Heavy quarkonium and dynamical gluon mass at non-zero temperature in instanton vacuum model

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Outline

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    - ILM at $T \neq 0$
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Talk based on: MM et al,
1. Dynamical gluon mass at non-zero temperature...arXiv:1804.07242v1;
2. Dynamical gluon mass...
Phys.Lett. B779(2018)206, arXiv:1706.06270;
3. Gluons...Quarks...QCD Vacuum,
EPJ Web Conf.182(2018)02092, arXiv:1802.06211;
4. ...quarks interactions generated by QCD vacuum,
EPJ Web Conf.137(2017)03013, arXiv:1703.07825;
Instanton effects on the heavy-quark static potential,
5. Chinese Phys. C41(2017)083102, arXiv:1602.06074.

Motivation and Introduction

- Heavy quarkoinium $Q\bar{Q}$ as a thermometer in high energy hadron-hadron/ion-ion collisions.
- The properties of QCD vacuum are important. We consider them in the instanton liquid model (ILM) at $T \neq 0$ at different scenarios for the mean instanton size $\rho(T)$ and density $n(T)$.
- ILM generated dynamical gluon mass is considered and compared with lattice measurements.
- The contributions of direct instantons and ILM modified one-gluon exchange to the central $Q\bar{Q}$ potential are calculated.

Classical gluon vacuum energy vs N_{CS}

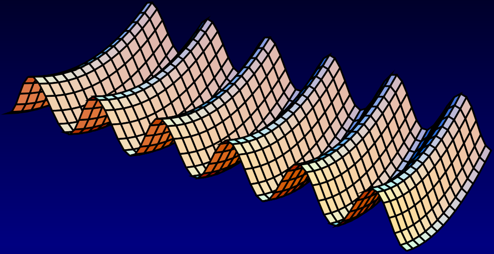
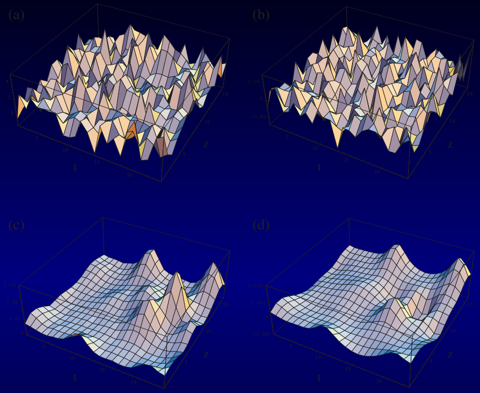


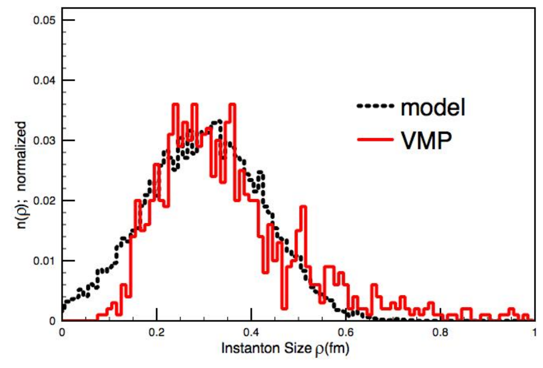
Figure: Potential energy of the gluon field is periodic along N_{CS} and oscillator-like in all other directions in functional space (Faddeev, Jackiw, Rebbi 1976). Quasi-classical quantization – band structure. The width of band $\sim$ amplitude of tunneling$= e^{-S_I}$. S_I is calculated on Euclidian classical trajectory between nearest minima–selfdual classical solution–QCD (anti)instanton. It means that (anti)instanton's $Q_T = N_{CS}(+\infty) - N_{CS}(-\infty) = \pm 1$.

QCD vacuum at temperature $T = 0$



Upper row: a typical full configuration of the gluon field from lattice simulations in the (z, t) hyperplane with (x, y) fixed. *Lower row*: the same after smearing of zero-point oscillations clearly shows 3 instantons and 2 anti-instantons. *Left column*: action density. *Right column*: topological charge density (Negele1999).

Instanton Liquid Model(ILM) at $T = 0$



(Millo,Faccioli2011); Phenom.(Shuryak1981), Var.(Diakonov-Petrov1983): $n^{-1/4} = R \approx 1\, fm$, $\rho \approx 0.33\, fm$;

Lattice(Negele1999): $R \approx 0.89\, fm$, $\rho \approx 0.36\, fm$;

Our with $1/N_c$ corr: $R \approx 0.76\, fm$, $\rho \approx 0.32\, fm \Rightarrow$

Strength of light quark-instanton interaction $M \approx 365\, MeV \Rightarrow$

Perfect description of light hadrons.

Lattice show a sizable portion of large instantons⇒DLM?

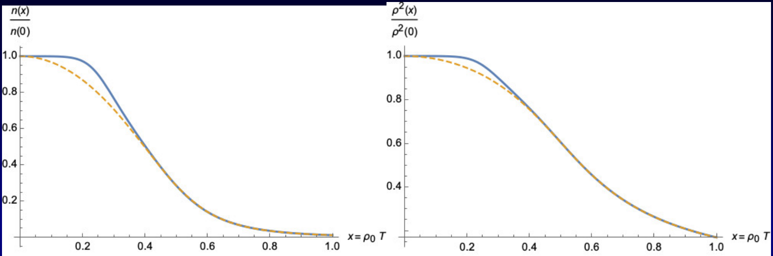
Instantons vs light hadron and heavy quarkonium $Q\bar{Q}$ sizes

Nucleon quark size $r_N \sim 0.3 - 0.45\, fm$ (Weise1985).
$Q\bar{Q}$ sizes (Satz ed 2012):

State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [Gev]	3.07	3.53	3.68	9.46	9.99	10.02	10.26	10.36
size r [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

Small quark size hadrons are insensitive to the confinement!!
We may safely apply ILM.

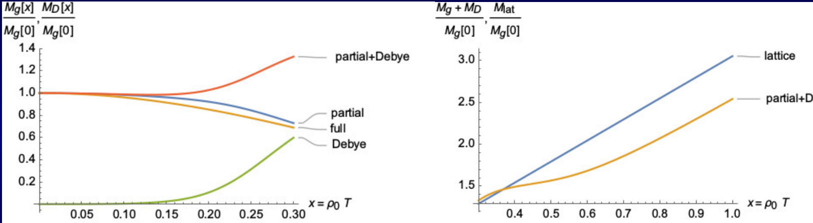
ILM at $T \neq 0$



Left figure: $\rho^2(\rho(0)T)/\rho^2(0)$, while the right: $n(\rho(0)T)/n(0)$ at $\rho(0) = 1/3\, fm$, $n(0) = 1\, fm^{-4}$. Full line corresponds interpolation between no suppression below T_c and full suppression above $T_c = 150\, MeV$, with a width $T = 0.3\, T_c$ (Shuryak et al 1996). Dashed lines correspond to the full suppression at the whole region of T (Diakonov,Mirlin1988).

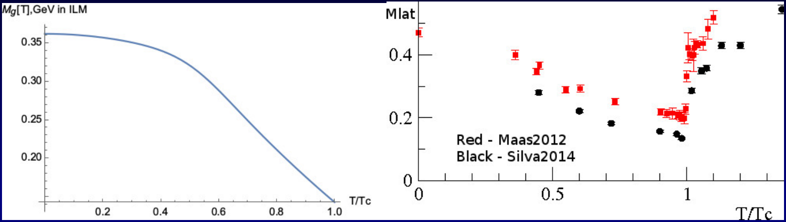
Gluons in ILM at $T \neq 0$

- Solve zero-mode problem;
- Average gluon propagator in ILM by means Pobylitca Eq. (Pobylitca1988) and find dynamical "electric" gluon mass $M_g(q, T)$.



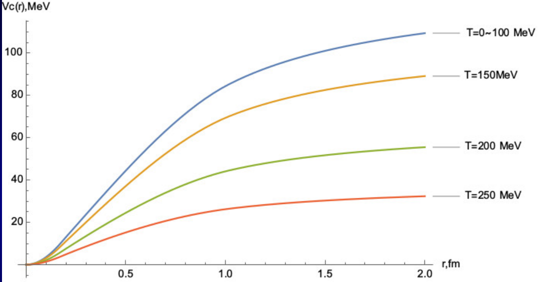
Here $x = T\rho(0)$, $x_c = 0.25$, $M_g(x) = M_g(0, T)$, $M_g(q, 0) = M_g(0, 0)F(q)$, $F(q) = q\rho(0)K_1(q\rho(0))$.
M_g – strength of gluon-instanton interaction.
At $\rho(0) = 0.33\, fm$, $n(0) = 1\, fm^{-4}$ $M_g(0, 0) = 362\, MeV$.
Lattice data fit for $T > 397\, MeV$:
$M_{lat}(T) = 193(88) + M_D(T)$, $M_D(T) = 1.52(20)\, T$ (in MeV) (Silva et al2014).

Dynamical gluon mass: ILM vs lattice at $T < T_c$



Left figure: ILM dynamical "electric" gluon mass $M_g(T)$ at $T < T_c$;
Right figure: lattice measurements of dynamical "electric" gluon mass $M_{lat}(T)$ (Maas et al2012, Silva et al2014). Pay attention here to the region $T < T_c$, $T_c = 273\,MeV$.

Direct instanton contribution to the singlet $Q\bar{Q}$ central potential in ILM at $T \neq 0$



The potential $V_c(r, T)$ is from Wilson loop averaged in ILM by means of Pobylitca Eq. .
Here $V_c(r \to \infty, T = 0) = 2\,\Delta m_Q = 140\,MeV$ at $\rho(0) = 0.33\,fm,\ n(0) = 1\,fm^{-4}$.
$\Delta m_Q = 70\,MeV$ – strength of a heavy quark-instanton interaction.

ILM direct instanton contribution to the charmonium states at $T = 0$

$\Delta M_{c\bar{c}} = 2m_c - M_{c\bar{c}}$ in [MeV]. $m_c = 1275\, MeV$.

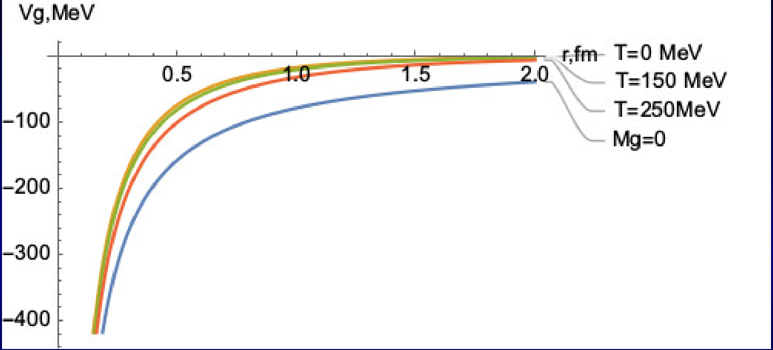
$\Delta M_{c\bar{c}}(J^P)$	Set I	Set II	Exp.
$\Delta M_{\eta_c}(0^-)$	118,81	203,64	$433, 6 \pm 0.6$
$\Delta M_{J/\psi}(1^-)$	119,57	205,36	$546, 916 \pm 0.11$
$\Delta M_{\chi_{c0}}(0^+)$	142,43	250,86	$864, 75 \pm 0.31$

Direct ILM effects are not small $\sim 30\,\%$ in comparison with the experimental data and strongly depend on ILM parameters.

Set I $\rho = 0.33$ fm and $R = 1\,\mathrm{fm}$.

Set II $\rho = 0.36$ fm, $R = 0.89\,\mathrm{fm}$.

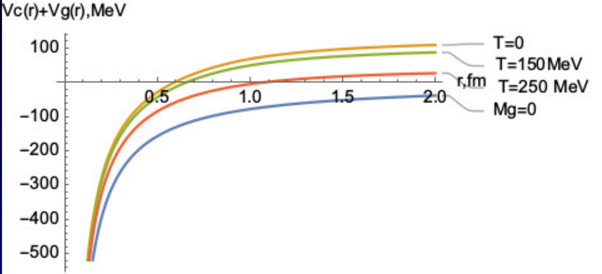
One-gluon exchange contribution to the singlet $Q\bar{Q}$ potential in ILM at $T \neq 0$



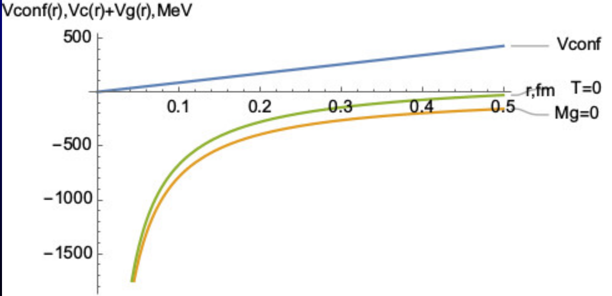
$$V_g(r,T) = \lambda \cdot \bar{\lambda}\, g^2 \int \frac{d^3k}{(2\pi)^3} \exp(i\vec{k}\vec{r})(\vec{k}^2 + M_g^2(\vec{k},T))^{-1},$$

$M_g(\vec{k},T) = M_g(0,T)F(k)$, $F(k) = k\rho K_1(k\rho)$.
$M_g(0,0) = 362\,MeV$ at $\rho(0) = 0.33\,fm$, $n(0) = 1\,fm^{-4}$.
$\lambda \cdot \bar{\lambda} = -4/3 \sim Q\bar{Q}$ singlet, $\lambda \cdot \bar{\lambda} = +1/6 \sim Q\bar{Q}$ adjoint state.

Singlet $Q\bar{Q}$ potential in ILM

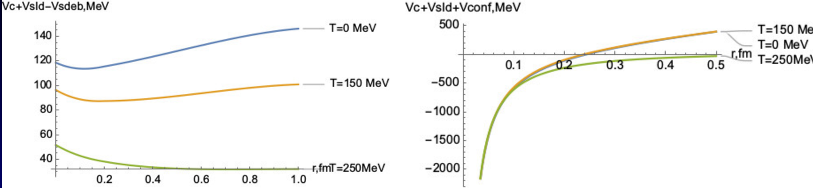


T dependence of $Q\bar{Q}$ potential in ILM.



ILM, $M_g = 0$ and confinement potentials at $T = 0$.

Singlet $Q\bar{Q}$ potential in ILM & Debye screening



Singlet Cornell-like potential: one-gluon exchange $V_{sdeb}(r, T)$ with Debye screening mass $m_D = 1.52\, T\, \Theta(T - T_c)$ (Silva et al2014)
and confinement $V_{conf}(r, T)$ potentials

$$V_{sdeb}(r, T) = -e/r \exp(-m_D r), \;\; V_{conf}(r, T) = \sigma\, r \Theta(T_c - T)$$

$e = 0.51 - 0.52, \;\; \sigma^{0.5} = 412 - 427\, MeV$ (Bali2000).

Left: difference between ILM and Cornell-like potentials. Right: ILM+confinement potentials1.

Discussion

- $Q\bar{Q}$ and QCD vacuum properties are correlates very much. ILM for QCD vacuum: instanton average size $\rho \sim 1/3\, fm \sim Q\bar{Q}$ sizes, while density $n \sim 1\, fm^{-4}$. Heavy quark-instanton interaction strength $\Delta m_Q \sim \rho^3 n = packing\ \ parameter\ \rho^{-1} \sim 70\, MeV$, while light quark-instanton and gluon-instanton strengths $M \sim M_g \sim (packing\ \ parameter)^{1/2}\ \rho^{-1} \sim 360\, MeV$.
- ILM generated gluon "electrical" dynamical mass is a falling function at $T < T_c$. This behaviour was found in lattice measurements.
- $Q\bar{Q}$ potential get sizeable changes from ILM direct instanton and ILM modified one-gluon exchange contributions. $Q\bar{Q}$ phenomenology at $T = 0$ have to be re-analysed.
- $T \neq 0 \Rightarrow$ essential changes of ILM contributions to $Q\bar{Q}$ potential. They must be taken into account in analysis of heavy quarks production processes.

Thanks for the attention.