi-free dissociation are the same process.

The EFT analysis finds that the factorization formula is not correct:
- Fails to account for stimulated emission
- The cross section has to be $T$-dependent

$$m_D a_0 = 0.1 \quad \sigma_{cq} = \frac{32}{3} \pi \alpha_s^2 a_0^2$$

Brambilla Escobedo JG Vairo, in preparation. Talk by M. Escobedo, Thursday
Potentials and free energies

- Thermodynamical free energies obtained from Polyakov loops are widely used and measured on the lattice.

- We have studied the correlator of Polyakov loops and the associated colour-average free energy: 
  \[ \langle \text{Tr} L^\dagger(0) \text{Tr} L(r) \rangle = e^{-\frac{F_{QQ}(r,T)}{T}} \]
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- We have studied the correlator of Polyakov loops and the associated colour-average free energy $\langle \text{Tr} L^\dagger(0) \text{Tr} L(r) \rangle = e^{-F_{QQ}(r,T)/T}$.

- We have shown that, with pNRQCD in imaginary time, it can be decomposed at short distances into gauge-invariant colour-singlet and octet free energies.
Thermodynamical free energies obtained from Polyakov loops are widely used and measured on the lattice.

We have studied the correlator of Polyakov loops and the associated color-average free energy

\[ \langle \text{Tr} L^\dagger(0) \text{Tr} L(r) \rangle = e^{-\frac{F_{Q\bar{Q}}(r,T)}{T}} \]

We have shown that, with pNRQCD in imaginary time, it can be decomposed at short distances into gauge-invariant color-singlet and octet free energies.

These free energies are quantitatively different from the real-time potentials

\[ \text{Im}(F) = 0, \text{Im}(V) \neq 0 \quad \text{Re}(F) \neq \text{Re}(V) \]

Brambilla JG Petreczky Vairo PRD82 (2010)
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Intuitively

\[ t \to \infty \neq it = \frac{1}{T} \]

Extra divergences can arise for observables spanning the entire imaginary axis

Talk by M. Berwein on Thursday
Conclusions

• Lessons from the EFT framework

  • Systematically take into account corrections and include all medium effects

  • Give a rigorous QCD derivations of the potential, bridging the gap with potentials models which appear as leading-order picture here

  • Compute potentials, spectra and widths in different regimes, with particular relevance for the new frontier of $\Upsilon(1S)$ phenomenology

• Potentials are not free energies

• Nonperturbative extensions
Extra
A lattice width?

- Rothkopf Hatsuda Sasaki PRL108 (2012), Burnier Rothkopf 1208.1899: determine the static potential on the lattice by extracting the spectral representation of the Wilson loop with MEM

\[ W^E(r, \tau) = \int_{-\infty}^{+\infty} d\omega e^{-\omega \tau} \rho(r, \omega). \]