



Quantum Spin Liquids in the Kitaev Model: Real Examples of Exotic Magnetism

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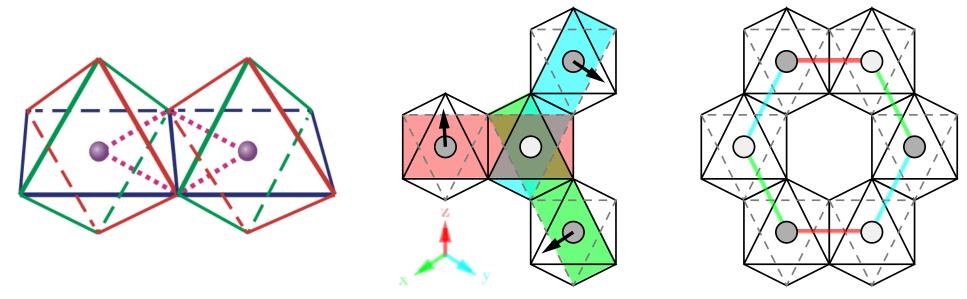




Outline

- 1. Introduction to Magnetism
- 2. Heisenberg and Kitaev Models
- 3. Real Materials and the Extended Kitaev Model
- 4. Types of Experimental Measurements in Condensed Matter
- 5. Experimental Results on β-Li₂IrO₃

The Kitaev Model

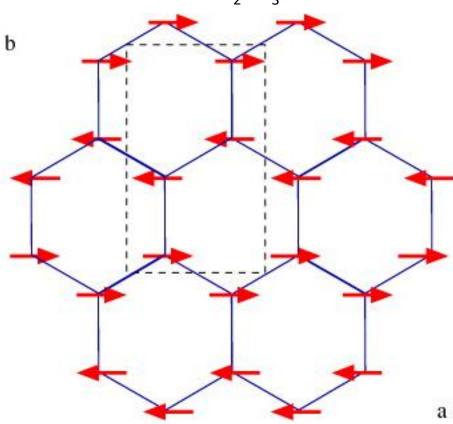


- A quantum spin liquid is a magnetic state in which no single spin order can be simultaneously satisfied, leading to a highly
 frustrated ground state; quantum spin liquids are thought to have applications in quantum computing, and theoretically
 host exotic magnetic phenomena
- The Kitaev model describes a theoretical type of quantum spin liquid; in the Kitaev model, spins interact on planes perpendicular to electron-electron interactions
- The Kitaev model can be exactly solved, and is thought to host Majorana excitations

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Real Materials

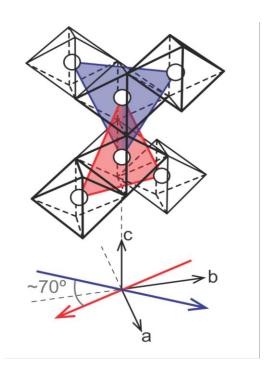
- RuCl₃
- Na₂IrO₃

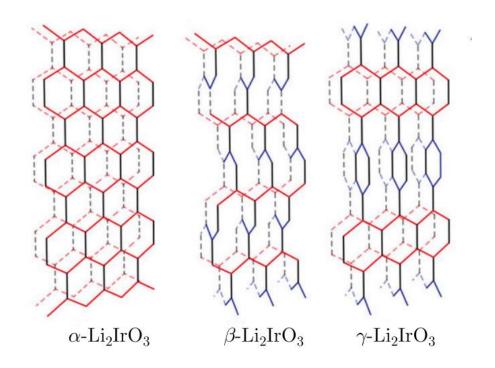


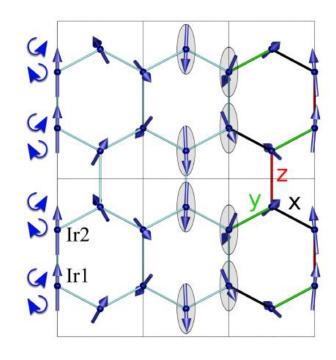
• Real materials proposed to satisfy the Kitaev model order at low temperatures, and therefore do not satisfy the quantum spin liquid ground state. Kitaev candidate materials ruthenium chloride and sodium iridate order into the exotic zig-zag state.

Real Materials

$$a, b, g - Li_2IrO_3$$





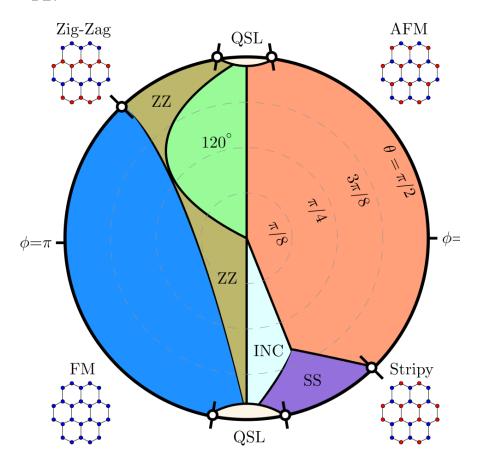


• Lithium iridate has been grown in single crystal and powder form. Lithium iridate can form three-dimensional beta and gamma structures, which order into the exotic incommensurate spiral state pictured on the right.

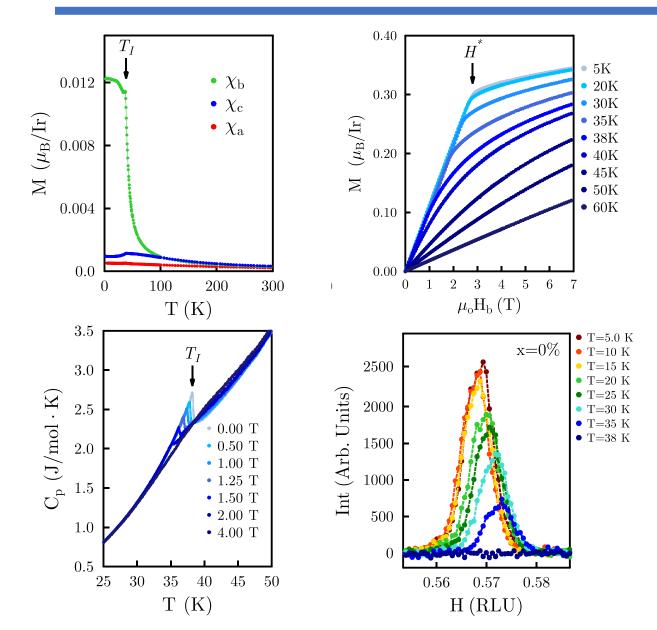
The Extended Kitaev Model

$$H_{ij}^{g} = \mathring{\mathbf{a}} - K_{g}S_{i}^{g}S_{j}^{g} + J_{ij}S_{i} \times S_{j} + G_{ij}(S_{i}^{a}S_{j}^{b} + S_{i}^{b}S_{j}^{a})$$
A.

 An alternate Hamiltonian has been proposed to describe these materials, which includes a Kitaev term (K) in addition to a Heisenberg-like interaction (J) and and off-diagonal term (Gamma). By altering the strengths of these terms, we can traverse through a variety of unusual magnetic ground states.



Types of Experimental Measurements



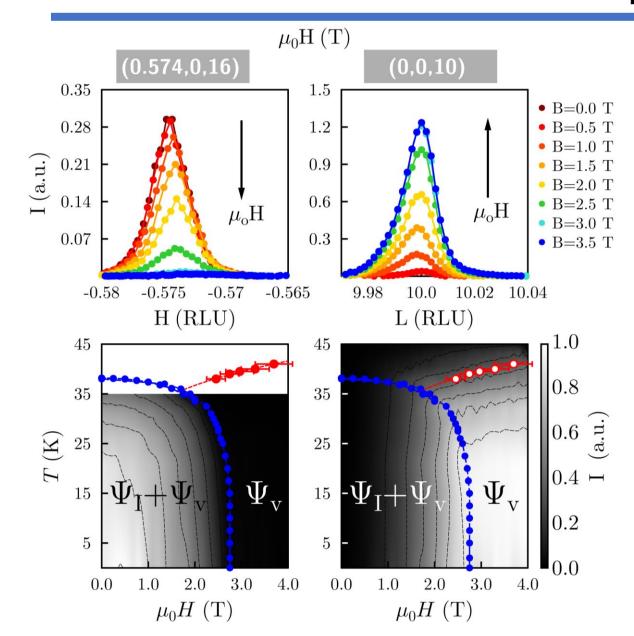
- Thermodynamics:
 - M vs. T
 - M vs. H
 - Cvs. T
 - Tvs. P
- Transport:
 - Conductivity
- Scattering:
 - RIXS
 - REXS
 - Raman Scattering
 - muSR

Types of Perturbations

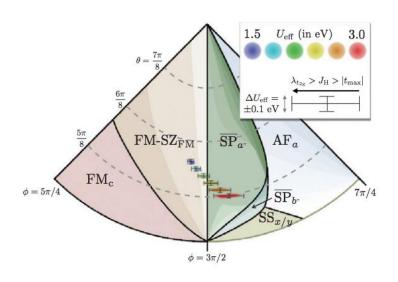
- Pressure
- High Magnetic Field
- Chemical Substitution (Doping)

Applying these perturbations allows us to attempt to drive Kitaev candidate materials into a quantum spin liquid ground state

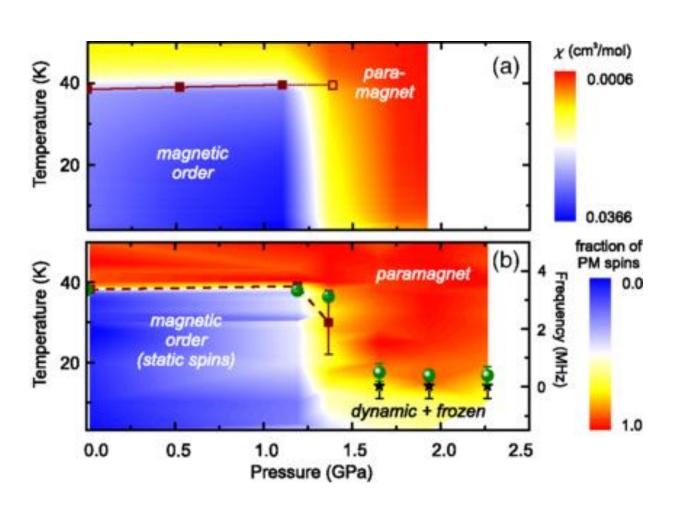
Effects of Applied Field



- Experiments have been conducted applying strong magnetic field to beta lithium iridate
- Fields above 2.7T allow us to traverse from the incommensurate spiral-type order to a zig-zag type order
- IC disappears completely above H*~2.7T.
- The system develops a uniform ZZ order which grows linearly with H.

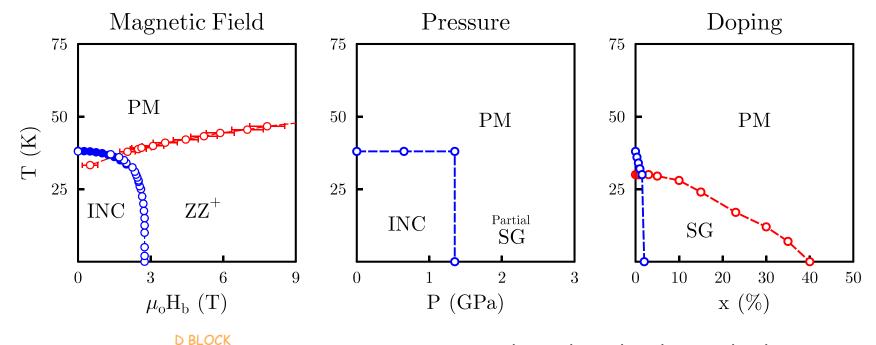


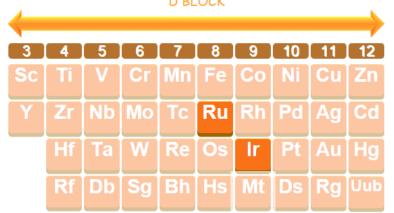
Effects of Applied Pressure



- Experiments have also been conducted applying pressure to beta lithium iridate
- Applying pressure above 1.4GPa allows for the coexistence of dynamic and frozen spins
- IC state vanishes upon a first order transition above 1.4 GPa.
- This transition gives way to a coexisting dynamic + frozen spins.

Chemical Substitution of Ruthenium

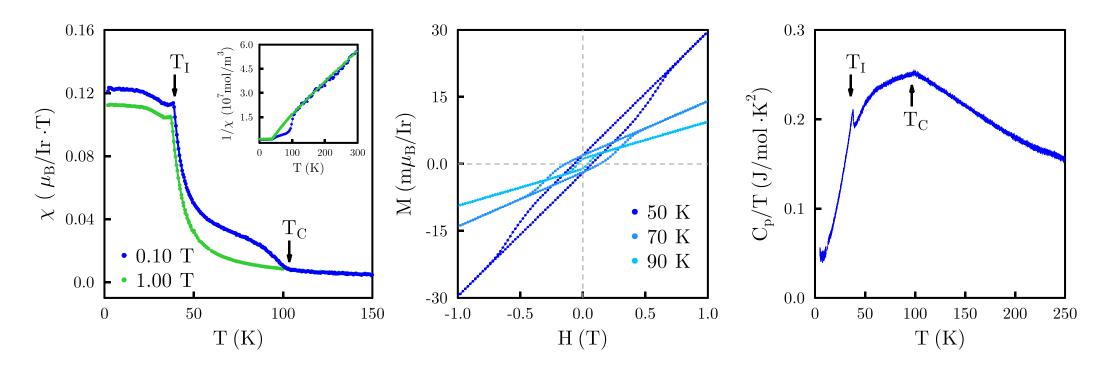




My work involves the chemical substitution of Ruthenium, which has a spin-1 moment, onto the spin-1/2 iridium lattice. Studies are still being conducted to understand the behavior of lithium iridate with ruthenium substitution; however, it appears that under low substitution levels, these materials order into a disordered but frozen spin glass state

$$\text{Li}_2\text{IrO}_3 + \text{Li}_2\text{RuO}_3 \rightarrow \text{Li}_2\text{Ru}_x\text{Ir}_{1-x}\text{O}_3$$

High-Temperature Thermodynamics



 Recent studies on larger single crystals have also shown a new magnetic transition in beta lithium iridate under low field at high temperatures of 100K. The cause of this transition is still unknown, but it is speculated that the onset of order at 100K may be related to Kitaev-like interactions

Conclusions

- Synthesis and manipulation of real materials offers the opportunity to explore theoretical models, and in doing so we can unlock new, rich physics not previously proposed by the theory
- Magnetic fields, pressure, and chemical substitution allow us to explore the magnetic phase diagram
- Still much more to be done to understand high-temperature behavior and mechanisms underlying the frustration in these materials
- Observed transition at T = 100K which is an intrinsic property