Scale-invariant magnetic anisotropy in RuCl$_3$

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Kitaev’s model - anisotropic exchange interactions on a honeycomb lattice

\[ H = -J_x \sum_{x\text{-links}} \sigma_j^x \sigma_k^x - J_y \sum_{y\text{-links}} \sigma_j^y \sigma_k^y - J_z \sum_{z\text{-links}} \sigma_j^z \sigma_k^z \]

- Spin liquid ground state!
- High-energy states are pulled down to zero energy by strong correlations
- Real materials that emulate this model exist
The honeycomb iridates (Li$_2$IrO$_3$ and Na$_2$IrO$_3$) and RuCl$_3$ are examples. Exchange is mediated by the surrounding oxygen or chlorine. Undistorted and edge-shared octahedral environment is key.

Is it a spin liquid?

- Unconventional antiferromagnetic ground state
- Exchange is spin-anisotropic (Kitaev-like)

Non-spin-wave dynamics

 Continuum of excitations persists to at least 120K

Banerjee, A. Science (2017)
The spectrum is fractionalized!

- Half-integer quantization from chiral edge currents
- Spin dissociates into Majorana fermions and fluxes
There are still a lot of questions to be answered...

- What other exchange interactions are at play?
- Reliable theory for Kitaev model in a magnetic field at finite temperature?
- Second phase transition?
- High quality single crystals are small - what can we do?
- Are there (what are the) thermodynamic signatures of a spin liquid??
Resonant torsion magnetometry

Bare quartz tuning forks:

\[ f_0 = 32,768 = 2^{15} \text{ Hz} \]

With silicon cantilever and sample attached:

\[ f_0 \sim 40-50 \text{ kHz} \]

\[ f_0 = 45 \text{ kHz} \]

Akiyama A-probe made by Nanosensors Inc.

The magnetotropic coefficient ($k$)

Greek word tropic = “to turn”

Thermodynamic coefficient: $\frac{\partial^2 F}{\partial \ldots^2}$

For small frequency shifts: $\frac{\Delta \omega}{\omega_o} \approx \frac{k}{2K}$

$$E = \frac{I}{2} \left( \frac{d\Delta \theta}{dt} \right)^2 + \frac{1}{2} \left[ K + \frac{d^2 F(\theta)}{d\theta^2} \right] (\Delta \theta)^2 + \frac{dF(\theta)}{d\theta} \Delta \theta$$

$$\theta_\tau = \frac{\tau}{K + k}$$

Unraveling spin-liquid physics in RuCl₃ - why the magnetotropic coefficient?

- Detects magnetic anisotropy
- Sharp jump at phase boundaries
- Sensitively detect frequency changes, even in high magnetic fields
- Measure small crystals!

Ehrenfest relation:
\[ \Delta k = -\frac{\Delta C}{T_C} \left( \frac{\partial T_C}{\partial \theta} \right)^2 \]

Conventional torque magnetometry
Resonant torsion magnetometry

Field aligned in the honeycomb planes

Anisotropic AFM phase boundary

Linear response regime $M_i = \chi_{ij} H_j$

\[
F = \frac{1}{4} B^2 (\chi_{\perp} - \chi_{\parallel}) \cos 2\theta \\
\tau = \frac{1}{2} B^2 (\chi_{\perp} - \chi_{\parallel}) \sin 2\theta \quad (\tau = \partial F/\partial \theta) \\
k = B^2 (\chi_{\perp} - \chi_{\parallel}) \cos 2\theta \quad (k = \partial^2 F/\partial \theta^2)
\]
Asymmetry develops near the c-axis in high fields

\[
B = \frac{12.5}{(B_0 - 0.5)}
T = 1.3 \text{ K}
\]

Asymmetry develops near the c-axis in high fields

6-fold symmetry in the honeycomb plane

Magnetic anisotropy is scale-invariant at high fields

- Magnetic anisotropy saturates at the AFM transition
- Singularity in the free energy at the north and south poles
- Curvature of the free energy is robust to temperature and magnetic field

What does the lack of an intrinsic energy scale tell us?

Giraldo-Gallo, P. Science (2018)
Conclusions:

- Scale-invariant behavior in a spin system
- Magnetic field introduces interactions between the low-energy excitations of the Kitaev model?
Thank you for your attention!

Mia
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