Detecting spin fractionalization in spinon Fermi surface spin liquid: Prediction and Application to YbMgGaO4

Gang Chen (陈钢)
Fudan University, Shanghai
People’s Republic of China
A rare-earth triangular lattice quantum spin liquid: \textbf{YbMgGaO$_4$}

- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2015).
- This is the \textbf{first strong spin-orbit coupled QSL with odd electron filling} and effective spin-1/2.
- It is the \textbf{first} clear observation of $T^{2/3}$ heat capacity. I think it is spinon Fermi surface U(1) QSL.
- Inelastic neutron scattering is consistent with spinon Fermi surface results.
- We understand the microscopic Hamiltonian and the physical mechanism.
Advantage for neutron scattering

Near $T = 0$, low but not-Very-low energy excitation

Yao Shen, Yaodong Li ... GC*, Jun Zhao*  
Nature 2016

Consistent results from Paddock et al, Nature Physics 2016
Parton construction and PSG classification

\[ S_i = \sum_{\alpha\beta} \frac{1}{2} f_{i\alpha}^{\dagger} \sigma_{\alpha\beta} f_{i\beta} \]

\[ H_{\text{MF}} = - \sum_{(rr')} \sum_{\alpha\beta} \left[ t_{rr',\alpha\beta} f_{r\alpha}^{\dagger} f_{r'\beta} + h.c. \right] , \]

<table>
<thead>
<tr>
<th>U(1) QSL</th>
<th>( W_r^{T_1} )</th>
<th>( W_r^{T_2} )</th>
<th>( W_r^{C_2} )</th>
<th>( W_r^{C_6} )</th>
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</thead>
<tbody>
<tr>
<td>U1A00</td>
<td>( I_{2\times 2} )</td>
<td>( I_{2\times 2} )</td>
<td>( I_{2\times 2} )</td>
<td>( I_{2\times 2} )</td>
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<tr>
<td>U1A10</td>
<td>( I_{2\times 2} )</td>
<td>( I_{2\times 2} )</td>
<td>( i\sigma_y )</td>
<td>( I_{2\times 2} )</td>
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<tr>
<td>U1A01</td>
<td>( I_{2\times 2} )</td>
<td>( I_{2\times 2} )</td>
<td>( I_{2\times 2} )</td>
<td>( i\sigma_y )</td>
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<tr>
<td>U1A11</td>
<td>( I_{2\times 2} )</td>
<td>( I_{2\times 2} )</td>
<td>( i\sigma_y )</td>
<td>( i\sigma_y )</td>
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</table>

The U1A00 state is the spinon Fermi surface state that we proposed in Shen, et al, Nature.

Yao-Dong Li, Yuan-Ming Lu, Gang Chen, arXiv 1612.03447
Dynamic spin structure factor

(a) U1A00

(b) U1A01

(c) U1B state

FIG. 2. Dynamic spin structure factor for six free spinon mean-field states other than U1A00. Note the U1A10 Hamiltonian is odd because they do not incorporate the enhanced periodicity due to anticommutative lattice flux.

The evolution of $\omega / B$, as a function of $q$, is zero. In all subfigures, the energy transfer is normalized against the corresponding bandwidth.
Two major questions

1. Whether the continuum represents the fractionalized spinon excitation? Probably most important!

   discussed in our new work
   Yao-Dong Li, Gang Chen, arXiv:1703.01876

2. What is the physical origin of the QSL physics?
Our Roadmap

1. Detect fractionalized excitations, i.e. spinons
   a) detect the fractionalization.
   b) detect the emergent fermion statistics.

2. Detect the emergent U(1) gauge field?

3. Detect the spinon-gauge coupling (i.e. Lorentz coupling)?
Our new idea: explore the weak field regime

Continuing the recent proposal of the spinon Fermi surface U(1) spin liquid state for YbMgGaO$_4$ in Yao-Dong Li, et al, arXiv:1612.03447 and Yao Shen, et al, Nature 2016, we explore the experimental consequences of the external magnetic fields on this exotic state. Specifically, we focus on the weak field regime where the spin liquid state is preserved and the fractionalized spinon excitations remain to be a good description of the magnetic excitations. From the spin-1/2 nature of the spinon excitation, we predict the unique features of spinon continuum when the magnetic field is applied to the system. Due to the small energy scale of the rare-earth magnets, our proposal for the spectral weight shifts in the magnetic fields can be immediately tested by inelastic neutron scattering experiments. Several other experimental aspects about the spinon Fermi surface and spinon excitations are discussed and proposed. Our work provides a new way to examine the fractionalized spinon excitation and the candidate spin liquid states in the rare-earth magnets like YbMgGaO$_4$.

**Reasonable, Feasible, and Predictable.**

Yao-Dong Li, GC, arXiv: 1703.01876
Strong Mott regime: only Zeeman coupling to field

Magnetic field splits the spin-up and down spinon bands
Prediction for dynamic spin structure factor

We predict:
1. The system remains gapless and spinon continuum persists
2. spectral weight shifts
3. the spectral crossing at Gamma point
4. the presence of lower and upper excitation edges

Very different from magnon in the field!!
Summary

1. We propose the weak field regime to detect the behavior of fractionalization.

2. Such a regime is quite feasible in current laboratory settings.

3. Predictions have been made. **It can be immediately tested by inelastic neutron.**

4. It is a small effect, but if it is observed, it gives a very strong support of the QSL ground state in this system. The idea can be well extended to other strong-Mott-insulating QSL systems.

**Lots of isostructure rare-earth materials, lots of opportunity!**

Yao-Dong Li, XQ Wang, GC, PRB 2016
Yao-Dong Li, YM Lu, GC, arXiv 1612.03447
Yao-Dong Li, GC, arXiv: 1703.01876