Probing excitations in insulators by injecting spin-currents

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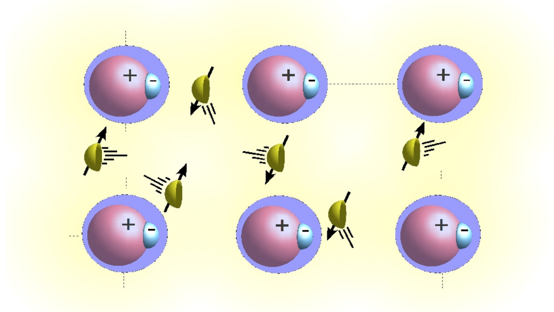
1. Introduction

- Recent experiments have provided strong evidence in favor of quantum-disordered ground states for certain Mott insulators.
- Conjectured ground states include quantum spin liquid states with no broken symmetry, fractionalized spin-half excitations, and topological order.



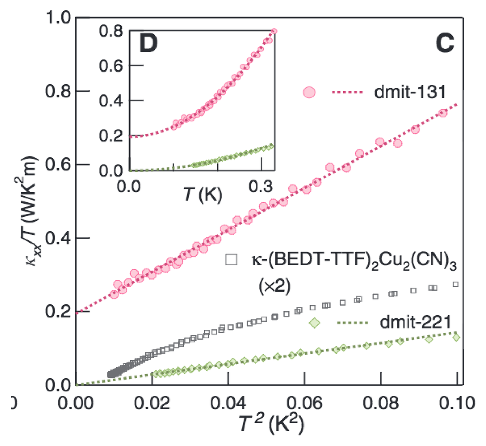
- Experiments till date:

Thermal conductivity, thermal and electric transport, NMR, inelastic neutron scattering, etc. Several puzzles remain.

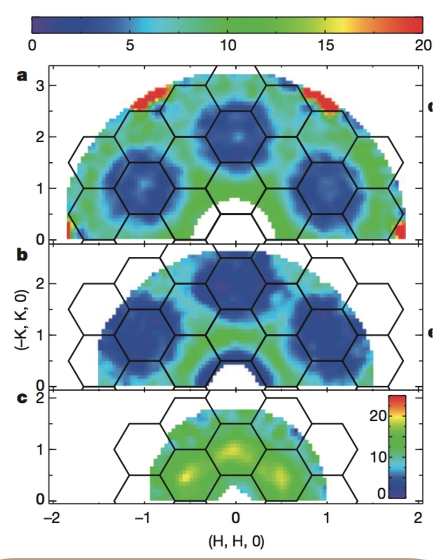
- Question:

What other experiments can be done to probe such systems? How can we learn more about the presence of fractionalized excitations?

M. Yamashita *et al*, Science **328** (2010)
Han *et al*, Nature **492** (2014)
Spin liquid cartoon – T. Senthil



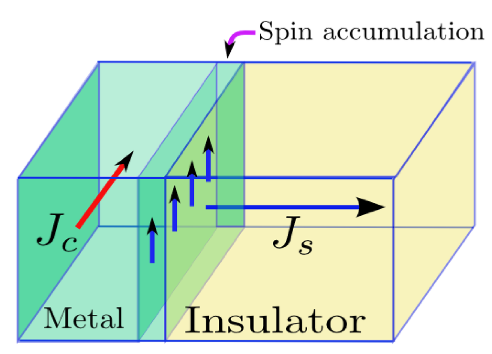
Thermal conductivity of dmit-131



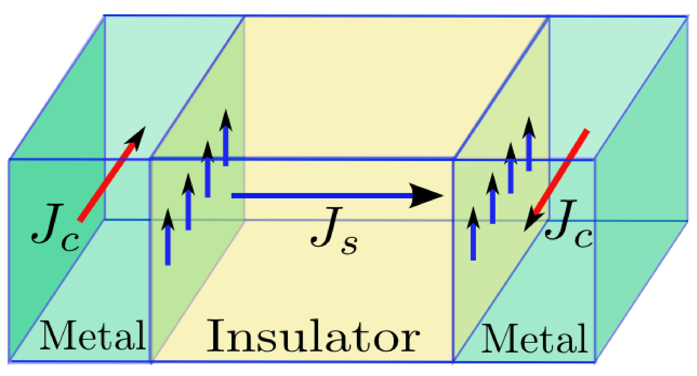
Dynamic structure factor of Herbertsmithite

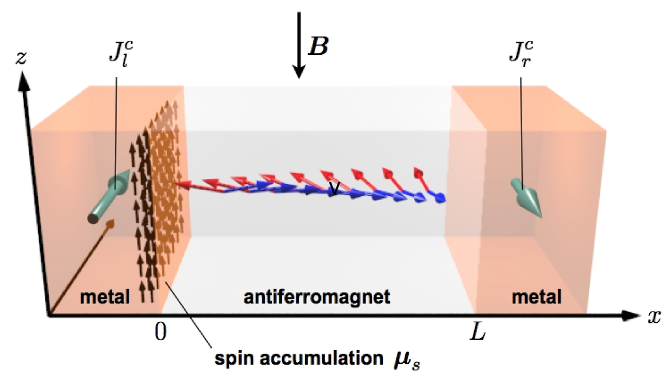
2. Probing via spin-currents

- Recent advances in the field of spintronics has enabled transmission of electric signals across insulators using spin-currents.
- Create a non-equilibrium accumulation of spin at metal-insulator boundary using the spin-hall effect.
- Inject spin into insulator at equilibrium.

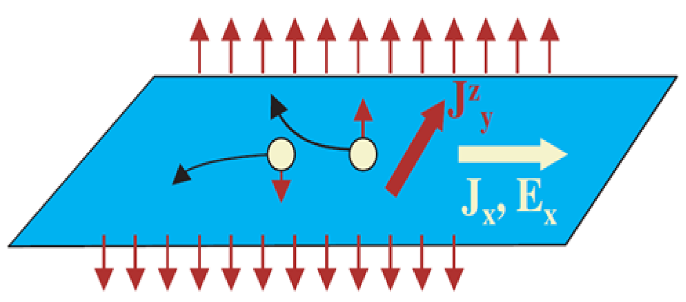


- Use the inverse spin-hall effect to detect the spin-current at the right metallic reservoir.
- Measure spin-currents by measuring electrical voltages or currents!





Superfluid spin transport across an antiferromagnet



Spin accumulation via spin-Hall effect

J Sinova *et al*, arXiv:1411.3249
Y Kajiwara *et al*, Nature **464**, 262 (2010)
S. Takei *et al*, Phys. Rev. B **90**, 094408 (2014)

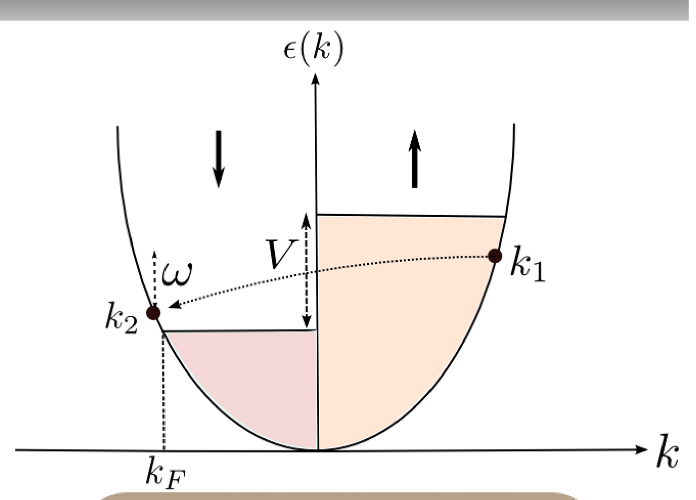
3. Model and formalism

$$H_{int} = J\sum_{j\in boundary} \vec{S}^e\cdot\vec{S}_j\,\delta(\vec{x}_e-\vec{X}_j)$$

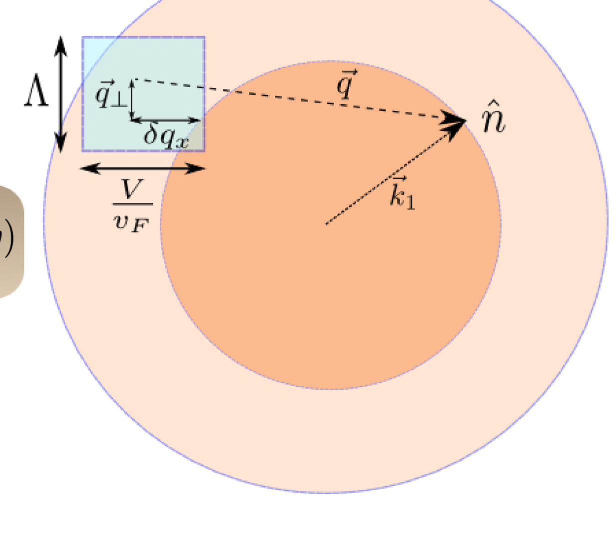
- Use Fermi's Golden rule to evaluate spin-flip scattering at the boundary.
- Spin-current related to the dynamic structure factor $S_{-+}(\vec{q}_\perp,\omega)$ of the boundary spins.
- Simplifies in the limit of strongly peaked structure factors at well-separated momenta in the insulator Brillouin zone.

Key result:

$$I_{spin} \overset{T\to 0}{=} \frac{\pi J^2 A_\perp \nu(\epsilon_F)}{4(2\pi)^d}\sum_{\vec{Q}_\perp} f_{ang}(k_F/Q_\perp)\int_{\omega,\vec{q}_\perp}(V-\omega)S_{-+}(\vec{q}_\perp,\omega)$$



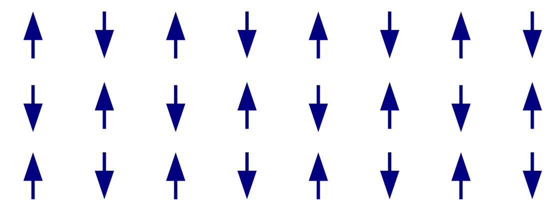
Non-equilibrium spin accumulation and a scattering event



4. Application to AF

- Long range Neel-ordered cubic lattice antiferromagnetic insulator.

Sandweg *et al*, Phys. Rev. Lett. **106**, 216601 (2011)
Bauer *et al*, Viewpoint, Physics 4, 40



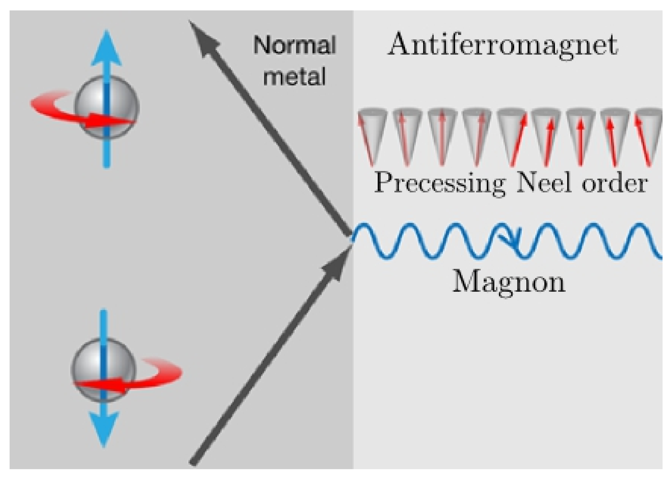
Neel order at 2d metal-insulator interface

- Contributions from both inelastic scattering by static moments, and inelastic scattering by magnons:

$$I_{spin} \overset{T\to 0}{\sim} \nu(\epsilon_F)V + c\,V^4$$

- Elastic contribution is proportional to the number of modes at the Fermi surface (as in Landauer formalism).
- Higher order correction due to magnons gives a non-linear spin-conductance!

Superfluid and magnon transport in AF

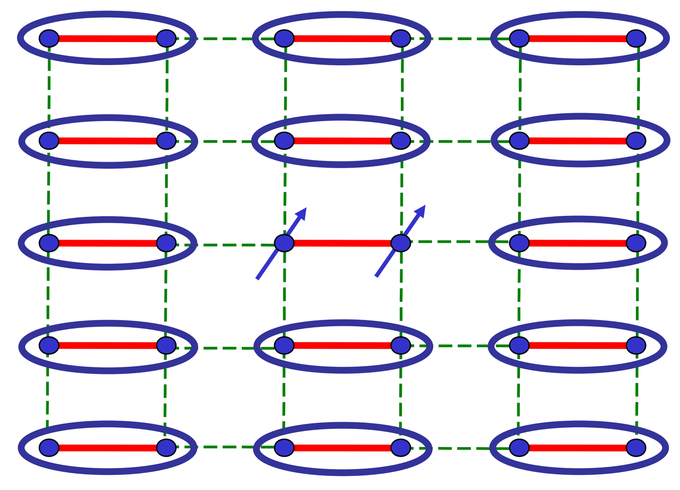


5. Insulators without magnetic order

- Valence bond solid (VBS) states with broken lattice symmetries but unbroken SU(2) symmetry.
- Excitations are S=1 *triplons*, which can hop around.

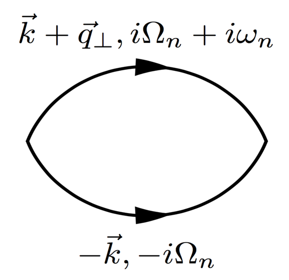
$$S_{-+}(\vec{q}_\perp,\omega) \sim \delta(\omega-\Delta_T-\vec{q}_\perp^2)$$
$$I_{spin} \overset{T\to 0}{\sim} (V-\Delta_T)^{d/2+1}\,\Theta(V-\Delta_T)$$

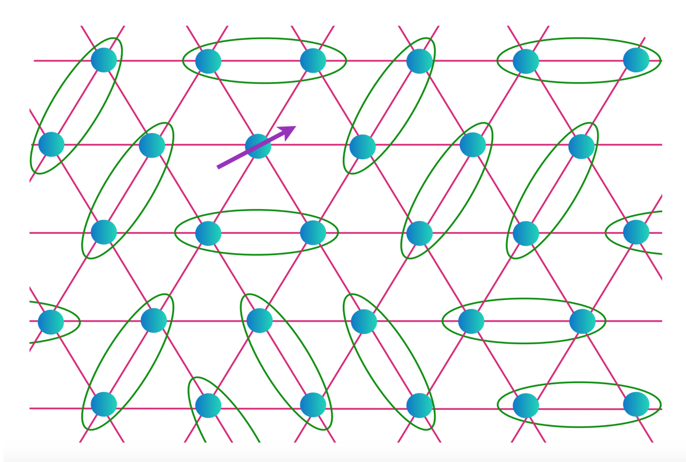
- Threshold at triplon gap with power law behavior.



Triplon in a VBS state

- Spin liquid states with fractionalized S=1/2 spin-carrying excitations - *spinons*.
- The energy and momentum transfer from the electron are shared by two spinons.





Spinon in RVB spin liquid

Read *et al*, Phys. Rev. B **42**, 4568 (1990)
S. Sachdev, Phys. Rev. B **45**, 12377 (1992)
Punk *et al*, Nature Physics **10** (2014)

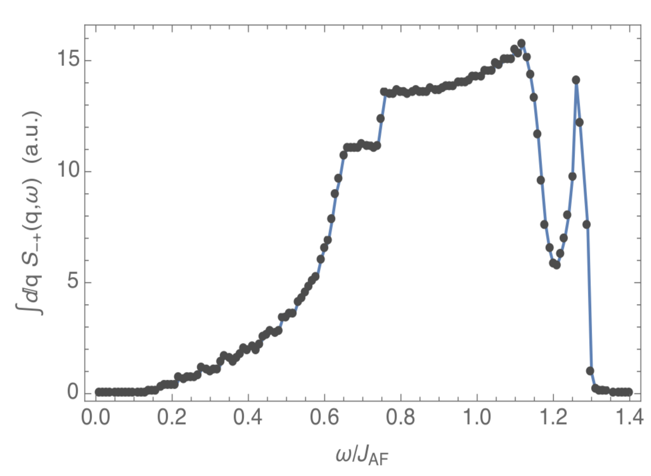
- Low-energy effective dispersion for spinons near band minima: exact results for quadratic spinon bands and gapless spinons at Dirac cones.
- Scaling arguments generalize to arbitrary spinon dispersion and dimension.

$$\epsilon_{\vec{k}} = v_\alpha|\vec{k}|^\alpha,\ \text{and}\ S_{-+}(\vec{q}_\perp,\omega)\sim\int dk\,k^{d-2}d\Omega\,\delta(\omega-\epsilon_{\vec{k}}-\epsilon_{\vec{k}+\vec{q}_\perp})$$
$$k = q_\perp\Phi(v_\alpha q_\perp^\alpha/\omega) \implies S_{-+}(\vec{q}_\perp,\omega)\sim q_\perp^{d-1-\alpha}\,\Psi(v_\alpha q_\perp^\alpha/\omega)\,\Theta(\omega-\zeta v_\alpha q_\perp^\alpha)$$
$$I_{spin}\sim\int_0^V d\omega\,(V-\omega)\int dq_\perp\,q_\perp^{d-2}\,d\Omega\,S_{-+}(\vec{q}_\perp,\omega)\sim V^{1+2(d-1)/\alpha}$$

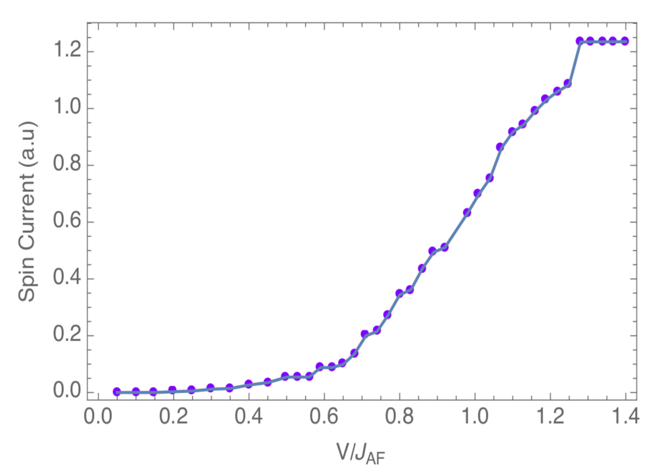
- Beyond analytical approximations: numerical results for the $Q_1 = Q_2$ ground state (strong candidate for Herbertsmithite).

Key result:

$$I_{spin}\sim(V-2\Delta_s)^{1+2(d-1)/\alpha}\Theta(V-2\Delta_s)$$



Integrated dynamic SF



Spin-current for $Q_1 = Q_2$ state

6. Conclusion and Outlook

- Obtain the spin-current by simply measuring electrical voltages or currents.
- Can predict spinon gap and dispersion, and get more information about spinon-bands from the spin-current!
- In absence of spin-orbit coupling/random-field impurities, the spin-current does not degrade.

Open Questions:

What is the effect of coupling of spinons to non-spin carrying degrees of freedom in the spin liquid (like visons)?

How does presence of disorder at the boundary affect the spin-current?