Spin liquids on the triangular lattice
1. Classification of spin liquids
   *Quantum-disordering magnetic order vs. projected Fermi sea*

2. Quantum-disordering magnetic order
   *Application to $\kappa-(ET)_2Cu_2(CN)_3$*

3. Fermi surfaces of spinful Majorana fermions
   *Candidate for EtMe$_3$Sb[Pd(dmit)$_2$]*
Outline

1. Classification of spin liquids
   Quantum-disordering magnetic order vs. projected Fermi sea

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   Application to $\kappa$-(ET)$_2$Cu$_2$(CN)$_3$

3. Fermi surfaces of spinful Majorana fermions
   Candidate for EtMe$_3$Sb[Pd(dmit)$_2$]$_2$?
Fractionalization of the electron spin and charge
Fractionalization of the electron spin and charge

A) Quantum “disordering” magnetic order

\[
\begin{pmatrix}
c_{\uparrow} \\
c_{\downarrow}
\end{pmatrix}
= \begin{pmatrix}
z_{\uparrow} & -z_{\downarrow}^* \\
-\z_{\downarrow} & z_{\uparrow}^*
\end{pmatrix}
\begin{pmatrix}
\psi_+ \\
\psi_-
\end{pmatrix}
\]
Fractionalization of the electron spin and charge

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\psi_+ \\
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\]

Neutral bosonic spinons which transform to a rotating reference from along the local antiferromagnetic order.
Fractionalization of the electron spin and charge

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spinless charge -e fermions
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\( SU(2)_{\text{spin}} \)
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\]

Theory has SU(2)_s gauge invariance
Fractionalization of the electron spin and charge

B) Projected Fermi sea

\[
\begin{pmatrix}
  c^\uparrow \\
  c^\downarrow \\
  c_\uparrow^{\dagger}
\end{pmatrix}
= 
\begin{pmatrix}
  b_1^* & b_2^* \\
  -b_2 & b_1
\end{pmatrix}
\begin{pmatrix}
  f_1 \\
  f_2^{\dagger}
\end{pmatrix}
\]

Fractionalization of the electron spin and charge

B) Projected Fermi sea  

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  f_2^\dagger
\end{pmatrix}
\]

charge $e$ spinless bosons (or “rotors”) whose fluctuations project onto the single electron states on each site


Monday, January 10, 2011
Fractionalization of the electron spin and charge

B) Projected Fermi sea

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  f_1 \\
  f_2^\dagger \\
\end{pmatrix}
\]

neutral fermionic spinons


Monday, January 10, 2011
Fractionalization of the electron spin and charge

B) Projected Fermi sea

\[
\left( \begin{array}{c} c^\uparrow \\ c^\downarrow \end{array} \right) = \bullet \left( \begin{array}{cc} b_1^* & b_2^* \\ -b_2 & b_1 \end{array} \right) \left( \begin{array}{c} f_1 \\ f_2^\dagger \end{array} \right)
\]

**SU(2) pseudospin ⊆ U(1) charge**
Fractionalization of the electron spin and charge

B) Projected Fermi sea

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\end{pmatrix}
\cdot
\begin{pmatrix}
    f_1 \\
    f_2^\dag
\end{pmatrix}
\]

\(SU(2)_{\text{spin}}\)

Fractionalization of the electron spin and charge

(b) Projected Fermi sea

Theory has $SU(2)_p$ gauge invariance


$\begin{pmatrix} c^\uparrow \\ c^\uparrow \end{pmatrix} = \begin{pmatrix} b_1^* & b_2^* \\ -b_2 & b_1 \end{pmatrix} \bullet \begin{pmatrix} f_1 \\ f_2^\dagger \end{pmatrix}$
Fractionalization of the electron spin and charge

B) Projected Fermi sea

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\]

On the triangular lattice, this leads to a U(1) spin liquid with a Fermi surface of spinons which has been proposed to apply to EtMe$_3$Sb[Pd(dmit)$_2$]$_2$. 
Fractionalization of the electron spin and charge

**B) Projected Fermi sea**

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = \begin{pmatrix} b_1^* & b_2^* \\ -b_2 & b_1 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2^\dagger \end{pmatrix}$$

On the triangular lattice, this leads to a U(1) spin liquid with a Fermi surface of spinons which has been proposed to apply to EtMe$_3$Sb[Pd(dmit)$_2$]$_2$.

This spin liquid has a thermal Hall response which is not observed.
Complete fractionalization: separate excitations carrying spin, charge, and Fermi statistics

**Complete fractionalization:** separate excitations carrying spin, charge, and Fermi statistics

Decompose electron operator into real fermions, \( \chi \):

\[
c_{\uparrow} = \chi_1 + i\chi_2 ; \quad c_{\downarrow} = \chi_3 + i\chi_4
\]

Introduce a 4-component Majorana fermion \( \zeta_i, \ i = 1 \ldots 4 \) and a SO(4) matrix \( \mathcal{R} \), and decompose:

\[
\chi = \mathcal{R} \zeta
\]

---

**Complete fractionalization:** separate excitations carrying spin, charge, and Fermi statistics

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$$\chi = \bullet \mathcal{R} \zeta$$

$$\text{SO}(4) \cong \text{SU}(2)_{\text{pseudospin}} \times \text{SU}(2)_{\text{spin}}$$

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$$
\chi = R \bullet \zeta
$$

$SO(4)_{\text{gauge}} \cong SU(2)_{p;\text{gauge}} \times SU(2)_{s;\text{gauge}}$

Complete fractionalization: separate excitations carrying spin, charge, and Fermi statistics

Decompose electron operator into real fermions, $\chi$:

$$c_{\uparrow} = \chi_1 + i\chi_2 \quad ; \quad c_{\downarrow} = \chi_3 + i\chi_4$$

Introduce a 4-component Majorana fermion $\zeta_i$, $i = 1 \ldots 4$ and a SO(4) matrix $\mathcal{R}$, and decompose:

$$\chi = \mathcal{R} \zeta$$

By breaking SO(4)$_{\text{gauge}}$ with different Higgs fields, we can reproduce essentially all earlier theories of spin liquids. We also find many new spin liquid phases, some with Majorana fermion excitations which carry neither spin nor charge.

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\[ H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j + \ldots \]

\( \vec{S}_i \Rightarrow \text{spin operator with } S = 1/2 \)
Anisotropic triangular lattice antiferromagnet

Classical ground state for small $J'/J$

Found in $\kappa$-(ET)$_2$Cu[N(CN)$_2$]Cl
Anisotropic triangular lattice antiferromagnet

Classical ground state for large $J'/J$

Found in $\text{Cs}_2\text{CuCl}_4$
Anisotropic triangular lattice antiferromagnet

Valence bond solid

Anisotropic triangular lattice antiferromagnet

Valence bond solid

Anisotropic triangular lattice antiferromagnet

Valence bond solid

Anisotropic triangular lattice antiferromagnet

Valence bond solid

Observation of a valence bond solid (VBS) in ETMe$_3$P[Pd(dmit)$_2$]$_2$

Spin liquid obtained in a generalized spin model with $S=1/2$ per unit cell

$$\frac{1}{\sqrt{2}} \left( |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

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Triangular lattice antiferromagnet

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Triangular lattice antiferromagnet

Spin liquid obtained in a generalized spin model with $S=1/2$ per unit cell

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Spin liquid obtained in a generalized spin model with $S=1/2$ per unit cell.

\[ \frac{1}{\sqrt{2}} \left( \langle \uparrow \downarrow \rangle - \langle \downarrow \uparrow \rangle \right) \]

Spin liquid obtained in a generalized spin model with $S=1/2$ per unit cell

$$\frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Excitations of the $\mathbb{Z}_2$ Spin liquid

A spinon

$$\frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$
Excitations of the $\mathbb{Z}_2$ Spin liquid

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$$= \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$
Excitations of the $\mathbb{Z}_2$ Spin liquid

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Excitations of the $\mathbb{Z}_2$ Spin liquid

A spinon

$$= \frac{1}{\sqrt{2}} \left( |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$
A characteristic property of a $\mathbb{Z}_2$ spin liquid is the presence of a spinon pair condensate.

A vison is an Abrikosov vortex in the pair condensate of spinons.

Visons are the dark matter of spin liquids: they likely carry most of the energy, but are very hard to detect because they do not carry charge or spin.

Excitations of the $\mathbb{Z}_2$ Spin liquid

A vison

$$= \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Excitations of the $\mathbb{Z}_2$ Spin liquid

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**Mutual Chern-Simons Theory**

Express theory in terms of the physical excitations of the $Z_2$ spin liquid: the spinons, $z_\alpha$, and the visons. After accounting for Berry phase effects, the visons can be described by complex fields $v_a$, which transforms non-trivially under the square lattice space group operations.

The spinons and visons have mutual semionic statistics, and this leads to the mutual CS theory at $k = 2$:

$$
\mathcal{L} = \sum_{\alpha=1}^{2} \left\{ |(\partial_\mu - ia_\mu)z_\alpha|^2 + s_z |z_\alpha|^2 \right\} \\
+ \sum_{a=1}^{N_v} \left\{ |(\partial_\mu - ib_\mu)v_a|^2 + s_v |v_a|^2 \right\} \\
+ \frac{ik}{2\pi} \epsilon_{\mu\nu\lambda} a_\mu \partial_\nu b_\lambda + \cdots
$$

Phase diagram of frustrated antiferromagnets

N. Read and S. Sachdev

Cenke Xu and S. Sachdev,
Phase diagram of frustrated antiferromagnets

Valence bond solid (VBS)

Neel antiferromagnet

Spiral antiferromagnet

\(Z_2\) spin liquid

Vanishing of gap to bosonic spinon excitations

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Valence bond solid (VBS) \(
\rightarrow \quad S_v
\)

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$Z_2$ spin liquid

Proposal:

$\kappa-(ET)_2Cu_2(CN)_3$ is here

Proposal: $\kappa-(ET)_2\text{Cu}_2(\text{CN})_3$ is a $Z_2$ spin liquid near a quantum phase transition to magnetic order

- Originally motivated by NMR relation. The quantum critical point has $O(4)$ symmetry and has $1/T_1 \sim T^\eta$ with $\eta = 1.374(12)$.

Spin excitation in $\kappa-(ET)_2Cu_2(CN)_3$

$^{13}$C NMR relaxation rate

$1/T_1 \sim$ power law of $T$

Low-lying spin excitation at low-$T$

Anomaly at 5-6 K

Shimizu et al., PRB 70 (2006) 060510
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- Recent $\mu$SR experiments show field-induced magnetic order at very small fields.

Field-induced QPT from $\mu$SR Line Width

Consistent with high field $^{13}$C NMR broadening of Shimizu et al PRB 73,140407 (2006)

F. Pratt et al. (ISIS, UK) preprint
Tiny $H_0$ implies that spin gap per spin1/2 is $\Delta_z \sim 3.5$ mK!

2D BEC:

$$T_c \propto \mu \frac{\ln(t_0/\mu)}{\ln \ln(t_0/\mu)}$$

$$\mu \propto H - H_0$$

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- Thermal conductivity is dominated by contribution of visons, and activated by the vison gap.

Thermal conductivity of $\kappa-(ET)_2\text{Cu}_2(CN)_3$

\[ \kappa = \alpha \exp\left( \frac{-\Delta}{k_B T} \right) + \beta T^3 \]

- Arrhenius behavior for $T < \Delta$
- Tiny gap $\Delta = 0.46 \text{ K} \sim J/500$

M. Yamashita et al., Nature Physics 5, 44 (2009)
Proposal: $\kappa$-(ET)$_2$Cu$_2$(CN)$_3$ is a $Z_2$ spin liquid near a quantum phase transition to magnetic order

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Shastry-Kitaev Majorana representation

On each site, we introduce neutral Majorana fermions $\gamma_i^0$, $\gamma_i^x$, $\gamma_i^y$, $\gamma_i^z$ which obey

$$\gamma_i^\alpha \gamma_j^\beta + \gamma_j^\beta \gamma_i^\alpha = 2 \delta_{ij} \delta_{\alpha\beta}$$

We write the $S = 1/2$ spin operators as

$$S_{jx} = \frac{i}{2} \gamma_j^y \gamma_j^z$$
$$S_{jy} = \frac{i}{2} \gamma_j^z \gamma_j^x$$
$$S_{jz} = \frac{i}{2} \gamma_j^x \gamma_j^y$$

along with the constraint

$$\gamma_j^0 \gamma_j^x \gamma_j^y \gamma_j^z = 1 \quad \text{for all } j$$
• Postulate an SU(2)-invariant effective Hamiltonian for physical $S = 1$ excitations created by Majorana fermions $\gamma_{ix}, \gamma_{iy}, \gamma_{iz}$.
SU(2)-invariant spin liquids with neutral, spinful Majorana excitations

- Postulate an SU(2)-invariant effective Hamiltonian for physical $S = 1$ excitations created by Majorana fermions $\gamma_{ix}, \gamma_{iy}, \gamma_{iz}$.

- Ensure there is a Projective Symmetry Group (PSG) under which physical observables have the full translational symmetry of the triangular lattice.

Rudro Biswas, Liang Fu, Chris Laumann, and S. Sachdev, to appear
• Postulate an SU(2)-invariant effective Hamiltonian for physical $S = 1$ excitations created by Majorana fermions $\gamma_{ix}, \gamma_{iy}, \gamma_{iz}$.

• Ensure there is a Projective Symmetry Group (PSG) under which physical observables have the full translational symmetry of the triangular lattice.

• Examine stability of the effective Hamiltonian to gauge fluctuations.

Rudro Biswas, Liang Fu, Chris Laumann, and S. Sachdev, to appear
Majorana fermions on the triangular lattice

\[ H = -i \sum_{\alpha=x,y,z} \sum_{i<j} t_{ij} \gamma_i \alpha \gamma_j \alpha \]

where \( t_{ij} \) is an anti-symmetric matrix with the following symmetry

Rudro Biswas, Liang Fu, Chris Laumann, and S. Sachdev, to appear
The Majorana fermions generically have Fermi surfaces with the structure shown. 6 Fermi surface lines intersect at \( \mathbf{k} = 0 \), and the excitation energy \( \sim k^3 \) as \( k \to 0 \).
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Excitation $\sim k - k_F$

Excitation $\sim k^3$
• Time-reversal symmetry ($\mathcal{T}$) and rotation by 60 degrees ($R_{\pi/3}$) are broken, but $\mathcal{T}R_{\pi/3}$ is unbroken.
Physical properties

- Time-reversal symmetry ($\mathcal{T}$) and rotation by 60 degrees ($R_{\pi/3}$) are broken, but $\mathcal{T}R_{\pi/3}$ is unbroken.

- The specific heat and spin susceptibility are dominated by excitations near $\mathbf{k} = 0$, with $C_V \sim T^{2/3}$ and $\chi \sim T^{-1/3}$.

- The thermal conductivity is dominated by fermions along the Fermi line. The excitations near $\mathbf{k} = 0$ move too slowly to contribute to transport.

- There is no thermal Hall transport.

Rudro Biswas, Liang Fu, Chris Laumann, and S. Sachdev, to appear
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• These power-laws are quenched by impurities: details under investigation.
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Physical properties

- Time-reversal symmetry ($T$) and rotation by 60 degrees ($R_{\pi/3}$) are broken, but $TR_{\pi/3}$ is unbroken.

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Conclusions

Unified perspective on spin liquids obtained by projection of a Fermi sea, and by “quantum-disordering” magnetic order.
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$\mathbb{Z}_2$ spin liquid proximate to magnetic order a viable candidate for $\kappa$-(ET)$_2$Cu$_2$(CN)$_3$
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Proposed novel spin liquid with Fermi surfaces of spinful Majorana fermions