Diagnosing phases of magnetic insulators via noise magnetometry with spin qubits

Shubhayu Chatterjee
University of California, Berkeley

Yao Lab Group Meeting
February 15, 2019
In collaboration with:

Joaquin F. Rodriguez-Nieva
Harvard University

Eugene Demler
Harvard University

SC, J. F. Rodriguez-Nieva and E. Demler

arXiv:1810.04183
Conventional phases of matter

- Paradigm of symmetry breaking and local order parameters

At room temperature, this magnet attracts iron pins.

When heated, it stops doing so

Solid ice → Liquid water
Conventional phases of matter

- Paradigm of symmetry breaking and local order parameters

- Density is non-uniform
- Moments are aligned

- Density is uniform
- Moments point random

Order parameter: Density
Order parameter: Magnetization

- Symmetry is broken
- Non-zero local order parameter

Lev. D. Landau
• Unconventional phases of matter in magnetic insulators

• NV centers as quantum sensors in condensed matter

• Footprints of a phase in magnetic noise

• Sensing anyonic statistics using NVs

• Material candidates

• Conclusions and outlook
Unconventional phases of matter in magnetic insulators

• NV centers as quantum sensors in condensed matter
• Footprints of a phase in magnetic noise
• Sensing anyonic statistics using NVs
• Material candidates
• Conclusions and outlook
Unconventional phases of matter

• Not described by broken symmetries or local order parameters

• Consider an insulator: Degrees of freedom are spins

• Frustration or larger quantum fluctuations: Additional possibilities beyond the paradigm of symmetry breaking

Antiferromagnetic exchange causes geometric frustration in non-bipartite lattices
Different possible phases of 2d magnetic insulators:

- **Quantum spin liquids:**
  - No broken symmetry
  - Long range entanglement + topological order
  - May be gapped or gapless

- **Valence bond solids (VBS):**
  - Broken translation symmetry
  - Gapped triplon (S=1) excitations

- **Disordered random singlet phases:**
  - Statistically preserves translation symmetry
  - Long-range singlets but topologically trivial

Figures: T. Senthil (MIT), S. Sachdev (Harvard), Kimchi *et al*, PRX 2018
Quantum spin liquids

Quantum spin liquids

Quantum spin liquids

Quantum spin liquids

Quantum spin liquids

• Long range entanglement: Non-trivial ground state degeneracy on a cylinder/torus: Can be used as stable qubits for quantum computation!

• More curiously, the excitations carry fractional quantum numbers of global symmetry (like $S = 1/2$ spinons) and are coupled to emergent gauge fields

• Gauge flux and spinon are mutual semions (like e and m particles of the Kitaev toric code)


Excitations in spin liquids: $S = \frac{1}{2}$ Spinons

- Low energy excitations: $S = \frac{1}{2}$ spinons, must occur in pairs

Figure: S. Sachdev (Harvard)
Excitations in ordered phases: $S = 1$ Magnons

- Contrast this with a magnetically ordered phase (ferromagnets or antiferromagnets)

- Low energy excitations: $S = 1$ magnons, Goldstone bosons of broken spin-rotation symmetry

Figure: rug.nl/research/zer

VBS phases

- Clean VBS phases break lattice translation symmetry
- Gapped S = 1 triplon excitations (discrete broken symmetry, no Goldstone modes)
- May have non-trivial triplon bands with gapless chiral edge modes

What is the fate of the VBS phase in presence of disorder?
Disordered VBS phases

- Disordered VBS phases in two dimensions naturally nucleate defects
- Defects carry spin-half because of topological reasons
- The low energy physics is governed by this random network of weakly coupled spins

\[ H_{\text{eff}} = \sum_{i,j} J_{i,j}^{\text{eff}} \mathbf{S}_i \cdot \mathbf{S}_j \]

Kimchi et al., PRX 2018
Quantum spin liquids in experiments

• Traditionally, cool down to very low temperatures, and look for signatures of *nothing*


![Graph showing linear thermal conductivity](image1)

*Linear in T thermal conductivity*

![Neutron scattering spectrum](image2)

*Broad continuum of two-particle like spectrum in neutron scattering*
• Unconventional phases of matter in magnetic insulators

• NV centers as quantum sensors in condensed matter

• Footprints of a phase in magnetic noise

• Sensing anyonic statistics using NVs

• Material candidates

• Conclusions and outlook
NV centers as quantum sensors

• Issues with transport/neutron scattering: contamination by phonons, lack of low energy resolution, etc

Can we probe the fractional spin-excitations directly and exclusively?

• Enter NV centers as quantum sensors of magnetic fluctuations!

• Measures AC magnetic noise at frequency $\omega_{\text{probe}}$

• In insulators, dominated by spin fluctuations due to large charge gap
NV centers as quantum sensors

- Polarized/Initialized via laser pumping
- Read-out via spin-dependent fluorescence

Figure: S. Hsieh (UC Berkeley)
NV centers as quantum sensors

- Couples efficiently to magnetic field created by fluctuating spins
- Sensitive to only spin-correlations (avoids phonons, charged disorder, localized modes etc)
- Excellent momentum (up to few nm) and energy resolution (up to few mK)
- Optical initialization and readout capabilities
- Minimally invasive (no external drive required)
NV centers as quantum sensors

- Relaxation time is sensitive to magnetic noise at momenta $q \sim d^{-1}$ and energy $\omega = \omega_{\text{probe}}$

$$\frac{1}{T_1} = \left( \frac{g_\sigma \mu_B \mu_0}{2} \right)^2 \coth \left( \frac{\omega}{2T} \right) \int \frac{d^2 q}{(2\pi)^2} F(d, q) \left[ \frac{1}{4} \left( S_{-+}(q, \omega) + S_{+-}(q, \omega) \right) + S_{zz}(q, \omega) \right], \quad F(d, q) \sim q^2 e^{-2qd}$$

- $S_{\alpha\beta}(q, \omega)$ is the retarded spin-spin correlation function in Fourier space
Outline

• Unconventional phases of matter in magnetic insulators

• NV centers as quantum sensors in condensed matter

• Footprints of a phase in magnetic noise

• Sensing anyonic statistics using NVs

• Material candidates

• Conclusions and outlook
Sensing quantum spin liquids

• Distinct behavior of $1/T_1$ as a function of experimentally tunable knobs:
  1. Probe frequency $\omega$
  2. Temperature $T$
  3. Sample-probe distance $d$
Sensing quantum spin liquids

- For a single magnetic dipole, \( B \approx \mu_0 \mu_B S_i / D^3 \)

\[
\frac{1}{T_1} \approx \mu_0^2 \mu_B^4 \sum_{i,j} \langle [S_{i\alpha} / D^3, S_{j\alpha} / D^3] \rangle_{\omega} = \frac{\mu_0^2 \mu_B^4}{D^6} \int d^2 \mathbf{r} \int d^2 \mathbf{r} \langle [S_{\alpha}(\mathbf{r}), S_{\alpha}(0)] \rangle_{\omega}
\]

- For a paramagnet, \( \langle [S_\alpha(\mathbf{r}), S_\alpha(0)] \rangle \sim e^{-r/\xi} \) so \( \frac{1}{T_1} \sim D^{-4} \)

- For a gapless spin liquid, \( \langle [S_\alpha(\mathbf{r}), S_\alpha(0)] \rangle \sim 1/r^\delta \) so \( \frac{1}{T_1} \sim D^{-(2+\delta)} \)
Sensing quantum spin liquids

• Concrete computation on Kitaev’s honeycomb model

• Exactly solvable model with a spinon Dirac cone (time-reversal preserved), spinon Fermi surfaces (time-reversal broken)

• Effect of disorder can be studied by mapping onto the problem of phase transition between trivial and integer quantum hall phase

Ludwig et al, PRB 1994
### Sensing quantum spin liquids

#### Parameter dependences of $1/T_1$

<table>
<thead>
<tr>
<th></th>
<th>$T$ dependence</th>
<th>$d$ dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clean</td>
<td>Dirty</td>
</tr>
<tr>
<td>$\omega \ll T$</td>
<td>$T^2$</td>
<td>$T^{2-\alpha_1}$</td>
</tr>
<tr>
<td>$Z_2$ Dirac</td>
<td>$T^0$</td>
<td>$T$</td>
</tr>
<tr>
<td>$U(1)$ FS</td>
<td>$T$</td>
<td>$T$</td>
</tr>
</tbody>
</table>

#### Contrast with ordered phases

<table>
<thead>
<tr>
<th></th>
<th>$\omega, T$</th>
<th>$d^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>$T$</td>
<td></td>
</tr>
<tr>
<td>AFM</td>
<td>$\omega^3 T$</td>
<td>$d^0$</td>
</tr>
</tbody>
</table>

#### Contrast with trivial paramagnet

\[
\frac{1}{T_1} \propto d^{-4}
\]

A. Kitaev, Annals Phys. 2006
Song, You, Balents, PRL 2016

#### Time reversal symmetry

- **Preserved**
- **Broken**
Sensing disordered VBS phases

- Clean VBS phases are gapped
- For a disordered VBS phase, the low energy physics is governed by a random network of weakly coupled spins, with a power law behavior of coupling $J$ (appears gapless)

\[ \frac{1}{T_1} \sim (\omega - \Delta_T)e^{-2d\sqrt{2m(\omega-\Delta_T)}}\Theta(\omega - \Delta_T) \]

Kimchi et al, PRX 2018

- Characteristic dip in $T_1$ at $\omega = h$ due to resonance
• Unconventional phases of matter in magnetic insulators
• NV centers as quantum sensors in condensed matter
• Footprints of a phase in magnetic noise
• Sensing anyonic statistics using NVs
• Material candidates
• Conclusions and outlook
Sensing anyonic statistics

- Identical particles in a two-dimensional world can have arbitrary phases under exchange – neither bosons nor fermions!

- Correlation functions of local observables have a robust universal threshold behavior depending on statistics parameter $\alpha$

\[
\begin{align*}
    \text{Boson: } & e^{i\pi \alpha} = 1 \\
    \text{Fermion: } & e^{i\pi \alpha} = -1
\end{align*}
\]

Morampudi et al, PRL 2017

Sensing anyonic statistics

- If the anyons carry spin, this translates to a universal relaxation rate at low energy for NV centers

\[ \frac{1}{T_1} \sim (\omega - \Delta_s)^{2+\alpha} \Theta(\omega - \Delta_s) \]

- Example: chiral spin liquid state with spin-ful semions (\( \alpha = \frac{1}{2} \))

  \[ e^{\pi i \alpha} \]

  Laughlin, Kalmeyer, PRL 1987

- Robust to short-range interactions because of statistical repulsion (except bosons that have logarithmic corrections)

  Morampudi et al, PRL 2017
• Unconventional phases of matter in magnetic insulators
• NV centers as quantum sensors in condensed matter
• Footprints of a phase in magnetic noise
• Sensing anyonic statistics using NVs
• Material candidates
• Conclusions and outlook
Confusion in the material world

- Spin-orbit coupled iridates, like $\alpha$-RuCl$_3$ are well-described by a Kitaev Hamiltonian, but order at low T. Magnetic order can be suppressed by magnetic fields – what is the nature of the tentative spin-liquid phase?
  
  Lampen-Kelly et al, PRL 2017
  Y. Kasahara et al, PRL 2018

- Inorganic compounds like YbMgGaO$_4$ are a subject of debate – spinon Fermi surface vs disordered VBS phase?
  
  Kimchi et al, PRX 2018

- Frustrated $S = 1$ compound Ba$_3$NiSb$_2$O$_9$: Candidate for quadratic band touching spin liquid and spinon Fermi surface.
  
  Xu et al, PRL 2012
  Fak et al, PRB 2017

Noise magnetometry can help answer all these questions
Outline

• Unconventional phases of matter in magnetic insulators

• NV centers as quantum sensors in condensed matter

• Footprints of a phase in magnetic noise

• Sensing anyonic statistics using NVs

• Material candidates

• Conclusions and outlook
Conclusions

- Single spin qubits (like NV centers) can be used to distinguish exotic ground states of magnetic insulators from conventional magnets.

- They can also detect elusive anyonic statistics in gapped systems, provided the anyons carry spin.

- They offer several advantages over conventional solid-state probes.

- Similar experiments have been done for magnetic metals in this group, so I hope insulators are not far away!

Hsieh et al, arXiv: 1812.08796
Conclusions

- Single spin qubits (like NV centers) can be used to distinguish exotic ground states of magnetic insulators from conventional magnets.
- They can also detect elusive anyonic statistics in gapped systems, provided the anyons carry spin.
- They offer several advantages over conventional solid-state probes.

Similar experiments have been done for magnetic metals in this group, so I hope insulators are not far away!

Hsieh et al, arXiv: 1812.08796

Thank you for your attention!