Theory of a competitive spin liquid state for weak Mott insulators on the triangular lattice

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PRL **111**, 157203 (2013)

Abstract

We propose a novel quantum spin liquid state that can explain many of the intriguing experimental properties of the low-temperature phase of the organic spin liquid candidate materials κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ and EtMe$_3$Sb[Pd(dmit)$_2$]$_2$. This state of paired fermionic spinons preserves all symmetries of the system, and it has a gapless excitation spectrum with quadratic bands that touch at momentum k=0. This quadratic band touching is protected by symmetries. Using variational Monte Carlo techniques, we show that this state has highly competitive energy in the triangular lattice Heisenberg model supplemented with a realistically large ring-exchange term.

Experimental motivation

Spin liquid candidate materials:
κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ and EtMe$_3$Sb[Pd(dmit)$_2$]$_2$

These are Mott insulators, with no evidence for magnetic order at low temperatures.

At low temperatures,
- Specific heat is linear with temperature $C_v = \gamma T$
- Magnetic susceptibility is constant χ

These properties are similar to a metallic state, but the system is insulating!

Model

spin-1/2 Heisenberg model on **triangular lattice** with ring-exchange term (Motrunich 2005):

$$H = J_1 \sum_{\langle i,j \rangle} 2\vec{S}_i \cdot \vec{S}_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} 2\vec{S}_i \cdot \vec{S}_j + K \sum_{\langle i,j,k,l \rangle} (P_{ijkl} + \text{H.c.})$$

$\langle i,j,k,l \rangle$ sums over elementary four-site rhombi

P_{ijkl} rotates the spin configurations around a rhombus

Our variational state

We begin with the spin-1/2 slave fermion representation:

$$\vec{S}_j = \frac{1}{2} \sum_{\alpha,\beta=\uparrow,\downarrow} f^\dagger_{j\alpha} \vec{\sigma}_{\alpha\beta} f_{j\beta}$$

This has a gauge constraint $\sum_\alpha f^\dagger_{j\alpha} f_{j\alpha} = 1$

The mean field spinon dynamics can be described by:

$$H_{\text{MF}} = -\sum_{i,j} \left[t_{ij} f^\dagger_{i\sigma} f_{j\sigma} + \left(\Delta_{ij} f^\dagger_{i\uparrow} f^\dagger_{j\downarrow} + \text{H.c.} \right) \right]$$

Within this framework, we consider the state with $d+id$ nearest-neighbor pairing and no hopping:

$$\Delta^{(d+id)}_{j,j+\hat{e}} = \Delta \left(e_x + i e_y \right)^2 \qquad t_{ij} = 0$$

The low-energy Hamiltonian at $\vec{k} = 0$ is then:

$$H_0 = \psi^\dagger \{ -\tau^x (\partial_x^2 - \partial_y^2) + 2\tau^y \partial_x \partial_y \} \psi$$

This state has **quadratic band touching** (QBT) at $\vec{k} = 0$.

Our variational states for the spin system are the Gutzwiller projected ground states $|\Psi_0\rangle$ of the mean field Hamiltonian above.

$$|\Psi(\{t_{ij}\}, \{\Delta_{ij}\})\rangle = \mathcal{P}_G \mathcal{P}_N |\Psi_0\rangle$$

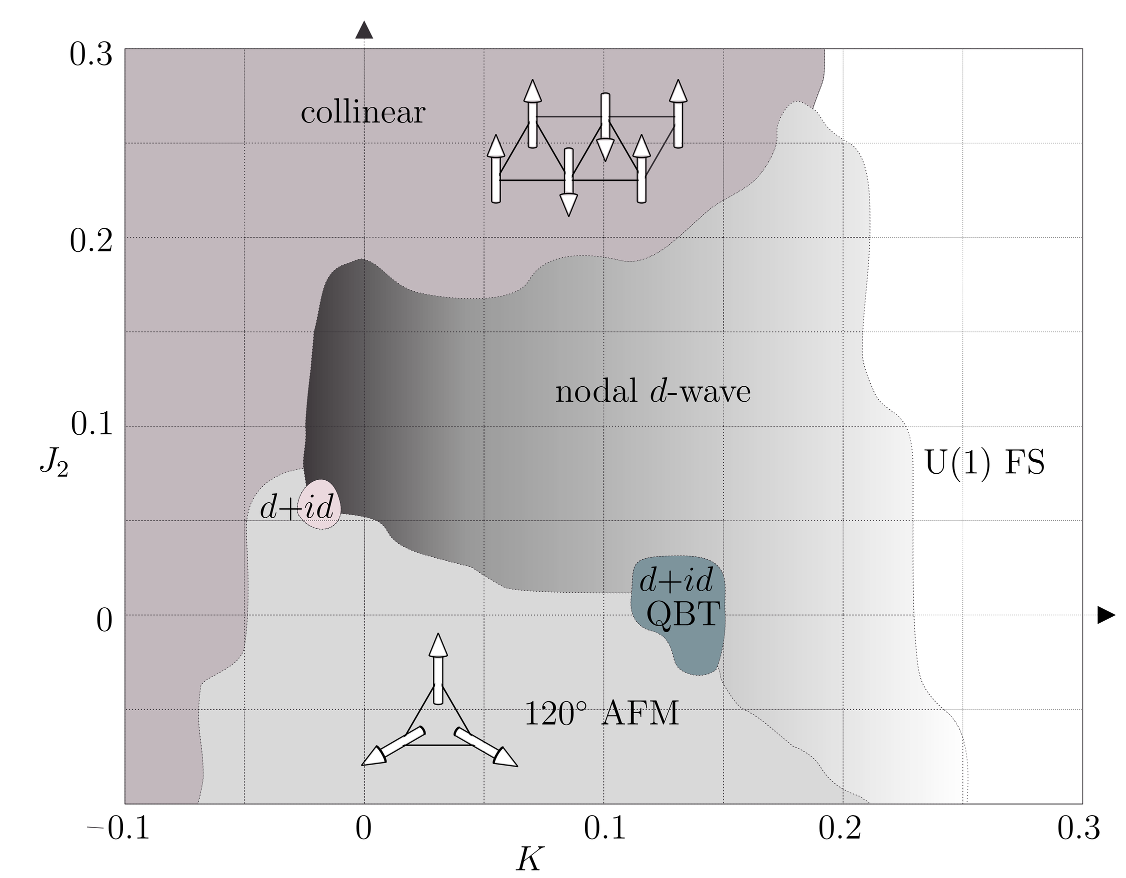
where the projection operators enforce the constraint of one spinon on each site.

Features

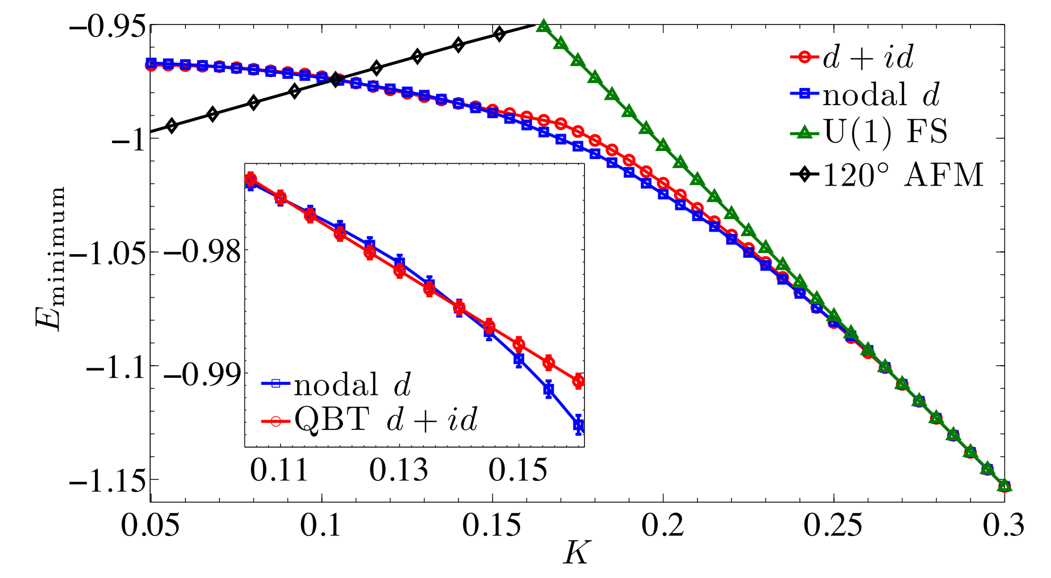
- finite γ and χ are generic properties of the state (they do not rely on disorder)
- gauge fluctuation is gapped => calculations are controlled
- the small energy gap experimentally observed in κ-BEDT can be explained by a marginally relevant short-range spinon interaction which is allowed by symmetries.
- it is consistent with experimental absence of thermal Hall effect
- the state is energetically competitive!

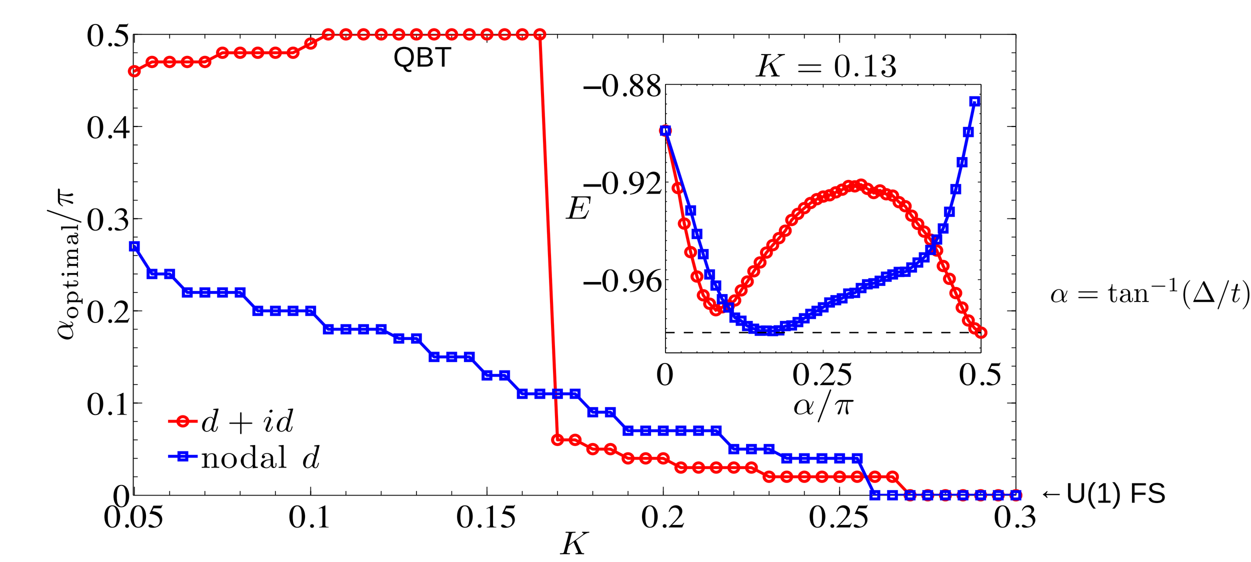
Results

Phase diagram



Energetics





QBT state has very competitive energy for $0.1 \lesssim K \lesssim 0.15$