Quantum spin liquids (QSLs) have exotic properties that go beyond the Landau scheme of symmetry breaking, and they are of great interest due to the presence of anyons that obey fractional statistics. Experimental detection of gapped QSLs is challenging due to the lack of charge and gapless modes. We propose using the Kondo effect to detect the symmetry fractionalization in gapped Z₂ QSLs. the Kondo screening phase will feature a non-Kramers doublet localized at the impurity site, protected by fractionalized crystalline symmetries in the Z₂ QSL.

Introduction

Detecting symmetry fractionalization in gapped quantum spin liquids by magnetic impurities
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Theory

Kondo screening

J_kondo

Kramers doublet
Non-Kramers doublet
Protected by symmetry fractionalization

Symmetry fractionalization
A, C : \( M_z M_y M_z^{-1} M_y^{-1} = -1 \)
B : \( (M_x T)^2 = 1 \)
Does not have trivial representation and has local degeneracy

Results

High-symmetry impurity sites that can be used to detect the symmetry fractionalization of spinons in a gapped symmetric Z₂ spin liquid.

Method 1: Exactly solvable model

Toric code model + spin-1/2 + impurity

\[
\hat{H} = -\sum_i A_i - \sum_j B_j - \sum_k \frac{1}{2} (A_k + 1) P(S = 0) + \frac{1}{2} (1 - A_k) P(S = 1/2) + J \sum_{(i,j)} S_i \cdot S_j
\]

The SU(2) symmetry is implemented in the Hilbert space of spin 0 \( \oplus 1/2 \) on each vertex.
The model shares the same ground state as toric code where all vertex spins are in the spin-0 state.
The low energy excitations are spin-0 m particles, and \( e, \epsilon \) particles each carry spin-1/2.

Ground state is unique if impurity is screened by \( \epsilon \) \( (M_z M_y M_z^{-1} M_y^{-1} = 1) \)
Ground state is degenerate if screened by \( \epsilon \) \( (M_z M_y M_z^{-1} M_y^{-1} = -1) \)

Method 2: large-N mean field theory

The parton construction of quantum spin liquids provides another aspect to look at the Kondo effect in Z₂ spin liquids.
In the case of a nontrivial fractionalization class with \( M_z M_y M_z^{-1} M_y^{-1} = (-1)^N \)
each energy level in the spectrum of the parton BdG Hamiltonian must be at least 2-fold degenerate
particle-hole symmetric spectrum must have 2 zero modes
the both filled and the both empty states are physical degenerate ground state

\[
H_{bulk} = -\sum_{\langle i,j \rangle} \epsilon_{i,j} c_{i,j}^\dagger c_{j,i} + \epsilon_{i,j}^\dagger c_{i,j}^\dagger + h.c.
+ \Delta \sum_{i,j} \epsilon_{i,j} c_{i,j}^\dagger c_{i,j} + \epsilon_{i,j}^\dagger c_{i,j}^\dagger + h.c.
\]
a labels N flavors. Large N limit is solvable.
\( u_{i,j} = \frac{\sigma_{i,j}}{\sqrt{N}} \) is a conserved quantity and gives us nontrivial PSG
Interaction between impurity and bulk is in form of sp(N) spin

\[
H_{imp} = \sum_{\langle i,j \rangle \in \text{imp}} \frac{J}{N^2} S_i^z S_j^z + \frac{J'}{N} \sum_{i \in \text{imp}} S_i^z \left( S_i^z + N \right)
\]
thermodynamic quantities from the mean-field calculation to illustrate the experimental implications of the anomalous Kondo effect.

In the presence of SO(3) spin rotational symmetry, the classification of symmetric Z₂ spin liquids on these lattices are summarized in TABLE above.
A part of the symmetry fractionalization data can be detected by presence/absence of non-Kramers doublets for Kondo-screened magnetic impurities located at different high-symmetry sites.