Deconfined quantum criticality
and
the underdoped cuprates

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T.S, Lee, cond-mat/0406066
Levin, T.S, cond-mat/0405702
Hermele et al, cond-mat/0404751
Cuprate phase diagram

Nature of pseudogap, and dSc at low non-zero doping?
Old idea: view as doped paramagnetic Mott insulator

\[ g = \text{frustration/ring exchange, ...} \]

Path of real material
What paramagnet? Some hints from experiments

- Softening of neutron resonance mode with decreasing $x$
  - consider paramagnets proximate to Neel state i.e potentially separated by 2$^{nd}$ order transition.

- Gapless nodal quasiparticles in dSC
  - consider paramagnets with gapless spin excitations.
Candidate states – gapless spin liquids

Rough description: Gapless spin-1/2
nodal spinons coupled to deconfined gauge fields.
(Eg: $\mathbb{Z}_2$ spin liquid with nodal spinons and gapped visons)

Can spin liquid states be reached from conventional
collinear Neel by second order transitions?

Orthodox answer: No!

Claim in this talk: Orthodox answer needs to be revisited.
Are the cuprates doped gapless spin liquids?

Natural (old) questions:
• Is the question meaningful?
• How to tell?

Revisit – exploit insights from study of deconfined criticality at Neel-VBS transition.
Deconfined criticality again – now from the valence bond solid (VBS) side

(Levin, TS, cond-mat/0405702)

Valence bond solid with spin gap.

\[
\begin{align*}
\text{ } & = \frac{\langle \rightarrow\leftarrow - \leftarrow\rightarrow \rangle}{\sqrt{2}}
\end{align*}
\]
Discrete $\mathbb{Z}_4$ broken symmetry
Neel-Valence Bond Solid transition

• Naïve approaches fail
  Attack from Neel ≠ Usual O(3) fixed point in D = 3
  Attack from VBS ≠ Usual Z\(_4\) fixed point in D = 3
  (= XY universality class).

Why do these fail?
Topological defects carry non-trivial quantum numbers!
Topological defects in $\mathbb{Z}_4$ order parameter

- Domain walls – elementary wall has $\pi/2$ shift of clock angle
Z$_4$ domain walls and vortices

- Walls can be oriented; four such walls can end at a point.
- End-points are Z$_4$ vortices.
$Z_4$ vortices in VBS phase

Vortex core has an unpaired spin-$1/2$ moment!!

$Z_4$ vortices are "spinons".

Domain wall energy confines them in VBS phase.
Disordering VBS order

- If $Z_4$ vortices proliferate and condense, cannot sustain VBS order.

- Vortices carry spin $\Rightarrow$ develop Neel order
Z₄ disordering transition to Neel state

- As for usual (quantum) Z₄ transition, expect clock anisotropy is irrelevant.

(confirm in various limits).

Critical theory: (Quantum) XY but with vortices that carry physical spin-1/2 (= spinons).
Alternate (dual) view

- Duality for usual XY model (Dasgupta-Halperin)
  Phase mode - ``photon”

Vortices – gauge charges coupled to photon.

Neel-VBS transition: Vortices are spinons
=> Critical spinons minimally coupled to fluctuating non-compact U(1) gauge field.
Proposed critical theory
``Non-compact CP\(_1\) model''

\[ S = \int d^2x d\tau \left| (\partial_\mu - ia_\mu) z \right|^2 + r \left| z \right|^2 + u \left| z \right|^4 + (\epsilon_\mu \partial_\nu a_\lambda)^2 \]

\(z = \) two-component spin-1/2 spinon field
\(a_\mu = \) non-compact U(1) gauge field.

Distinct from usual O(3) or Z\(_4\) critical theories.

Reobtain same result as by attack from Neel state!
Renormalization group flows

Clock anisotropy = quadrupled monopole fugacity

Deconfined critical fixed point

Monopoles are \textit{``dangerously irrelevant''}.

Precise meaning of deconfinement:
Conservation of gauge flux $\iff$
Extra emergent global (topological) U(1) symmetry associated with skyrmion conservation
Two diverging length scales in paramagnet

``Critical'' \( \xi \) ``U(1) spin liquid'' \( \xi_{\text{VBS}} \) VBS ~ \( \xi^k \) diverges faster than \( \xi \)

Spinons confined in either phase but `confinement scale’ diverges at transition.
Pertinent lessons

• **Lesson 1:** Gapless spinons may kill confinement in U(1) gauge theories in $d = 2$.

• **Lesson 2:** Even unstable spin liquids may control broad intermediate regime near certain quantum transitions.
Application to cuprates: theory of gapless U (1) spin liquids

- Affleck-Marston ’88, Marston’91: Flux phase of large-N spin models.

Mean field: Half-filled tight binding band of fermionic spinons with $\pi$-flux through each plaquette.

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Low energies: massless Dirac theory in $D = 2+1$.  

Band structure: four gapless Fermi points
Beyond mean field

Describe by fermionic massless Dirac spinons coupled to compact U(1) gauge field

Ultimate fate?? Confinement??

- Doped versions: Lee, Nagaosa, Wen, .......... (1996 - ....)

Mostly ignore compactness (and hence possibility of confinement).
Stability of gapless U(1) spin liquids (Affleck-Marston pi-flux phase)

Hermele et al, cond-mat/0404751

• Analyse in limit of large number $2N$ of Dirac spinons (appropriate for SU(N) spin model).

• First ignore monopole events in space-time
  ⇒ Gauge flux exactly conserved.

Low energy theory is critical with no relevant perturbations (non-compact QED$_3$) : conformally invariant with power law spin correlations.

\[ \mathcal{L} = \bar{\psi}_j \gamma^\mu (\partial_\mu + ia_\mu) \psi_j + \frac{1}{8\pi e^2} (\epsilon_{\mu\nu\lambda} \partial_\nu a_\lambda)^2. \]
Monopoles

- Break flux conservation symmetry

Careful consideration: monopoles irrelevant at low energy critical fixed point for large enough $N$.

$\Rightarrow$ Deconfined critical phase

Precise meaning of "deconfinement": extra global topological U(1) symmetry associated with gauge flux conservation.
Second order transition to Neel
(induce by increasing strength of quartic spinon interaction)

- Spin density wave of spinons
- Monopoles continue to be irrelevant at critical point to Neel.
- Spinons gapped in Neel phase => monopoles no longer irrelevant, cause confinement to yield conventional Neel state.
- Deconfined critical point with dangerous irrelevant monopoles, 2 diverging length scales, etc.
General lesson I

- Stable gapless U(1) spin liquids exist in $D = 2+1$ (at least for SU($N$) models and $N >$ some $N_{c1}$).

$N_{c1}$ possibly smaller than 2, not known at present*.

$N_{c1} < 2 \Rightarrow$ appealing description of cuprates as doped U(1) spin liquids.

*Indications from numerics: $N_{c1} < 4$ (Assaad, cond-mat/0406...)
Alternate possibility
(or how Z2 and U(1) spin liquids may give each other 2nd lives)

$\mathbb{Z}_2$ spin liquid with nodal spinons and gapped $\mathbb{Z}_2$ vortices (visons) – clearly stable even for SU(2) spin models.

?? 2nd order transition to conventional collinear Neel state ??

Z2 state: Higgs phase of compact U(1) gauge theory coupled to charge-2 boson (spinon pair) field.

Neel: some confined phase of same theory.
Confinement transition from gapless $Z_2$ SL

Transition where spinon pair field gets gapped.

First ignore monopoles: Phase with gapped spinon pair described by non-compact QED$_3$ for spinons (i.e. the U(1) SL)

**Diagram:**

- U(1) SL
- Z$_2$ SL
- Critical point
Z$_2$ SL – Neel transition

- Expect monopole scaling dim at critical point > at U(1) SL fixed point

⇒ Can get situation where monopoles are irrelevant at critical point but relevant at U(1) SL fixed point (for $N_{c2} < N < N_{c1}$)

⇒ Possibility of direct 2$^{nd}$ order transition from Z$_2$ SL to conventional collinear Neel.
A deconfined critical point again

Monopole fugacity
General lesson II

- Can possibly reach $Z_2$ spin liquid with nodal spinons by direct second order transition from conventional Neel state.

- The (unstable) gapless $U(1)$ spin liquid controls a large intermediate length scale regime in Neel state near the transition.
Summary, conclusions, etc - I

- Gapless spin liquids exist as stable phases in $D = 2+1$.

They may be accessed from conventional Neel by second order transitions.

Needed: Numerics to determine $N_{c1}$, $N_{c2}$
• U(1) SL with ``gapless Dirac spinons” apparently plays an important role whether it is stable or not.

Are the cuprates doped U(1) spin liquids?

How to tell?

Detect conserved U(1) gauge flux!
Gauge flux detector

Cuprate sample with spatially modulated doping as below
Gauge flux detection

- Start with outer ring superconducting and trap an odd number of hc/2e vortices (choose thin enough so that there is no physical flux).

- Cool further till inner annulus goes superconducting.

- For carefully constructed device will spontaneously trap hc/2e vortex of either sign in inner annulus.
How does it work?

• Odd $hc/2e$ vortex inside outer ring $\Rightarrow \pi$ flux of internal gauge field spread over the inner radius.  
  (Lee, Wen, 2001)

• If inner annulus sees major part of this internal flux, when it cools into SC, it prefers to form a physical vortex.

• For best chance, make both SC rings thinner than penetration depth and device smaller than roughly a micron.