Signatures of fractionalization in spin liquid candidate

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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.
- We think it is a spinon Fermi surface U(1) QSL.
Inelastic neutron scattering

A consequence of fractionalization is the broad continuum in the inelastic neutron scattering.

\[ P = q_1 + q_2 \]

\[ E = \omega(q_1) + \omega(q_2) \]
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

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

\[ H_{\text{MFT}} = -t \sum_{\langle ij \rangle} (f_{i \alpha}^\dagger f_{j \alpha} + \text{h.c.}) - \mu \sum_i f_{i \alpha}^\dagger f_{i \alpha} \]
The experiments are inconsistent with a Dirac QSL nor a Z2 QSL. How to further ensure the fractionalization?

**An idea: explore the weak field regime**

1. Under a weak field, the spin liquid state would be preserved, and the fractionalized spinon remains to be a good description of the magnetic excitations.

2. Due to the small energy scale of rare-earth moments, this proposal can be realized.

3. We can predict the spectral weight shift under the field and predict the evolution of the continuum.

**Realizable and Predictable.**

Yao-Dong Li, GC, PRB 96, 075105 (2017)
Spinon excitations with external field: One dimensional systems

Zeeman splitting in Spinon band with field

Corresponding modulation on neutron spectra


1D spin liquid is simple Luttinger liquid, and
1D spinons are simply domain walls, cannot extend to high dims.
Strong Mott regime: only Zeeman coupling

\[ H_{\text{MFT}} = -t_1 \sum_{\langle ij \rangle, \alpha} f_{i\alpha}^\dagger f_{j\alpha} - t_2 \sum_{\langle\langle ij \rangle\rangle, \alpha} f_{i\alpha}^\dagger f_{j\alpha} - \mu \sum_i f_{i\alpha}^\dagger f_{i\alpha} \]

\[-g_\beta \mu_B H \sum_i f_{i\alpha}^\dagger \frac{\sigma^\beta}{2} f_{i\beta}\]

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

arXiv: 1708.06655
Summary

We study both zero and weak field regimes to understand the signatures of fractionalization in a spin liquid candidate.

Further directions:
1. how to detect spinon-gauge coupling?
2. confirm 2kF effect?
3. how to detect gauge field?
4. any other rare-earth magnets with similar properties?
Use new materials to support 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>
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</thead>
<tbody>
<tr>
<td>YbMgGaO$_4$</td>
<td>Yb$^{3+}$$(4f^{13})$</td>
<td>R$ar{3}$m</td>
<td>Kramers doublet</td>
<td>$-4$</td>
<td>PM down to 60 mK</td>
<td>$f &gt; 66$</td>
<td>[4]</td>
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<tr>
<td>CeCd$_3$P$_3$</td>
<td>Ce$^{3+}$$(4f^1)$</td>
<td>P6$_3$/mmc</td>
<td>Kramers doublet</td>
<td>$-60$</td>
<td>PM down to 0.48 K</td>
<td>$f &gt; 200$</td>
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<tr>
<td>CeZn$_3$P$_3$</td>
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<td>P6$_3$/mmc</td>
<td>Kramers doublet</td>
<td>$-6.6$</td>
<td>AFM order at 0.8 K</td>
<td>$f = 8.2$</td>
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<tr>
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<td>Ce$^{3+}$$(4f^1)$</td>
<td>P6$_3$/mmc</td>
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<td>Unknown</td>
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<tr>
<td>PrZn$_3$As$_3$</td>
<td>Pr$^{3+}$$(4f^2)$</td>
<td>P6$_3$/mmc</td>
<td>Non-Kramers doublet</td>
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<td>$-11$</td>
<td>Unknown</td>
<td>Unknown</td>
<td>[8]</td>
</tr>
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</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

M. B. Sanders, F. A. Cevallos, R. J. Cava
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many ternary chalcogenides NaRES$_2$, NaRES$_2$, KRES$_2$, KRES$_2$, KRETe$_2$, RbRES$_2$, RbRES$_2$, RbRETe$_2$, CsRES$_2$, CsRES$_2$, etc.)

Lots of isostructural materials
Major collaborators for this piece of work

Yaodong Li  
(now transferred to UCSB)

Yao Shen  
(Fudan)

Jun Zhao  
(Fudan)

Others: Yuesheng Li, Qingming Zhang, Yuan-Ming Lu, etc