New Developments in Thermal Field Theory

Chihiro Sasaki
Frankfurt Institute for Advanced Studies

Selected Issues:

- interplay between chiral symmetry breaking and confinement
- role of QCD trace anomaly
- hadrons near chiral symmetry restoration
- chiral thermodynamics of charmed mesons
QCD

holographic models

lattice gauge theory
effective theories
topologies
functional RG
cold atoms

holographic models
I. Chiral Symmetry Breaking vs. Confinement
Probing deconfinement with Polyakov-loop fluctuations

- Polyakov loop $L$: quite broaden in QCD [HotQCD Collaboration]
- susceptibilities of $L$ and their ratios: [Lo, Friman, Kaczmarek, Redlich, CS ('13)] modulus (A), real (R) and imaginary (l) part of $L$: $\chi_A, \chi_R, \chi_I$
  - ratios: $R_A = \chi_A/\chi_R$, $R_T = \chi_I/\chi_R$ vs. $T$
  - ambiguity of renor. prescription can be avoided to large extent!
  - pure YM vs. $N_f = 2 + 1$ QCD (HISQ) on lattice ($T_{chiral} = 155$ MeV): broad $R_T$ due to exp. $Z(3)$ symmetry
• a clear remnant of $Z(3)$ in $R_A$! pseudo-critical temperatures $T_{ch} \sim T_{dec}$!

• quark number fluctuations: kurtosis measures fermion number $B^2$

  Lattice QCD: $T_{ch} \sim T_{dec}$ at zero density  
  [also talk by H.-T. Ding]

• Polyakov-loop model with quarks (a la PNJL/PQM) does not reproduce $R_A, R_T \cdots$ dynamics of confinement missed!
Confinement vs. dynamical chiral symmetry breaking (D\(\chi\)SB) to which extent does D\(\chi\)SB contain information on confinement?

- Banks-Casher relation: low-lying Dirac eigenmodes generate \(\langle \bar{q}q \rangle\).

  \[
  \text{removal of low-lying Dirac modes} \Rightarrow \text{NO D\(\chi\)SB}
  \]

  Q. does confinement disappear simultaneously?

- linking Polyakov loop to spectral function of lattice Dirac operator

  [Gattringer ('06); Bruckmann, Gattringer, Hagen ('07); Synatschke, Wipf, Langfeld ('08)]

  manifestly gauge invariant formalism

  [Gongyo, Iritani, Suganuma ('12); Doi, Iritani, Suganuma ('13,14)]

\[
\langle L \rangle = \frac{(2i)^{N_t-1}}{12V} \sum_n \lambda_n^{N_t-1} \langle n | \hat{U}_4 | n \rangle \tag{\ast}
\]

NO particular Dirac-modes that crucially affect confinement!

\[\Downarrow\]

disappearance of D\(\chi\)SB DOES NOT mean deconfinement?
Wilson loop, quark potential:
\[ \langle W \rangle \propto e^{-\sigma RT} \]: slope parameter = string tension \( \Rightarrow \) unchanged!
• no D\( \chi \)SB \( \neq \) no confinement
• survival hadrons in chiral symmetric phase
• NOTE: static quarks? but (\(^*\))?
**Dual Ginzburg-Landau picture**

[‘t Hooft (‘75); Mandelstam (‘76)]

QCD in MAG

- monopole part
- "photon" part

confinement

- monopoles

chiral SB

- confinement chiral SB

- dual Meissner effect ⇒ monopole condensation: QCD with Maximal Abelian Gauge (MAG) [‘t Hooft (‘81); Ezawa, Iwasaki (‘82)]
  - monopole part: linear confinement potential, $D\chi_{SB}$, instantons
  - Abelian part: trivial vacuum (no confinement, no $D\chi_{SB}$)

**confinement and $D\chi_{SB}$ induced by monopole condensation**

- how monopoles and Dirac eigenmodes are related?
- effective theory in continuum?
II. Role of QCD Trace Anomaly
Fate of hadron masses toward chiral symmetry restoration

- hadron masses vs. truncation level on lattice  [Glozman, Lang, Schrock ('12)]
  - removal of lowest Dirac-eigenmodes ⇐ NO $\langle \bar{q}q \rangle$
    ⇒ parity partners degenerate and stay quite massive!
  - no universal scaling ($m_{\text{meson}} \sim 2m$, $m_{\text{baryon}} \sim 3m$) found
    ⇒ the system remains confined!

- origin of a scale in $\chi$-sym. phase?  ⋯ ⋯ trace anomaly $T^\mu_\mu \sim \langle \frac{\alpha_s}{\pi} G^2 \rangle$

$$\frac{d}{dm_q} \frac{\alpha_s}{\pi} \langle G^2 \rangle = -\frac{24\langle \bar{q}q \rangle}{\frac{11}{3} N_c - \frac{2}{3} N_f}$$  [Novikov, Shifman, Vainstein, Zakharov ('81)]

⇒ in-medium gluon condensate: melting toward $T_{\text{ch}}$, but non-vanishing
• **embedding gluon condensate:** \( U(1) \) vs. \( SU(2) \) [Paeng, Lee, Rho, CS ('13)]
  – RGE analysis: \( \rho NN \)-int. “runs” whereas \( \omega NN \)-int. “walks” with \( n_B \)!
    IR fixed point (cf. walking techni-color model)
  – \( m_N^* \sim \text{const.}: \) emergence of a \( \chi \)-inv. mass!

• **tetra-quark states in chiral transition:**
  – crucial to nuclear compressibility \( K(n_0) \) [Gallas, Giacosa, Pagliara ('11)]
  – new CP? intermediate phase? enlarged symmetry? [Heinz, Struber, Giacosa, Rischke ('08); Harada, CS, Takemoto ('09); Mukherjee, Huang ('13)]
III. Hadrons near Chiral Symmetry Restoration
Chiral symmetry restoration and in-medium axial-vector spectrum

- **Weinberg sum rules**: $f_\pi \Leftrightarrow \rho_{V,A}(s)$  
  [Weinberg ('67); Kapusta, Shuryak ('94)]

- **strategy**: phenomenologically accepted $\rho_V(T)$ & ansatz for $m_{a_1}(T), \Gamma_{a_1}(T)$
  \[ \text{WSRs} \Rightarrow \text{in-medium } \rho_A(T) \]
  - smooth reduction of $m_{a_1} \rightarrow m_{\rho}$ and broader width
  - importance of higher-lying states: $\rho', a'_1, \ldots$

[Hohler, Rapp ('14)]
V-A mixing at finite density

\begin{align*}
\text{no charge-conjugation inv. at finite density} & \Rightarrow \rho-a_1 \text{ mixing at tree level} \\
L \text{mix} = 2C\epsilon^{0\nu\lambda\sigma}\text{tr} [\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma] \\
\text{transv: } p_0^2 - \vec{p}^2 & = \frac{1}{2} \left[ m_\rho^2 + m_{a_1}^2 \pm \sqrt{(m_{a_1}^2 - m_\rho^2)^2 + 16C^2\vec{p}^2} \right] \\
\text{mixing strength: } \chi_{\text{EFT}} & \text{ [Harada, CS ('09)] } \text{ vs. } \text{AdS/QCD [Domokos, Harvey ('07)]} \\
C = 0.1 \text{ GeV } & \text{ vs. } 1 \text{ GeV at } n_B = n_0! \\
C = 1 \text{ GeV} & \Rightarrow \text{vector-meson condensation at } n_0!?
\end{align*}
why $C(n_0) = 1$ GeV in AdS/QCD?

$$C_\omega \ll C = C_\omega + C_\omega' + C_\omega'' + \cdots?$$

role of infinite KK modes in nuclear potential from Sakai-Sugimoto model [Hashimoto, Sakai, Sugimoto ('09)]

- repulsive core, tensor force, spin/isospin dep., $V(r) \propto 1/r^2$
- truncation vs. integrating-out \cdots different $r$ dependence!

$$V_\infty(r) = \frac{1}{r} + \frac{e^{-r}}{r} + \frac{e^{-2r}}{r} + \cdots \text{ small } r \sim \frac{1}{r^2}$$

$$V_N(r) = \frac{1}{r} + \frac{e^{-r}}{r} + \frac{e^{-2r}}{r} + \cdots + \frac{e^{-Nr}}{r} \exp[-mr] \sim 1 \frac{N}{r}$$
Role of higher-lying hadronic states near phase transitions increasing $T$ and $n_B$ toward QCD phase transition:

More and more hadronic states activated!

... How to handle them?

- holographic QCD models: $1/N_c$ corrections?
- 4d effective field theories:
  unknown interactions among higher-lying states?
  if renormalized/integrated out, $T, n_B$-dep. interactions?

$$
\mathcal{L}_\infty(\pi, \rho, \omega, \cdots) \sim \mathcal{L}_{\text{low-lying}}(\pi, \rho, \omega, \cdots ; g(T, n_B))
$$

... might be bridged via DS eq. and FRG?
IV. Chiral Thermodynamics with Charm
Fine splitting of D-meson masses

- no charge-conjugation inv. at $n_B \neq 0 \Rightarrow m_{D^-} - m_{D^+} \sim 50$ MeV
- spontaneous chiral symmetry breaking:
  - chiral doublers $D(0^-, 1^-)$ and $D(0^+, 1^+)$ \(\Rightarrow \delta m_D \sim 350\) MeV
- flavor symmetries
  - chiral symmetry: $m_{u,d}/\Lambda_{QCD} \ll 1$, $m_s/\Lambda_{QCD} < 1$
  - heavy quark symmetry: $\Lambda_{QCD}/m_{c,b} \ll 1$

when $m_Q \to \infty$,
  - light d.o.f. (q) do not feel the flavor and spin of the heavy quark (Q).
$N_f = 2 + 1 + 1$ LQCD simulations: downward shift of $T_{ch}$ by 20 MeV (ETMC, $m_\pi \sim 400$ MeV)  
[Poster A-11 by Burger, Hotzel, Muller-Preussker, Ilgenfritz, Lombardo]

chiral MF theory with heavy quark symmetry: [CS, Redlich ('14)]  
$\Rightarrow D - D_s$ splitting effectively reduced toward $T_{ch}$: $h_q \ll h_s \rightarrow h_q^* \lesssim h_s^*$

D,B mesons in nuclear matter: modifications of color-electric and color-magnetic gluon condensates  
[Yasui, Sudoh ('14)]

interesting testing ground of quark-gluon interplay in matter!
Summary

• Polyakov-loop ratio & quark number fluc. suggest $T_{ch} \sim T_{dec}$ at $\mu = 0$
  survival hadrons in confined phase at $\mu \neq 0$?

• importance of higher-lying states near phase transitions

• $N_f = 2 + 1 + 1$ lattice QCD simulations: a downward shift of $T_{ch}$

• effective theories: reduction of $D - D_s$ splitting, gluon dynamics in hot/dense matter

More to come from Exp, LQCD, EFTs!
Exciting moments in nuclear/hadron physics!