Frustrated Magnets (III) [Balents]

- Frustrated Magnets Hunter Guide:
  1. Is it an insulator? (from transport, ARPES)
  2. Is it a magnet? Curie Law (from χ)
  3. Sign of frustration?
     - Jθ vs. J (from transition Tc, Cv, etc.)
     - low-T entropy (Cv) and density of states (from NMR)
  4. Identify state & compare with theory

- AB₂X₄ spinels
  - Common valence: A²⁺, B³⁺, X²⁻
  - X = O, S, Se
  - A sites form diamond lattice (which is bipartite)
  - B atoms form pyrochlore — decorate the plaquettes of the diamond lattice

- EXAMPLE: ACr₂O₄
  - S = 3/2 isotropic moments
  - Dominant exchange: antiferro
  - Zn: -390°C, 12, 33
  - Cd: -70°C, 7.8, 9
  - Hg: -32°C, 5.8, 6

- Reduced f caused by increasing coupling to lattice distortions.
- Classical spin liquid — no long-ranged moment; dipolae correlative
- Plateaus in magnetization — 3:1 structure
- Plateaus caused by spin-lattice coupling, which favours colinearity
A-site Spinels

- In FeSc$_2$S$_4$ has $s=2$ but also has $s=1/2$ orbital degeneracy, which may act as $s=1/2$ pseudospin & increase quantum effects
- 2nd & 3rd neighbor exchange important
- Minimal model: $J_1 - J_2$ exchange

- Fix $J_2/J_1$ & introduce $J_3$

- Cs$_2$CuCl$_4$ — Cu$^{2+}$ spin - 1/2

- quasi-D. In the 2D plane is spatially anisotropic triangular lattice
  $J > J' > D$

- To fit neutron scattering data at 0 field to Heisenberg spin-wave theory, value of $J,J'$ has to be adjusted by 40% in opposite direction ($J,J'$ obtained from high-field measurement)

- Physical explation — dimensional reduction

  1st order interchain energy correction vanishes.
  Excitations include spin-1/2 spinons (domain wall)
  Spinons cannot hop between chain alone, but can hop in pairs $\Rightarrow$ spinons tend to stay close to each other.
Quantum Spin Liquids

- Quantum fluctuation may prevent ordering at $T=0$.
- e.g., RVB states

Quantum Spin Liquid

1. $1/f = 0 \implies$ no ordering
2. no spin freezing (hysteresis, NMR, $\gamma$SR)
3. Structure of low-energy excitations ($\varepsilon(T)$, $C_v(T)$, $\nu T$, neutrons, inelastic)

Varieties of QSL:

1. ($U(1)$ states: (i) spinons unpaired
   (ii) strong gauge fluctuations
   (iii) gapless in $d=2$
   (iv) stable in $d=3$ at $T=0$ only.
2. $\mathbb{Z}_2$ states: (i) spinons paired
   (ii) weak gauge fluctuations
   (iii) stable in $d=2$
   (iv) Ising transitions in $d=3$.

Diagram:

- Dimension
- Spin gap
- $\mathbb{Z}_2$ state
- $C_v$
- $T$
- $\nu T$
- $d=2$
- $d=3$
- $T_c$
- $R_\nu = 1$
- $U(1)$
- Fermi surface

???
QSL candidates

1. $(\text{BEDT-TTF})_2\text{Cu}_2(\text{CN})_3$
   - Organic
   - $S = \frac{1}{2}$ triangular lattice, $t'/t \approx 1.06$
     - (nearly isotropic)
   - Suggestion: $SU(1)$ spin liquid with spinon FQHE surface
   - Susceptibility $\checkmark$
   - Heat capacity $\times$ (too large)
   - Spinon pairing?
2. $\text{EtMe}_3\text{Sb}[\text{Pd(dmit)}_2]_2$
   - Less investigated than $(\text{BEDT-TTF})_2\text{Cu}_2(\text{CN})_3$, but similar to it
3. $\text{ZnCu}_3(\text{OH})_6\text{Cl}_2$ — 2D kagome $\delta\text{ Cu}^{2+}$
   - 2d spin-$\frac{1}{2}$ antiferromagnetic
   - Problem: inversion between $\text{Zn}$ & $\text{Cu}$ (5-10%)?
   - Spin susceptibility has peak at low-$T$ $\Rightarrow$ local disorder?
   - Heat capacity $C_v \sim T^x$, $x \in \{0.5, 1\}$ $\Rightarrow$ many low-$T$ excitations
   - Inelastic neutron $(\xi^2(E))/T$ $\uparrow$ show evidence of gapless spin excitations
   - Proposal: $SU(1)$ Dirac algebraic spin liquid predicts $\xi \sim T$, $C_v \sim T^2$, in pure system
4. $\text{Na}_4\text{Ir}_3\text{O}_8$ — hyperkagome $\delta\text{ Ir}^{4+}$ $\uparrow$
   - Less disordered than $\text{ZnCu}_3(\text{OH})_6\text{Cl}_2$
   - $T_{\text{Beu}} \approx 650K$
   - Specific heat — broad peak around 30K, power-law
     - (exponent $1 < \alpha < 2$)
   - Transport shows it a Mott insulator, but close to Mott transition
Strong spin-orbit coupling (J = 1/2 instead of s = 1/2)

\[ \chi(T) \text{ no longer tell low energy excitations.} \]