Are the cuprates doped spin liquid Mott insulators?

T. Senthil (MIT)

Meaning of the question?
How might we find answers?
Don't we already know?

T.Senthil, Patrick Lee, cond-mat/0406066

Are the cuprates doped spin liquid Mott insulators?

- ``Obvious" answer: No!

Undoped material has antiferromagnetic order – not a spin liquid.

However ``obvious" answer may be too quick……..

Aspects of underdoped phenomenology (at not too low doping or temperature)

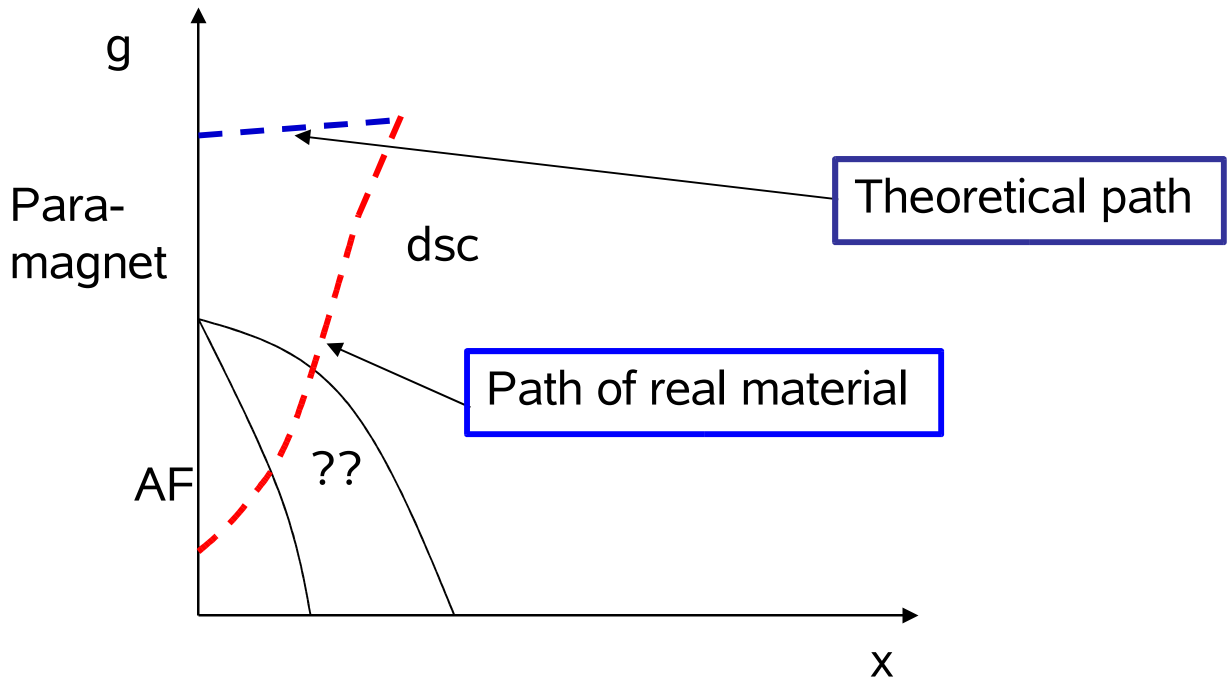
- Charge transport is by holes
- No magnetic long range order (AF LRO quickly destroyed by hole motion)
- Existence of spin gap

Perhaps useful to view as doped paramagnetic Mott insulator.

Further theoretical bonus: Superconductivity a natural outcome of doping paramagnetic Mott states

(old RVB notion – Anderson, Kivelson et al, Kotliar-Liu,………)

View as doped paramagnetic Mott insulator (a very old idea actually)



g = frustration/ring exchange,….

Questions

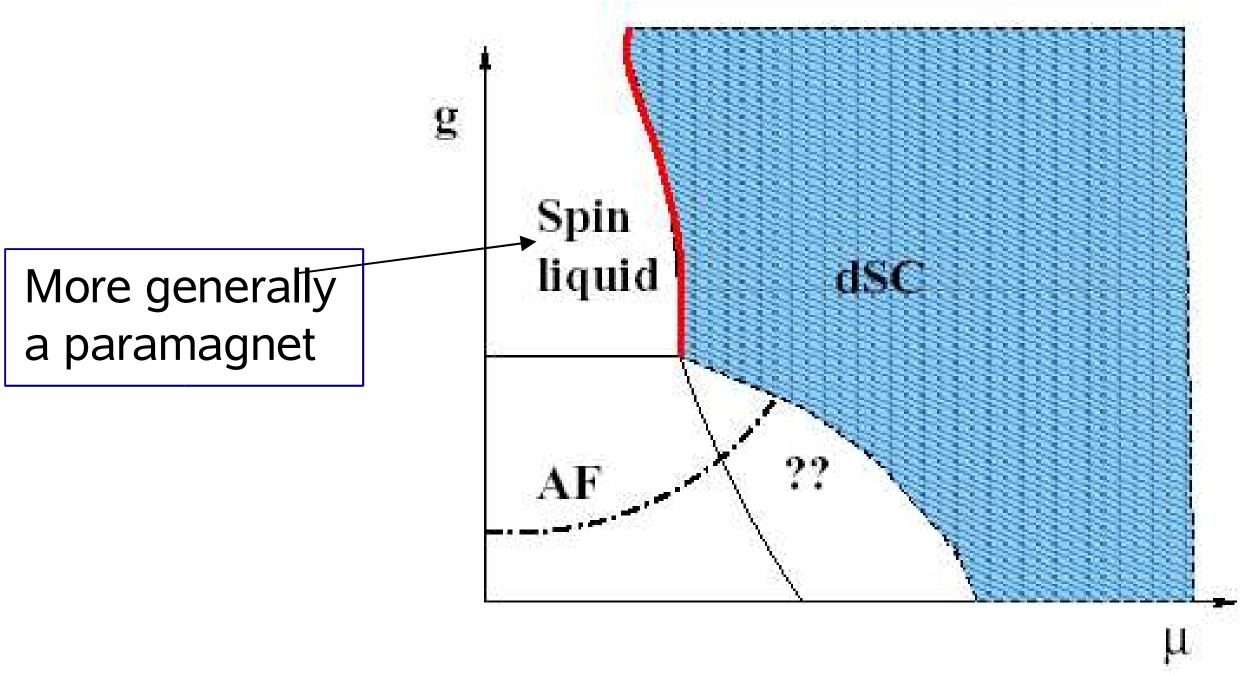
1. How to sharpen?

3. What paramagnet to dope?

5. How to test?

How to sharpen?

- Useful to consider phase diagram as a function of chemical potential rather than doping



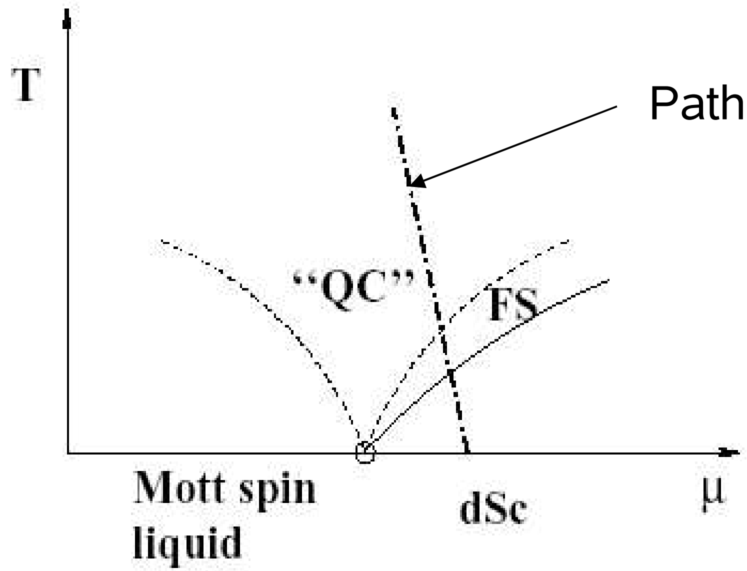
Theoretical suggestion

(implicit in much previous work)

- Physics at moderately low doping:

Influenced by proximity to chemical potential tuned Mott transition between spin liquid Mott insulator and dSc.

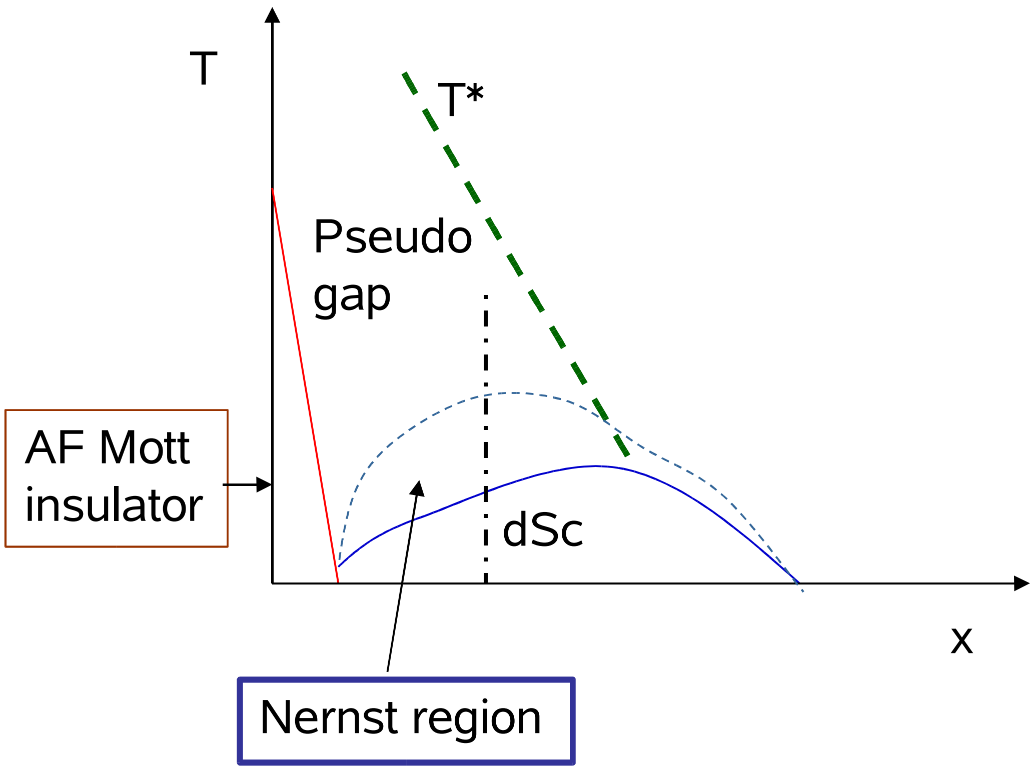
Doping induced Mott criticality from a spin liquid

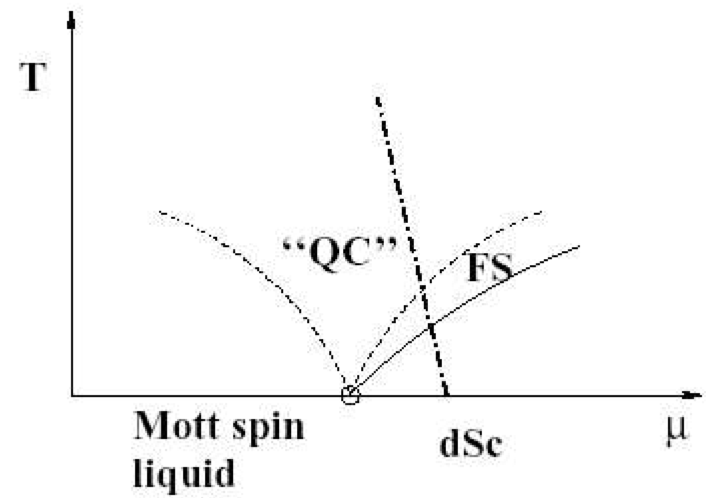


Path of system at fixed doping

QC: ``quantum critical" region of Mott transition.
FS: Fluctuating superconductor associated with T > 0 superconducting transition

Comparison to cuprate phase diagram



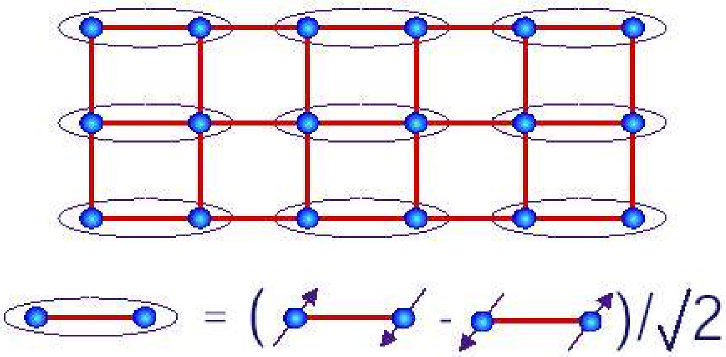


FS: Nernst region
QC: ``High-T" pseudo-gap region

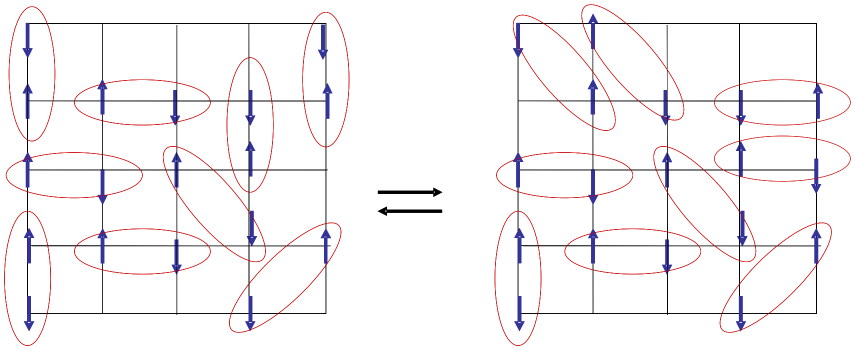
What paramagnet to dope?

Theoretical candidates

3. Valence bond solid (spin Peierls) states



7. Various kinds of RVB spin liquids



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 2nd order transition.

- Gapless nodal quasiparticles in dSC

- consider paramagnets with gapless spin excitations.

Tight constraints

=> Only few candidates: ``gapless spin liquids”

Theory of spin liquids

(enormous progress in last few years due to several people)

Spin liquid = translation invariant paramagnetic Mott state with one electron per unit cell.

Excitation spectrum of all known examples – describe in terms of spin-1/2 neutral spinons.

Specific examples of interest – spinons are gapless at 4 nodal points with linear dispersion

=> Very appealing starting points to dope to get dSc with nodal quasiparticles.

Theoretical characterization of spin liquids*

- Topological structure:

Extra `topological' conservation law not present in microscopic spin model.

Conveniently viewed as a conserved gauge flux.

Different classes of spin liquids distinguished by nature of gauge flux.

Spinons couple minimally to corresponding gauge field.

*abelian

Gauge theories and spin liquids

- Conserved gauge flux – important PHYSICAL property of excitation structure of spin liquid phase

Effective theory – `deconfined' gauge theory

=> Gauge description not just a calculational device

Conserved gauge flux in spin liquid can in principle be detected by experiments.

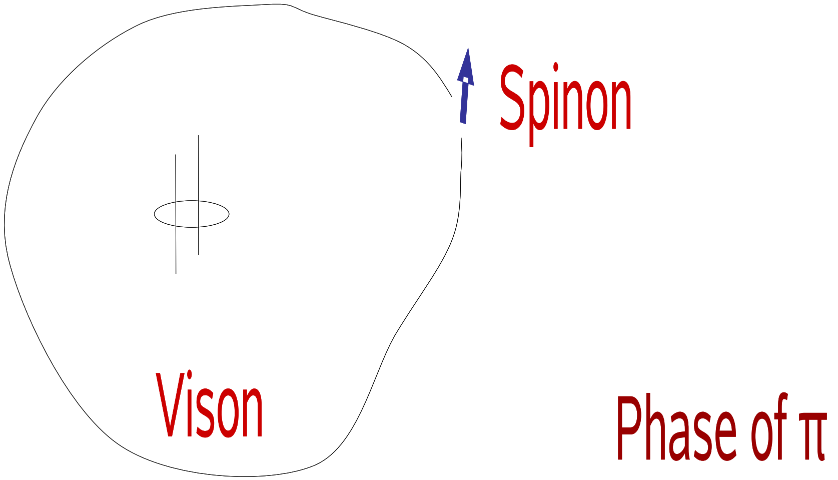
Example of spin liquid with nodal spinons

Gapless Z_2 spin liquid:

Conserved Z_2 gauge flux (= ``vison”).

Doping a Z_2 spin liquid – attractive theory of cuprates but apparently not supported by experiments

(eg: no evidence for visons or their consequences – Bonn-Moler flux-trapping and other experiments).

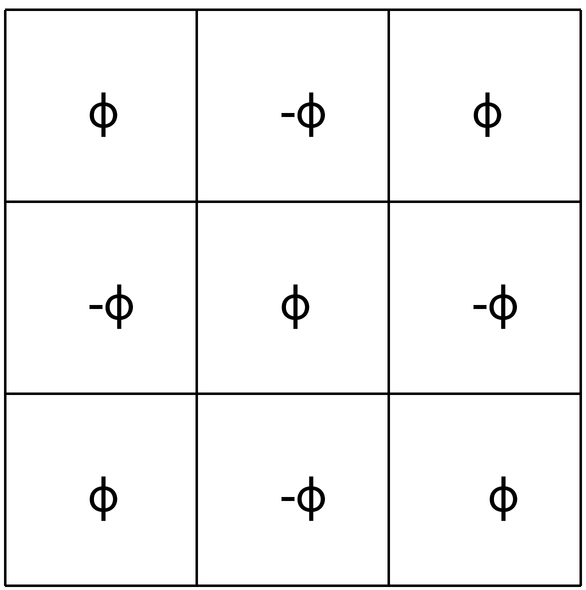


Are there any other alternatives??

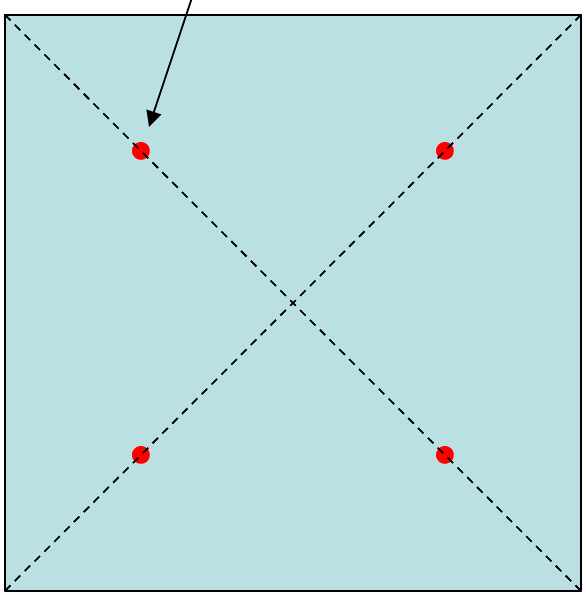
Alternate possibility: gapless U(1) spin liquids

- Affleck-Marston '88: Flux phase of large-N spin models.

Mean field: Half-filled tight binding band of fermionic spinons (f) with
a staggered flux through each plaquette (no real breaking of lattice symmetry)



Band structure: four gapless Fermi points



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

Beyond mean field

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

Compactness: Allow for monopole events in space-time where the gauge flux changes by 2π.

Ultimate fate?? Confinement??

- Doped versions: Lee, Nagaosa, Wen, ……..

(1996 - ….)

Mostly ignore possibility of confinement.

Stability of gapless U(1) spin liquids

Hermele,TS,Fisher,Lee,Nagaosa,Wen,

cond-mat/0404751

- Monopole events irrelevant for low energy physics – at least within a systematic 1/N expansion (N: number of Dirac species)

Low energy theory is critical with no relevant perturbations (non-compact QED$_3$) :

conformally invariant with power law spin correlations.

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

Physics of the gapless U(1) spin liquid

Monopoles irrelevant ~ ``deconfined'' spinons.

Precise meaning of ``deconfinement'': extra global topological U(1) symmetry associated with gauge flux conservation.

Power-law correlations in various physical quantities
(staggered magnetization, VBS order, etc….).

Gauge flux conservation is physical – can in principle be measured!

Doping the U(1) spin liquid

A natural possibility [realized in slave boson mean field calculations (Lee, Nagaosa, Wen, ...)]

Doped holes spin-charge separate

⇒ Spin of holes carried away by spinons leaving behind spinless-charged bosons which condense to give dSc.

[Alternate:

Doped holes retain spin and charge

⇒ At low doping get exotic small Fermi surface metal violating conventional Luttinger theorem]

Decay routes of hole

- Both $f^\dagger_\uparrow$ and $f_\downarrow$ operators create an up spin

=> Expect

$$c^+_\uparrow = b_1 f^+_\uparrow + b_2 f_\downarrow$$

$b_{1,2}$ = spin − 0 bosons with physical charge e but with opposite gauge charges ± 1.

$b_1 b_2$ = gauge neutral spin - 0 boson with physical charge 2e

= identify with Cooper pair. >

Physics at finite doping

- Superconductivity: Both bosons condense (=> physical Cooper pair is condensed).

- Nernst region: Bosons have local amplitude but

phase fluctuates.

- High-T pseudogap: Bosons above their `degeneracy' temperature (=> ``incoherent'')

Is all this really correct?

Experimental tests

- Crucial ingredient

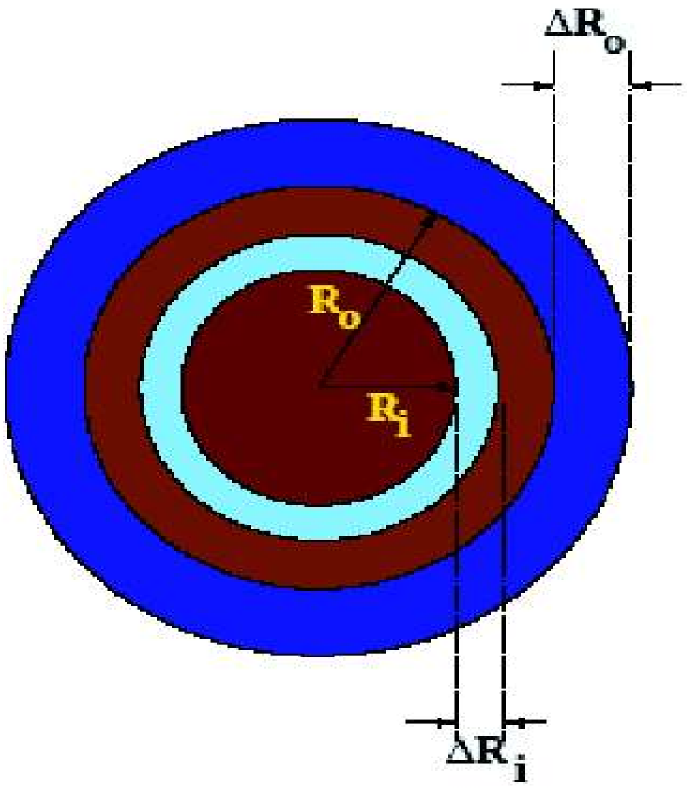
Conservation of gauge flux of undoped spin liquid approximately true at finite-T in doped normal state; justifies use of slave particle degrees of freedom.

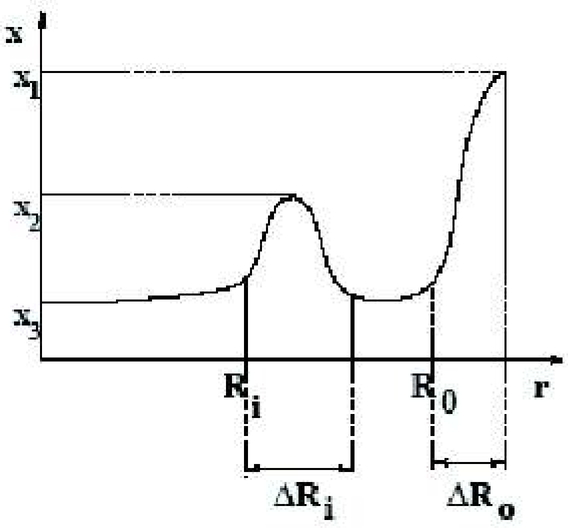
=> Crucial experiment: directly detect the gauge flux.

An idea for a gauge flux detector

TS, Lee, cond-mat/0406066

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 => π 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.

Other possible tests

- Spin physics in high-T pseudogap region

expected to be only weakly modified from undoped spin liquid

=> Approximate characteristic finite-T scaling in number of measurable correlators (eg: in (π,π) spin response)

Summary-I

- View of underdoped cuprates as doped Mott paramagnets very appealing starting point.

- Experiments tightly constrain nature of paramagnet to dope.

Current understanding of Mott paramagnet allows for only one surviving candidate – the gapless U (1) spin liquid

Summary-II

- Gapless U(1) spin liquids potentially stable in two dimensions, have low energy ``gauge fluctuations'' characterized by extra conserved quantity (gauge flux) not present in microscopic model.

$\Rightarrow$ Gauge flux is physical.

Doped version: Proposal for experiment to detect gauge flux.

Large number of open questions ----------------------------→

Some open questions-I
Phenomenology

- Description of location of nominal ``Fermi surface”?

(Why does leading edge more or less match band theory? How does node of dSc move away from spinon node at (π/2, π/2)?)

- Description of Fermi arcs?

(Early crude attempt (Wen, Lee) manages to get Fermi pocket with Z small in back portion)

- Velocity anisotropy of nodal quasiparticles?

(At spin liquid fixed point, expect no velocity anisotropy for spinons – can this evolve into large anisotropy seen in dSc?)

- Slope of penetration depth versus T inside dSc?

(Simplest calculations: slope ~ x^2 in disagreement with expt on moderately underdoped samples).

Some open questions-II

Basic theory

2. Stability of U(1) spin liquid at half-filling established for large enough $N > N_c$.

Is $N_c < 2$ so that SU(2) spin models have such phases?

(Current numerical evidence: N_c at least < 4)

Needed: numerics to determine N_c. .

What if Nc > 2 – can theory be salvaged? (see TS, Lee, cond-mat/0406066 for a suggestion)

2. Better theoretical control on charge physics in doped spin liquids.

3. Better microscopic understanding for why doping might push spins into spin liquid state

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*.

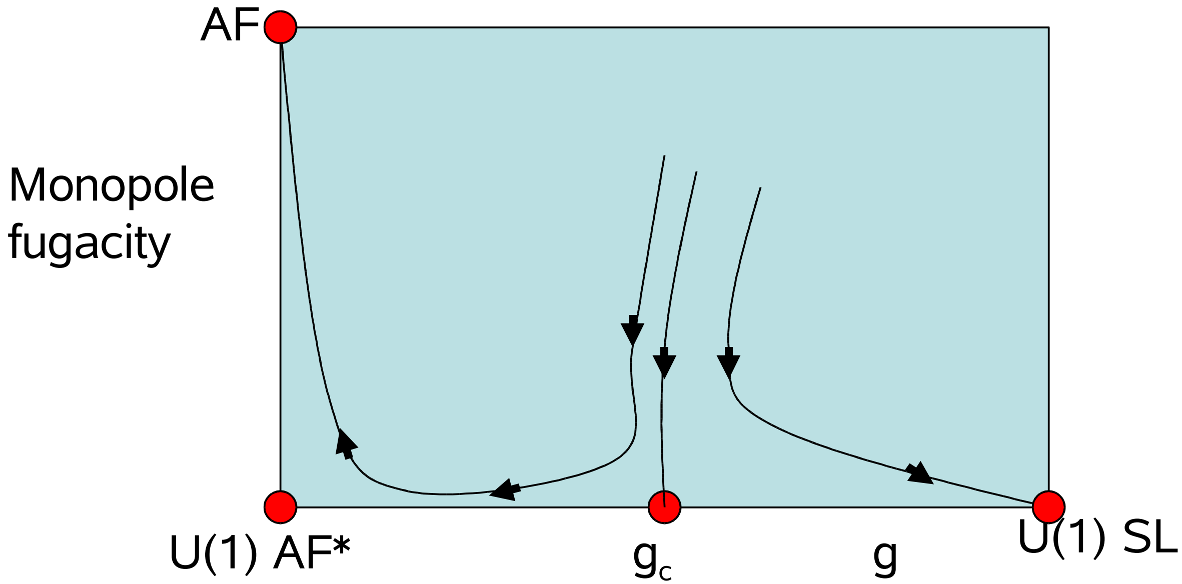
N_{c1} < 2 => appealing description of cuprates as doped U(1) spin liquids.

*Indications from numerics: $N_{c1}<4$ (Assaad, cond-mat/0406…)

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.



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}

Summary, conclusions -II

- 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!


b1
c↑
f↑
b2
c↑
f†↓