Quantum spin fluid states of frustrated quantum magnets

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Spin liquids and other exotica in quantum magnets

- Traditional quantum magnetism: Ordered ground states

(Neel, spin Peierls, …………)

Concept of broken symmetry

Modern theory (last 2 decades): Possibility of `spin liquid' states in any dimension d.

Eg: Mott insulators with 1 electron/unit cell with no broken symmetry

Maturing theoretical understanding -

extensive developments in last few years

What is a quantum spin liquid?

Rough description: Quantum paramagnet that does not break any symmetries of microscopic Hamiltonian.

More precise: Mott insulator with ground state NOT smoothly connected to band insulator.

Well known in $d=1$ spin chains.

Some natural questions

Can quantum spin liquids exist in d > 1? (Anderson '73)

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Theoretical question

Do quantum spin liquids exist in d > 1?

Experimental question

Some natural questions

Can quantum spin liquids exist in d > 1? (Anderson '73)

Theoretical question: YES!!

Do quantum spin liquids exist in d > 1?

Experimental question: Remarkable new materials possibly in spin liquid phases

- talk by Kanoda (Tuesday 9 am)
- talk by Y.S. Lee (Wednesday 10.30 am)

(Also solid He3 in 2d, talk by Saunders Monday 5 pm)

Why are quantum spin liquids interesting?

1. Exotic excitations

Excitations with fractional spin (spinons),

non-local emergent interactions described through gauge fields

As rich in possibility if not richer than the fractional quantum Hall systems………..but requires less extreme conditions (eg: no strong B-fields)

Why are quantum spin liquids interesting?

2. Ordering not captured by concept of broken symmetry

- new concepts of `topological order' and generalizations

Order is a global property of ground state wavefunction

Possibility of encoding information non-locally.

?? Useful for computing?? (Kitaev)

Why are quantum spin liquids interesting?

3. Platform for onset of many unusual phenomena

Eg: (i) Superconductivity in doped Mott insulators

?? Relevant to cuprates ??

(Anderson '87; Kivelson, Rokhsar, Sethna '88)

(ii) Non-fermi liquid phenomena in correlated d or f-electron metals.

Why are quantum spin liquids interesting?

4. Excellent experimental setting for exploration of violation of long cherished notions of condensed matter physics

- quasiparticles with fractional quantum numbers and unusual statistics

- the very existence of a quasiparticle description

- inadequacy of Landau order parameter to describe phases and phase transitions of correlated matter

Stability of spin liquids

1. Solution of concrete quantum spin models within 1/N expansions (Read, Sachdev '91)
   Similar general theoretical arguments (Wen '91)

2. Effective field theory descriptions (Read, Sachdev '91; Wen '91; TS, Fisher'00,…..)

3. Solution of concrete effective models of quantum dimers (Moessner,Sondhi'01; Misguich,Serban,Pasquier'02;….)

4. Exact solution of various quantum spin models (Kitaev'97,'06;Balents,Fisher,Girvin '02;Wen'02,……)

5. Numerical calculations on simpler and more realistic models (Misguich,Lhuillier'98;Sheng,Balents'05;,Isakov,Paramekanti,Kim,Sen,Damle'07)

Wavefunctions

An example

Anderson '87

Ground state : $|\Psi_{gd}\rangle = P_G \,|\text{s-wave gapped BCS}\rangle$

P_G : Gutzwiller projection to 1 electron/site ;

yields RVB spin wave function .

Spinon excitations $|\text{spinon}\rangle = P_G \,|\text{BCS quasiparticle}\rangle$

Projection "neutralizes" the charge to leave behind a spinon .

Other excitations

Excitations of a superconductor - (i) quasiparticles

(ii) $hc/2e$ vortices

$$P_G |BCS\rangle \rightarrow |\text{spin liquid}\rangle$$

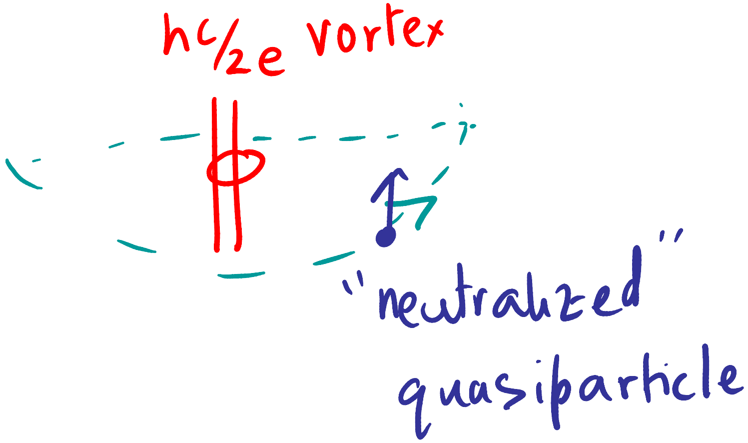
$$P_G |\text{quasiparticle}\rangle \rightarrow |\text{spinon}\rangle$$

$$P_G | hc/2e \text{ vortex}\rangle = |v\rangle = ??$$

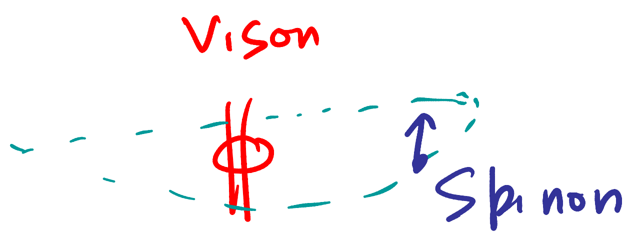
$|v\rangle$: a "topological" excitation of the spin liquid

("vison": TS, Fisher '00)

Full description of excitation spectrum



: Phase of π



: Phase of π

Full excitation spectrum: Spin-$\frac{1}{2}$ spinons, spin-0 visons with infinitely non-local "stastical" interaction.

Utility of gauge theory

Convenient mathematical formulation of non-local interaction :

Spinons – Ising "electric charge"

Visons – Ising "magnetic flux"

Non-locality : Aharanov-Bohm interaction

Gauge theory forced upon us as natural language for describing spin liquids.

Varieties of spin liquids

Different kinds of spin liquids with different "emergent" gauge structure.

Eg: $U(1)$ spin liquids in $d=3$ quantum magnets

- spinons with emergent Coulomb interaction mediated by emergent photon.

(Wen, Motrunich, TS, Hermele, Fisher, Balents, ...)

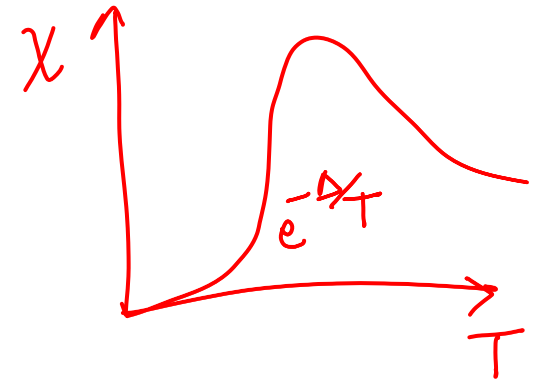
Recent numerical confirmation: Bannerjee et. al. '07

A useful distinction:

Gapped versus gapless spin spectrum

(i) Spin liquids with spin gap

Best understood theoretically

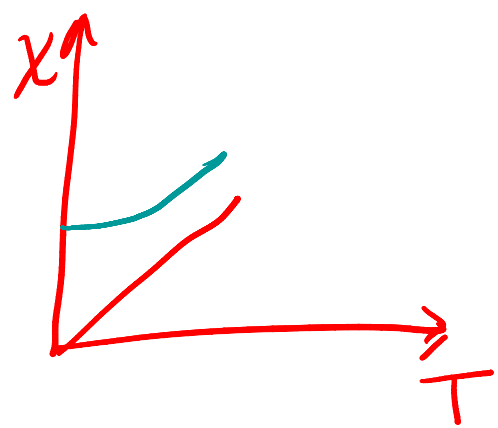


(ii) Spin spectrum may be gapless

Spinons with Fermi statistics

that have Fermi points or

Fermi surfaces ($\Rightarrow$ Nontrivial low-T thermal transport)



The frontier: Critical spin liquids

(Self Organized Quantum Criticality)

Certain gapless spin liquids with unusual low energy physics in $d = 2$.

(i) Scale invariant excitation spectrum

(ii) Breakdown of quasiparticle concept

- no particle description of spectrum.

(iii) Slow power law correlations for various orders

- either at isolated k-points or even along entire lines.

Possible examples

(i) $d_{x^2-y^2}$ - RVB / staggered flux spin liquid in d=2 □ lattice

$$|\psi_{gd}\rangle = P_G \, |d\text{-wave BCS}\rangle$$

(ii) Spinon Fermi surface state proposed for organics (Motrunich '05, Lee & Lee '05)

$$|\psi_{gd}\rangle = P_G \, |\text{Fermi sea}\rangle$$

Can critical spin liquids exist?

For d-RVB state, answer within systematic 1/N expansion: (Hermele, TS, Fisher, Lee, Nagaosa, Wen '04)

Stable critical spin liquid phase for N large enough!

Many similarities to d=1 S=½ antiferro chain

Slow power laws for Neel, dimer, etc (Rantner, Wen '02; Hermele, TS, Fisher '05)

"d=2 Luttinger-like liquid"

Experimental signatures of critical spin liquids

(i) Scale invariant spin fluctuation spectrum

$$\int d^2q \; \chi''(q, \omega, T) \sim \omega^{\alpha} F(\omega / T) \quad (\alpha \geq 0 \, ?)$$

(ii) Sharp "$2k_F$"-like structures in q-space

(iii) Nontrivial thermal transport at low-T

Critical spin liquids are important but challenging!

Important : Experiments on

(a) Spin-$1/2$ Kagome magnet (Y.S. Lee Wednesday talk)

(b) κ-$(ET)_2Cu(CN)_3$ (Kanoda, next talk)

– likely critical spin liquid systems

Also important for hiTc theory ..

Challenging : Only one known theoretical technique

Fermionic spinon mean field + gauge fluctuations

Poor analytic control

Summary/outlook

- Maturing theoretical understanding of quantum spin liquid phases in $d > 1$

- Theoretically demonstrable violations of long cherished notions of condensed matter physics

- Interesting candidate materials exist – exciting times ahead!

- Important general lessons for correlated metallic systems