The competing spin liquids and symmetry fractionalization for triangular lattice

J1-J2 spin-1/2

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FTPI workshop

Research is supported by NSF (magnetic systems)
and DOE (topological matter)
Research team:

Wenjun Hu, ShouShu Gong (frustrated spins)

Wei Zhu (topological matter)

Hu, Gong, Zhu, Sheng, arXiv1504.00654 (SLs competing)

A related work by Z. Zhu and Steve White
arXiv1502.04831 (Z2 SL)
The intermediate phase for triangular J1-J2 Heisenberg model
\( J_2=(0.08, 0.16)J_1 \) ---- nonmagnetic, spin liquids candidate

Evidence of Chiral spin liquid: long-range chiral correlations in even sector (no pinning or inserting flux), TRS breaking

Evidence of \( \mathbb{Z}_2 \) spin liquid: exponential decay chiral correlations in spinon sector (with pinning or inserting \( 2\pi \) spin flux) --- \( \mathbb{Z}_2 \) sector agrees with Zhu and Steve’s work

Energy near degeneracy; entanglement spectrum, chiral edge spectrum in even sector; Evidence of symmetry fractionalization for “fermionic spinon Sector”

We don’t know which one will win at thermodynamic limit!
Magnetic systems intend to develop orders by breaking symmetry

- Ferromagnetic order
- Antiferromagnetic order with NN $J_1$
- Valence Bond Solid (VBS) order
- Plaquette VBS (possibly identified in $J_1$-$J_2$ square model)
Spin Liquid (SL) State

A new state of matter with no symmetry broken, with topological order and fractionalized spinons

X. G. Wen (1990, 1991)

Z2 SL in contrived theoretical models

Gapped SL State
Gaps to all spin excitations exponential decay correlations J1-J2-J3 (Ising) kagome, Balents et al and J1 kagome model
Spin liquids in Heisenberg models with increasing frustration

Triangular lattice

Three-sublattice AF order

Resonating valence bond (P. W. Anderson), RVB is a quantum spin liquid (SL) 1973, 1989

NN Kagome lattice: A primary candidate for Z2 SL

Spin Liquid
H.C. Jiang, Z.Y. Weng, DNS (2008), not converged DMRG for wider systems
Yan, Huse, White, Science (2010)---new milestone: A possible gapped spin liquid

Main evidence for possible Z2 for J1 kagome spin1/2 (DMRG, Yan et al)

Yan, Huse, White, 2010 found two topological sectors in DMRG; Challenge to find four sectors to fully establish topological nature of the phase

Evolving to uniform SL from VBS on kagome
Adiabatic DMRG: by pinning and inserting flux adiabatically on cylinder to access all top. Sectors
Y. He, Sheng, Y. Chen

J1-J2-J3 model with large Jz (or small Jxy1)
He, DNS, Chen PRB(2014)

Inserting flux to get 4 sectors (adiabatic DMRG) did not work for NNK because “vison-like” excitations are gapless; and fractionalized spinon in CSL is still there.
Spin-1/2 KAF: Experimental findings for Herbertsmithite

✓ No magnetic order down to 50 mK
✓ No observable spin gap down to 0.1 meV

SL Phase, but different from identified by DMRG

Gapless SL for kagome, Y. Iqbal et al., arXiv:1209.1858

Time reversal symmetry (TRS) broken chiral Spin liquid (CSL): a bosonic FQHE state

Kalmeyer and Laughlin 1987
Wen, Wilczek, Zee 1989

anyon quasiparticles obey fractional statistics, chiral ordering, TRS and parity broken spontaneously

Haldane and Arovas 1995
Chern number to distinguish it from chiral spin state
Yang, Warman and Girvin 1993.
Yao and Kivelson: a contrived CSL state (for Kitaev model) 2007

Induce CSL using (S1XS2)*S3 interaction

Induce CSL with TRS broken terms
Approx. Methods find CSL
robust examples of discovering CSL in kagome spin $\frac{1}{2}$ models

$$H = J_1 \sum_{\langle i, j \rangle} S_i \cdot S_j + J_2 \sum_{\langle\langle i, j \rangle\rangle} S_i \cdot S_j + J_3 \sum_{\langle\langle\langle i, j \rangle\rangle\rangle} S_i \cdot S_j$$
Density matrix renormalization group (DMRG) 
m=6000--30000 (U1 equivalent) states using SU2

S. R. White 1992

1D DMRG algorithm

Mapping a 2D lattice onto a 1D

Jiang, ZY Weng, DNS(2008)

DMRG with Su2 invariant 
up to 30,000 states
Shoushu Gong

Depenbrock et al. 2012
Frustrated triangular lattice spin $\frac{1}{2}$ J1-J2 models

Spin structure factors

1\textsuperscript{st} order sign of SL to stripe phase

SL with size independent $S$
Even sector: short range spin, dimer but long-range chiral correlations
SL phase around $J_2=0.1$, spinon sector, nemetic order?

(b) $J_2=0.1$ YC8-24, odd sector

Pinning, odd sector: short range spin, dimer
Also short-range chiral
SL phase around $J_2=0.1$, time reversal symmetry is broken: chiral order is strong in even sector

(b) $J_2=0.1$, $YC10-24$, $M_{SU(2)}=4000$, complex, $E=-122.993$
SL phase around $J_2=0.1$, vacuum sector

(a) $J_2=0.1$, YC10-24, $M_{SU(2)}=5000$, real, $E=-123.019$
SL phase around $J_2=0.1$, odd sector, the nematic order is strong

\(c) \ J_2=0.1, \ YC10-24, \ odd \ sector\)
SL phase around $J_2=0.1$, spin and dimer exponential decay.
Long range chiral-chiral correlation is robust in even sector.
Comparing of the chiral correlations in two sectors
The transfer matrix longest correlation length is about 1
Anisotropy is stronger in spinon sector.
SL phase around $J_2=0.1$, inserting flux $2\pi$ gives fermionic spinon sector

(a) $J_2=0.1$, $\text{YC8-16}$, $\theta=2\pi$, $\Delta Q_R=0.48$

(b) $\text{YC8-20}$, $J_2=0.1$
spectrum of the vacuum and spinon sectors
Entanglement spectrum of the vacuum sector and additional $J_x$ $(S_1 \times S_2) \times S_3$

$J_1 = 1.0$, $J_2 = 0.1$, $N = 8 \times 20$, vacuum sector

(a) $J_x = 0.0$  (b) $J_x = 0.05$  (c) $J_x = 0.2$
Entanglement spectrum of the spinon sector and additional $J_x (S_1 x S_2) \ast S_3$

$J_1 = 1.0$, $J_2 = 0.1$, $N = 8 \times 20$, spinon sector

(a) $J_\chi = 0.0$
(b) $J_\chi = 0.05$
(c) $J_\chi = 0.2$

Fermionic spinon sector at $J_x = 0$?

Competing Chiral Spin Liquid and Z2 Spin Liquid on Triangular Spin-1/2 J1-J2 Model

Two topological sectors, their bulk energies are near degenerating.

The CSL is identified in the vacuum sector; TRS is spontaneously breaking; it connects to a robust CSL by adding three spin chiral vector terms ($J_x - 0.02$).

The fermionic spinon sector for Z2 spin liquid is identified in the spinon sector---no TRS breaking with characteristic ES for Z2 (sign for symmetry fractionalization?).

$J_x = 0.02$ to 0.05 will induce a quantum phase transition in the spinon sector so that the whole system becomes CSL.
Thank you