Fractionalization and its experimental consequences in spin liquids

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Outline

1. Signatures of fractionalization in U(1) spin liquid?

   GC PRB 94,205107 (2016)
   GC PRB 96,085136 (2017)
   GC arxiv1706.04333(2017)

2. Spin quantum number fractionalization in YbMgGaO4?
   Is it spinon Fermi surface spin liquid?

   YD Li, XQ Wang, GC*, PRB 94, 035107 (2016)
   YD Li, XQ Wang, GC*, PRB 94, 201114 (2016)
   YD Li, Y Shen, YS Li, J Zhao, GC*, arXiv 1608.06445
   YD Li, YM Lu, GC*, PRB 96, 054445 (2017)
   YD Li, GC*, PRB 96, 075105 (2017)
   Y Shen, YD Li, .., GC*, J Zhao*, arXiv 1708.06655
The odd number “2”

Chenjie Wang
(PI, Canada -> City University of Hong Kong, China)
Spin ice

Dy$_2$Ti$_2$O$_7$

Pauling entropy in spin ice, Ramirez, etc, Science 1999
Lattice gauge theory for U(1) spin liquid

\[ \mathcal{H}_{XXZ} = \sum_{\langle ij \rangle} J_{zz} S_i^z S_j^z - J_\perp (S_i^+ S_j^- + S_i^- S_j^+) , \]

3rd order degenerate perturbation 
(Hermele, Fisher, Balents 2004)

\[ \mathcal{H}_{\text{eff}} = -\frac{12J_\perp^3}{J_{zz}^2} \sum_{\Omega_p} (S_i^+ S_j^- S_k^+ S_l^- S_m^+ S_n^- + \text{h.c.}) , \]

\[ K = 24J_\perp^3 / J_{zz}^2 \]

\[ E_{rr'} \simeq S_{rr'}^z \]

\[ e^{iA_{rr'}} \simeq S_{rr'}^\pm \]

\[ \mathcal{H}_{\text{LGT}} = -K \sum_{\Omega_d} \cos(\text{curl } A) + U \sum_{rr'} (E_{rr'} - \frac{\eta_{rr'}}{2})^2 \]

inserting spinon matter (Savary Balents 2012)

\[ H = \sum_{r \in I, II} \frac{J_{zz}}{2} Q_r^2 - J_\perp \left\{ \sum_{r \in I} \sum_{\mu, \nu \neq \mu} \Phi_{r+e_\mu}^{\dagger} \Phi_{r+e_\mu} S_{r,r+e_\mu}^+ S_{r,r+e_\nu}^+ + \sum_{r \in II} \sum_{\mu, \nu \neq \mu} \Phi_{r-e_\mu}^{\dagger} \Phi_{r-e_\mu} S_{r,r-e_\mu}^+ S_{r,r-e_\nu}^- \right\} \]
One could think more realistically, ...

- Kramers’ doublet

  \[ H = \sum_{\langle ij \rangle} \left\{ J_{zz} S^z_i S^z_j - J_{\pm} (S^+_i S^-_j + S^-_i S^+_j) \right\} \]
  \[ + J_{\pm \pm} (\gamma_{ij} S^+_i S^+_j + \gamma^*_{ij} S^-_i S^-_j) \]
  \[ + J_{\pm \mp} [S_i^z (\zeta_{ij} S^+_j + \zeta^*_{ij} S^-_j) + i \leftrightarrow j], \]

  Savary, Balents, PRL 2012

- Non-Kramers’ doublet

  \[ H = \sum_{\langle ij \rangle} \left\{ J_{zz} S^z_i S^z_j - J_{\pm} (S^+_i S^-_j + S^-_i S^+_j) \right\} \]
  \[ + J_{\pm \pm} (\gamma_{ij} S^+_i S^+_j + \gamma^*_{ij} S^-_i S^-_j) \]

  S. Onoda, etc, 2009
  Y-D LI, Onoda, Balents, 2012

- Dipole-octupole doublet

  \[ H = \sum_{\langle ij \rangle} J_x S^x_i S^x_j + J_y S^y_i S^y_j + J_z S^z_i S^z_j \]
  \[ + J_{xz} (S^x_i S^z_j + S^z_i S^x_j). \]

  Y-P Huang, GC, M Hermele, PRL 2014
  Y-D LI, GC, PRB 2017

Nd₂Ir₂O₇, Nd₂Sn₂O₇, Nd₂Zr₂O₇, Ce₂Sn₂O₇ do not have a sign problem for QMC on any lattice.
It supports nontrivial phases...
Besides the quantitative differences, are there sharp distinctions between the \( U(1)_{\pi} \) QSL on the left and the \( U(1)_0 \) QSL on the right?

Related by unitary transformation (Hermele, Fisher, Balents 2004)

\[ J_\perp = 0 \]

Transverse spin order

\[ \frac{J_\perp}{J_z} \]

SB Lee, Onoda, Balents 2012

"Magnetic" monopoles

\[ \frac{J^3_{\perp \pm}}{J^2_{zz}} \]

Spinon

Gapless gauge photon

Energy

Low energy scale suppressed intensity

\[ I(\omega) \sim \omega \]

Nic Shannon, etc 2012, Savary, Balents, 2012
Pi flux and the spinon translation

\[ \mathcal{H}_{\text{LGT}} = -K \sum_{\mathcal{O}_d} \cos(\text{curl } A) + U \sum_{rr'} (E_{rr'} - \frac{\eta r}{2})^2 \]

If \( K < 0 \), \( \text{curl } A = \pi \)

If \( K > 0 \), \( \text{curl } A = 0 \)

\[ T^s_\mu T^s_\nu (T^s_\mu)^{-1} (T^s_\nu)^{-1} = \pm 1 \]

Aharonov-Bohm flux experienced by spinon via the 4 translation is identical to the flux in the hexagon.
Pi flux means crystal symmetry fractionalization

\[ T^s_\mu T^s_\nu = -T^s_\nu T^s_\mu \]

2-spinon scattering state in an inelastic neutron scattering measurement

\[ |a\rangle \equiv |q\rangle; z_a \]

construct another 3 equal-energy states by translating one spinon by 3 lattice vector

\[ \begin{align*}
|b\rangle &= T^s_1(1)|a\rangle, \\
|c\rangle &= T^s_2(1)|a\rangle, \\
|d\rangle &= T^s_3(1)|a\rangle
\end{align*} \]

\[ \begin{align*}
T_1|b\rangle &= T^s_1(1)T^s_1(2)T^s_1(1)|a\rangle = +T^s_1(1)[T_1|a\rangle], \\
T_2|b\rangle &= T^s_2(1)T^s_2(2)T^s_1(1)|a\rangle = -T^s_1(1)[T_2|a\rangle], \\
T_3|b\rangle &= T^s_3(1)T^s_3(2)T^s_1(1)|a\rangle = -T^s_1(1)[T_3|a\rangle],
\end{align*} \]

\[ \mathbf{q}_b - \mathbf{q}_a = 2\pi(100) \]

Gang Chen, 1704.02734
Spectral periodicity of the spinon continuum

Lower edge of 2-spinon continuum

\[ \mathcal{L}(\mathbf{q}) = \mathcal{L}(\mathbf{q} + 2\pi(100)) = \mathcal{L}(\mathbf{q} + 2\pi(010)) = \mathcal{L}(\mathbf{q} + 2\pi(001)), \]

Upper edge of 2-spinon continuum

\[ \mathcal{U}(\mathbf{q}) = \mathcal{U}(\mathbf{q} + 2\pi(100)) = \mathcal{U}(\mathbf{q} + 2\pi(010)) = \mathcal{U}(\mathbf{q} + 2\pi(001)). \]

But elastic neutron scattering will NOT see extra Bragg peak.

Gang Chen, 1704.02734
Calculation to demonstrate the above prediction

\[ \mathcal{H}_{XXZ} = \sum_{\langle ij \rangle} J_{zz} S^z_i S^z_j - J_\perp (S^+_i S^-_j + S^-_i S^+_j), \]

**FIG. 3.** (Color online.) The lower excitation edge of the spinon continuum in U(1)$_0$ and U(1)$_\pi$ QSLs. Here, $\Gamma_0\Gamma_1 = 2\pi(\bar{1}11)$, $\Gamma_0\Gamma_2 = 2\pi(1\bar{1}1)$. We set $J_\perp = 0.12 J_{zz}$ for U(1)$_0$ QSL in (a) and $J_\perp = -J_{zz}/3$ for U(1)$_\pi$ QSL in (b).

**Lower excitation edge of spinon continuum within the gauge MFT calculation**
How to observe the “magnetic monopole”?

\[ S_z \sim E \text{ (emergent electric field)} \]

\[ \text{Im} [E_{-k,-\omega} E_{k,\omega}] \propto [\delta_{\alpha\beta} - \frac{k_\alpha k_\beta}{k^2}] \omega \delta(\omega - \nu|\mathbf{k}|), \]

Low energy theory

Electric loop current \rightarrow Magnetic field
Magnetic loop current \rightarrow Electric field

at higher energy, detect monopole continuum

Suggestion 1: combine thermal transport with inelastic neutron scattering.

For non-Kramers doublets such as Pr ion in Pr$_2$Zr$_2$O$_7$ and Tb ion in Tb$_2$Ti$_2$O$_7$,

Visible in thermal transport

Visible in inelastic neutron scattering
The “magnetic monopole” is the source or the sink of processes. So we turn to the “magnetic monopoles” or out of the spin ice manifold and are created by the tetrahedral centers. These spinon are excitations emergent monopoles”. The spinons are sources and sinks of the gapped matters into our consideration.

To leave the low-energy Maxwell field theory and include information than just the photon mode from the low-energy field theory that describes the long-distance quantum spin dynamics, that is captured by the INS measurement, operates in a broad energy scale spin dynamics, that is captured by the INS measurement was obtained by considering the low-mode is suppressed angular dependence, the spectral weight of the photon is identical to the flux in the (colored) buckled hexagon. To the two sublattices of the dual diamond lattice. In (c) and (d), the background flux trapped in the (dashed) parallelogram is located in the mid of the link on the diamond lattice. The spinons (“monopoles”) hop on the diamond (dual diamond) lattice. The colored dots correspond to the tetrahedral centers of the pyrochlore lattice. (b) Every buckled hexagon on the is visible dual U(1) flux that is experienced by the “monopole” hopping. “I” and “II” refer to the spinon band structure, creating “Hofstadter” monopole band, which may be detectable in inelastic neutron.

\[ H_{Zeeman} = \vec{B} \cdot \sum_i S_i^z \hat{z}_i \]

The weak magnetic field polarizes Sz slightly, and thus modifies the background electric field distribution. This further modulates monopole band structure, creating “Hofstadter” monopole band, which may be detectable in inelastic neutron.
Summary 1

1. We point out the existence of "magnetic monopole continuum" in the U(1) quantum spin liquid, and monopole is purely quantum origin.

2. We point out that the "magnetic monopole" always experiences a Pi flux, and thus supports enhanced spectral periodicity with folded Brillouin zone, while spinons most of the time experience Pi flux.

In fact, continuum has been observed in Pr$_2$Hf$_2$O$_7$ (R. Sibille, et al, arXiv 1706.03604).
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   - YD Li, GC*, PRB 96, 075105 (2017)
   - Y Shen, YD Li, .., GC*, J Zhao*, arXiv 1708.06655
A rare-earth triangular lattice quantum spin liquid: \( \text{YbMgGaO}_4 \)

- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2015).
- This is likely the first strong spin-orbit coupled QSL with odd electron filling and effective spin-1/2.
- It is the first clear observation of \( T^{2/3} \) heat capacity. (needs comment.)
- Inelastic neutron scattering is consistent with spinon Fermi surface results.
- I think it is a spinon Fermi surface U(1) QSL.
The microscopics

Yb$^{3+}$ ion: $4f^{13}$ has $J=7/2$ due to SOC.

At $T \ll \Delta$, the only active DOF is the ground state doublet that gives rise to an effective spin-1/2.

YS Li, …QM Zhang, Srep 2015

YS Li, GC, …, QM Zhang, PRL 2015

YD Li, XQ Wang, GC, arXiv1512, PRB 2016
Modeling

4f electron is very localized, and dipolar interactions weak.

\[ \mathcal{H} = \sum_{\langle ij \rangle} [J_{zz} S_i^z S_j^z + J_\pm (S_i^+ S_j^- + S_i^- S_j^+)] 
+ J_\pm (\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-) 
- \frac{iJ_z}{2} (\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle) ] , \quad (1) \]

where \( S_i^\pm = S_i^x \pm iS_i^y \), and the phase factor \( \gamma_{ij} = 1, e^{i2\pi/3}, e^{-i2\pi/3} \) for the bond \( ij \) along the \( a_1, a_2, a_3 \) direction (see Fig. 1), respectively. This generic Hamil-

anisotropic both in spin space and in real space!

YD Li, XQ Wang, GC, arXiv1512, PRB 2016
YD Li, Y Shen, YS Li, J Zhao, GC*, arXiv 1608.06445

DMRG: Chernyshev, White, 2017
Jize Zhao, XQ Wang, 2017
Polarized neutron scattering

Strong exchange anisotropy in YbMgGaO$_4$ from polarized neutron diffraction

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4 Department of Quantum Matter Physics, University of Geneva, 1211 Genève, Switzerland
(Dated: May 17, 2017)

We measured the magnetic correlations in the triangular lattice spin-liquid candidate material YbMgGaO$_4$ via polarized neutron diffraction. The extracted in-plane and out-of-plane components of the magnetic structure factor show clear anisotropy. We found that short-range correlations persist at the lowest measured temperature of 52 mK and neutron scattering intensity is centered at the $M$ middle-point of the hexagonal Brillouin-zone edge. Moreover, we found pronounced spin anisotropy, with different correlation lengths for the in-plane and out-of-plane spin components. When comparing to a self-consistent Gaussian approximation, our data clearly support a model with only first-neighbor coupling and strongly anisotropic exchanges.

arXiv 1705.05699
Inelastic neutron scattering

Y Shen, YD Li ...GC*, J Zhao*  Nature 2016

consistent neutron results from Martin Mourigal’s group, Nature Physics
Spinon Fermi surface state

\[ S_r = \frac{1}{2} \sum_{\alpha, \beta} f^\dagger_{r \alpha} \sigma_{\alpha \beta} f_{r \beta}, \]

\[ H_{\text{MFT}} = -t \sum_{\langle ij \rangle} (f^\dagger_{i \alpha} f_{j \alpha} + \text{h.c.}) - \mu \sum_{i} f^\dagger_{i \alpha} f_{i \alpha} \]

Prediction from the 0 flux uniform spinon hopping

Y Shen, YD Li ... GC*, J Zhao* Nature 2016
Particle-hole continuum of the spinon Fermi surface

Y Shen, YD Li ...GC*, J Zhao* Nature 2016
More assurance from projective symmetry group analysis

YD Li, XQ Wang, GC, arXiv1512, PRB 2016

YD Li, YM Lu, GC, arXiv 1612.03447, PRB

The spin transformation and gauge transformation commute with each other.

XG Wen PRB 2002

\[
T^{-1}_1 T_2 T_1^{-1} = T^{-1}_1 T_2^{-1} T_1 T_2 = 1, \\
C_2^{-1} T_1 C_2 T_2^{-1} = C_2^{-1} T_2 C_2 T_1^{-1} = 1, \\
S_6^{-1} T_1 S_6 T_2 = S_6^{-1} T_2 S_6 T_2^{-1} T_1^{-1} = 1, \\
(C_2)^2 = (S_6)^6 = (S_6 C_2)^2 = 1.
\]

\[
S_r = \frac{1}{2} \sum_{\alpha, \beta} f^\dagger_{r \alpha} \sigma_{\alpha \beta} f_{r \beta}, \\
\Psi_r = \begin{pmatrix} f_{r \uparrow}, f_{r \downarrow}, f_{r \downarrow}, -f^\dagger_{r \uparrow} \end{pmatrix}^T \\
S_r = \frac{1}{4} \Psi^\dagger_r (\sigma \otimes I_{2 \times 2}) \Psi_r, \\
G_r = \frac{1}{4} \Psi^\dagger_r (I_{2 \times 2} \otimes \sigma) \Psi_r, \\
[S^\mu_r, G^\nu_r] = 0.
\]
Reduction and simplification: classification mean field states

Mean-field model

\[ H_{MF} = -\frac{1}{2} \sum_{(r,r')} [\Psi_r^* u_{rr'} \Psi_{r'} + h.c.] \]

\[ \Psi_r = (f_{r\uparrow}, f_{r\downarrow}, f_{r\downarrow}, -f_{r\uparrow})^T \]

Symmetry transformation \( \mathcal{O} \)

\[ u_{rr'} = g_{\mathcal{O}(r)}^\mathcal{O} \mathcal{U}_{\mathcal{O}}^\mathcal{O} u_{\mathcal{O}(r)\mathcal{O}(r')} \mathcal{U}_{\mathcal{O}} g_{\mathcal{O}(r')}^\mathcal{O} \]

Spin rotation

Gauge rotation

Group relation \( \mathcal{O}_1 \mathcal{O}_2 \mathcal{O}_3 \mathcal{O}_4 = 1 \)

\[ \mathcal{U}_{\mathcal{O}_1} g_{\mathcal{O}_1}^\mathcal{O}_1 \mathcal{U}_{\mathcal{O}_2} g_{\mathcal{O}_2}^\mathcal{O}_2 \mathcal{O}_3 \mathcal{O}_4(r) \mathcal{U}_{\mathcal{O}_3} g_{\mathcal{O}_3}^\mathcal{O}_3 \mathcal{O}_4(r) \mathcal{U}_{\mathcal{O}_4} g_{\mathcal{O}_4}^\mathcal{O}_4 \mathcal{O}_4(r) \]

\[ = \mathcal{U}_{\mathcal{O}_1} \mathcal{U}_{\mathcal{O}_2} \mathcal{U}_{\mathcal{O}_3} \mathcal{U}_{\mathcal{O}_4} g_{\mathcal{O}_1}^\mathcal{O}_1 \mathcal{O}_3 \mathcal{O}_4(r) g_{\mathcal{O}_2}^\mathcal{O}_2 \mathcal{O}_4(r) g_{\mathcal{O}_3}^\mathcal{O}_3 \mathcal{O}_4(r) g_{\mathcal{O}_4}^\mathcal{O}_4 \]

\( \in \text{IGG} \),

\[ \mathcal{U}_{\mathcal{O}_1} \mathcal{U}_{\mathcal{O}_2} \mathcal{U}_{\mathcal{O}_3} \mathcal{U}_{\mathcal{O}_4} = \pm I_{4\times 4}, \quad \{ \pm I_{4\times 4} \} \subset \text{IGG} \]

\[ g_{\mathcal{O}_1}^\mathcal{O}_1 g_{\mathcal{O}_2}^\mathcal{O}_2 g_{\mathcal{O}_3}^\mathcal{O}_3 g_{\mathcal{O}_4}^\mathcal{O}_4 \mathcal{O}_4(r) g_{\mathcal{O}_3}^\mathcal{O}_3 \mathcal{O}_4(r) g_{\mathcal{O}_4}^\mathcal{O}_4 \mathcal{O}_4(r) \in \text{IGG} \]

Square lattice by J. Alicea’s group 2014
The spinon mean-field states of the U1A01 state and the U1B01 state are plotted in the main text. Clearly, we observe three types of spinon mean-field states: (i) an integer-letter state, (ii) a spinon mean-field state, and (iii) a spinon state. The spinon mean-field state of the U1A01 state and the U1B01 state is denoted by \( r \). The spinon mean-field state of the U1B01 state is denoted by \( r' \).

The total number of spins, the summation is over all \( x, y \).

For the symmetry multiplication \( T \), the gauge transformations are given by:

- \( T_{r} \)
- \( T_{r'} \)
- \( T_{c} \)
- \( T_{s} \)

The gauge transformations are given by:

- \( e^{i \pi x} f(x, y) \)
- \( e^{i \pi y} f(x, y) \)
- \( e^{i \pi y} f(x, y) \)
- \( e^{i \pi y} f(x, y) \)

The gauge transformations are given by:

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The gauge transformations are given by:

- \( e^{i \pi x} f(x, y) \)
- \( e^{i \pi y} f(x, y) \)
- \( e^{i \pi y} f(x, y) \)
- \( e^{i \pi y} f(x, y) \)
Spectroscopic constraints

We use PSG to predict the corresponding spectrum.

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

<table>
<thead>
<tr>
<th>U(1) QSL</th>
<th>(W^T_1)</th>
<th>(W^T_2)</th>
<th>(W^C_2)</th>
<th>(W^C_6)</th>
</tr>
</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>
</tr>
<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>
</tr>
<tr>
<td>U1A01</td>
<td>(I_{2 \times 2})</td>
<td>(I_{2 \times 2})</td>
<td>(i\sigma^y)</td>
<td>(i\sigma^y)</td>
</tr>
<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>
</tr>
</tbody>
</table>

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

VMC study has been done by Balents’ group
Dynamic spin structure factor

FIG. 2. Dynamic spin structure factor for six free spinon mean-field states other than U1A00. Note the U1A10 Hamiltonian is with that only includes isotropic spinon hoppings for the first neighbors. None of them is consistent with the spinon Fermi surface picture.

For the U1A00 state, the spin structure factor is shown in (a). Qualitatively similar results are obtained for the other states. For instance, the spin structure factor for the U1A01 state with \( t_1 \) and \( t_2 \) is shown in (b), and for the U1A11 state with \( t'_1 \) and \( t_2/t_1 \) in (c).}

For the U1B00 state, the spin structure factor is shown in (c). For the U1B state, the spin structure factor is shown in the bottom right panel.
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

YD Li, GC, arXiv: 1703.01876
PhysRevB, 96, 075105

ESR response in a field by Oleg Starykh’s group, 2017
Organic spin liquids?

- No magnetic order down to 32mK
- Constant spin susceptibility at zero temperature

Other experiments: transport, heat capacity, optical absorption, etc, unfortunately, **no neutron scattering** so far.
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 !!
Excitation continuum in weakly magnetized YbMgGaO\textsubscript{4}

Experiment:
Y Shen, YD Li, ..., GC*, J Zhao*
arXiv: 1708.06655

Theoretical results for

We chose the Zeeman splitting gap combined dynamic spin structure factor defined in Eq. 2 that is proportional to the observed neutron scattering density. In all the figures these are analogous to the particle-hole excitations in the zero-field case, and also gives rise to an upper excitation edge at \( b \), dominant events that are responsible for the spectral peak at \( \omega \).

The horizontal dotted line indicates the Fermi level. The solid arrows indicate the spin-flipped inter-band particle-hole points (vertical dashed lines) in momentum space.

Contour plot of the energy dependent intensity in the nearly polarized state at 9.5 T. The colour scale is shown in linear scale.

The energy dependent intensity at 2.5 T along the high symmetry directions illustrated by the black lines in reciprocal space. The dashed lines indicate the Brillouin zone boundaries.

Contour plot of the energy dependent intensity at 2.5 T along the high symmetry directions illustrated by the black lines in reciprocal space. The dashed lines indicate the Brillouin zone boundaries.

We propose that the modulation of the spectral weights of the continuum in the low field regime is consistent with the previously predicted behavior of the spinon Fermi surface QSL state under magnetic fields (Fig. 2b). Moreover, the high-field spin-wave spectrum shows a clearly distinct dispersion from that in the low field regime measured. It was previously shown in ref. 29 that, the degenerate spinon bands are split and the splitting is given by the description of the magnetic excitation that at the mean-field level corresponds to both the inter-band and intra-band particle-hole excitation of the spin excitation that at the mean-field level corresponds to both the inter-band and intra-band particle-hole excitation of the spinon bands and leads to the spectral peak at the spinon Fermi surface QSL state.

Supplemental Materials. In an inelastic neutron scattering measurement, the neutron energy-momentum loss creates the measured. It was previously shown in ref. 29 that, the degenerate spinon bands are split and the splitting is given by the...
Finally, lots of isostructural materials

<table>
<thead>
<tr>
<th>Compound</th>
<th>Magnetic ion</th>
<th>Space group</th>
<th>Local moment</th>
<th>(\Theta_{CW}) (K)</th>
<th>Magnetic transition</th>
<th>Frustration para. (f)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>YbMgGaO(_4)</td>
<td>Yb(^{3+})(4(_f)^{13})</td>
<td>R(_{3m})</td>
<td>Kramers doublet</td>
<td>(-4)</td>
<td>PM down to 60 mK</td>
<td>(f &gt; 66)</td>
<td>[4]</td>
</tr>
<tr>
<td>CeCd(_3)P(_3)</td>
<td>Ce(^{3+})(4(_f)^{1})</td>
<td>P(_6)/mmc</td>
<td>Kramers doublet</td>
<td>(-60)</td>
<td>PM down to 0.48 K</td>
<td>(f &gt; 200)</td>
<td>[5]</td>
</tr>
<tr>
<td>CeZn(_3)P(_3)</td>
<td>Ce(^{3+})(4(_f)^{1})</td>
<td>P(_6)/mmc</td>
<td>Kramers doublet</td>
<td>(-6.6)</td>
<td>AFM order at 0.8 K</td>
<td>(f = 8.2)</td>
<td>[7]</td>
</tr>
<tr>
<td>CeZn(_3)As(_3)</td>
<td>Ce(^{3+})(4(_f)^{1})</td>
<td>P(_6)/mmc</td>
<td>Kramers doublet</td>
<td>(-62)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>[8]</td>
</tr>
<tr>
<td>PrZn(_3)As(_3)</td>
<td>Pr(^{3+})(4(_f)^{2})</td>
<td>P(_6)/mmc</td>
<td>Non-Kramers doublet</td>
<td>(-18)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>[8]</td>
</tr>
<tr>
<td>NdZn(_3)As(_3)</td>
<td>Nd(^{3+})(4(_f)^{3})</td>
<td>P(_6)/mmc</td>
<td>Kramers doublet</td>
<td>(-11)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>[8]</td>
</tr>
</tbody>
</table>

**YD Li, XQ Wang, GC*, PRB 94, 035107 (2016)**

Magnetism in the KBaRE(BO\(_3\))\(_2\) (RE=Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) series: materials with a triangular rare earth lattice

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Summary

1. We propose YbMgGaO$_4$ to be a spin-orbit-coupled spin liquid.

2. The signature of spin fractionalization has been discovered and interpreted as spinons.

3. Predictions have been made for the weakly magnetized regime. It can be immediately tested by inelastic neutron. It has been confirmed in Jun Zhao's recent experiment.