Kitaev Spin Liquids

Context
The Model

Ying-Ting "Layered Nickelates"
Michael "Thin-Film Pyrochlore Irridiates"
Skanda "Twisted Bilayer Graphene"

Experimental Realizations
Kitaev Model

- Topological Physics
- Strongly Correlated Electrons
- Quantum Magnetism
- Quantum Computation
- Solid State Chemistry
The Kitaev Model on the Honeycomb Lattice

\[ H = - \sum_{\langle ij \rangle_{\gamma}} K_{\gamma} S^{\gamma}_i S^{\gamma}_j \]

Classical Model

Two “happy” bonds/plaquette

Classical Model has Extensive Ground State Degeneracy

Ising Spins with Bond Anisotropies
The Kitaev Model on the Honeycomb Lattice

\[ H = - \sum_{<ij>\gamma} K_{\gamma} S_{i\gamma}^{\gamma} S_{j\gamma}^{\gamma} \]

Ising Spins with Bond Anisotropies

Quantum Model

Superposition of Classical Configurations (similar to RVB)

Highly Entangled Quantum Spin Liquid State
The Kitaev Model on the Honeycomb Lattice

\[ W_p = 2^6 S^z_1 S^x_2 S^y_3 S^z_4 S^x_5 S^y_6 \]

\[ S^\gamma_i = \frac{\hbar}{2}\sigma^\gamma \]

\[ \sigma^a \sigma^b = \delta_{ab} I + i\epsilon_{abc}\sigma^c \]

\[ [\sigma^a, \sigma^b] = 2i\epsilon_{abc}\sigma^c \]

\[ [W_p, H] = 0 \]

Ising Spins with Bond Anisotropies
The Kitaev Model on the Honeycomb Lattice

\[ H = - \sum_{\gamma} \sum_{<ij>_{\gamma}} K_{\gamma} S_{i_{\gamma}} S_{j_{\gamma}} \]

Ising Spins with Bond Anisotropies

\[ W_p = 2^6 S_1^z S_2^x S_3^y S_4^z S_5^x S_6^y \]

\[ [W_p, H] = 0 \]

Infinitely Many Conserved Quantities

\[ W_p = \pm 1 \]

Each many-body eigenstate can be labelled by conserved flux quanta through each hexagon
The Kitaev Model on the Honeycomb Lattice

\[ H = - \sum_{<ij>,\gamma} K_{\gamma} S^\gamma_i S^\gamma_j \]

Ising Spins with Bond Anisotropies
The Kitaev Model on the Honeycomb Lattice
The Kitaev Model on the Honeycomb Lattice

\[ H = -\frac{1}{4} \sum_{<ij>^\gamma} K^\gamma u^\gamma_{ij} c_i c_j \]

\[ (u^\gamma_{ij} = b^\gamma_i b^\gamma_j) \]
The Kitaev Model on the Honeycomb Lattice

\[
H = -\frac{1}{4} \sum_{\langle ij \rangle_{\gamma}} K_{\gamma} u_{ij}^{\gamma} c_i c_j \quad (u_{ij}^{\gamma} = b_i^{\gamma} b_j^{\gamma})
\]

(if \( W = -1 \))
The Kitaev Model on the Honeycomb Lattice

\[ H = -\frac{1}{4} \sum_{<ij>\gamma} K_\gamma u_{ij}^\gamma c_i c_j \]

\[(u_{ij}^\gamma = b_i^\gamma b_j^\gamma)\]

Dirac Dispersion

uniform phase
The Kitaev Model on the Honeycomb Lattice

Kitaev Materials

The diagram illustrates the phase diagram of Kitaev materials as a function of the correlation parameter $U/t$ and the spin-orbit coupling parameter $\lambda/t$. The different regions correspond to different types of insulators:

- Mott insulator
- Metal band insulator
- Kitaev materials
- Spin-orbit entangled Mott insulator
- Topological insulator
- Weyl semi-metal

S. Trebst, arXiv 1701.0705
**Fig. 2:** Formation of spin-orbit entangled $j = 1/2$ moments for ions in a $d^5$ electronic configuration such as for the typical iridium valence $\text{Ir}^{4+}$ or the ruthenium valence $\text{Ru}^{3+}$.

**Fig. 3:** Illustration of possible geometric orientations of neighboring $\text{IrO}_6$ octahedra that give rise to different types of (dominant) exchange interactions between the magnetic moments located on the iridium ion at the center of these octahedra. For the corner-sharing geometry (I) one finds a dominant symmetric Heisenberg exchange, while for the edge-sharing geometries (II) one finds a dominant bond-directional, Kitaev-type exchange.
Ab Initio Calculations

\[ H = - \sum_{\gamma\text{-bonds}} J \ S_i S_j + K \ S_i^\gamma S_j^\gamma + \Gamma \left( S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha \right) \]

\[ J = \cos \phi, \quad K = \sin \phi \]

**Fig. 6:** Phase diagram of the Heisenberg-Kitaev model, reproduced from Ref. [63].