Emergent fermions at 3D

—— $Na_4Ir_3O_8$ as a 3D spin liquid with fermionic spinons

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Abstract

Spin liquid states for spin-1/2 antiferromagnetic Heisenberg model on a hyperkagome lattice are studied. We classify and study plausible states according to symmetries. Applying this model to $Na_4Ir_3O_8$, we propose that the high temperature phase is a state with a spinon Fermi surface, which forms a pairing state with line nodes below ~20K. The possibility of mixed spin singlet and spin triplet pairing states is suggested according to the lattice symmetry which breaks inversion.

Reference: Yi Zhou, Patrick A. Lee, Tai-Kai Ng and Fu-Chun Zhang, Phys. Rev. Lett. 101, 197201 (2008)

Spin liquids as emergent phenomena

◆ **What's a spin liquid:** a spin liquid is a spin system where *quantum fluctuations* dominate its low energy behavior, thereby a long range spin order can not be established even at zero temperature.

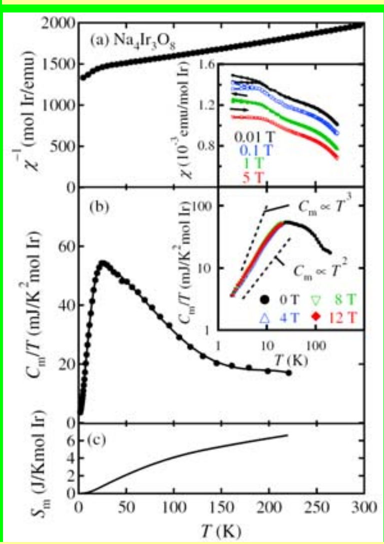
◆ **Spin liquids are novel states of matter:**

- ◆ Low lying excitations: ***S=1/2***, charge neutral spinons.
- ◆ The spinons may obey Fermi or Bose statistics and there may or may not be an energy gap.
- ◆ These spinons are generally accompanied by gauge fields.

◆ **Emergent phenomena**: new particles and fields emerge at low-energy scale which are absent in the Hamiltonian that describes the initial system.

The first 3D candidate for spin liquids: $Na_4Ir_3O_8$

Y. Okamoto, M. Nohara, H. Aruga-Katori, H. Takagi, PRL, 99, 137207 (2007)



Experimental observations

◆ AFM Mott insulator, spins come from Ir^{4+} $5d^5$ electrons.

◆ Curie-Weiss fitting around room temperature → θ_W ~650K.

◆ Despite large AFM exchange *J*~300K, *no magnetic order* was found in spin susceptibility χ down to 1K and below; consistent with NMR data.

◆ Effective magnetic moment is *1.96* μ_B → *S=1/2.*

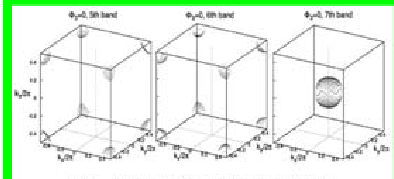


FIG. 2. Fermi surfaces of the zero flux state at half-filling.

issues

◆ What kind of spin state it is?

◆ Wilson ratio is close to 1 at specific heat peak: R_W *=0.88.*

◆ For a wide range of temperature T_c(~20K) < T << θ_W(650K), the system seems behave like *a Fermi liquid*.

◆ Below T_c~20K, the specific heat decreases to zero as C_V~T^2, indicating *a line nodal gap*.

- ◆ ***How this line nodal gap forms?***
- ◆ ***Why*** χ ***remains almost constant across*** T_c ***at the same time?***

A spin model on a hyperkagome lattice

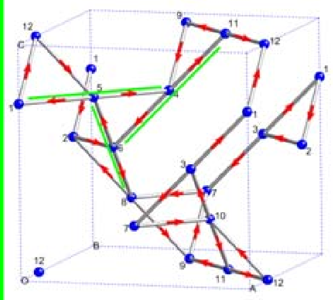
$$H = J\sum_{\langle i\mu,j\nu\rangle}\vec{S}_{i\mu}\cdot\vec{S}_{j\nu}$$

Variational approach

◆ Low energy physics is governed by a trial Hamiltonian H_{trial}.

◆ A fermionic trial wave function will be given by the ground state of such a trial Hamiltonian.

◆ The spin liquid ground state is formed by Gutzwiller projection of the trial wave function into a state with no double occupancy.



$$H_{trial} = H_0 + H_{pair}$$

$$H_0 = -\sum_{\langle i\mu,j\nu\rangle,\alpha} t_{i\mu,j\nu}c^\dagger_{i\mu\alpha}c_{j\nu\alpha} + h.c.,$$

$$H_{pair} = -\sum_{\mathbf{k}\alpha\beta}\Delta_{\alpha\beta}(\mathbf{k})c^\dagger_{\mathbf{k}\alpha}c^\dagger_{-\mathbf{k}\beta} + h.c.,$$

Symmetry

◆ *Symmetry will dramatically reduce the number of variational parameters t's & Δ's!*

Above T_c: *U(1)* spin liquid

◆ H_0 determines the physics at T > T_c, which is a Fermi liquid of spinons.

◆ Such a Fermi liquid can be described as a flux state with *only one parameter*.

$$c_{i\mu\alpha} \to e^{-i\phi_i}c_{i\mu\alpha}, \quad t_{i\mu,j\nu} \to e^{i(\phi_i-\phi_j)}t_{i\mu,j\nu}$$

◆ Associated gauge field is *U(1) gauge field* → *U(1) spin liquid.*

◆All these symmetric flux states have *finite Fermi surfaces.*

◆ For the isotropic Heisenberg model, *zero flux state* is the lowest energy state among flux states at mean field level.

Below T_c: Z_2 spin liquid

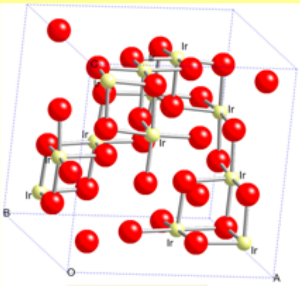
◆ A spinon pairing gap characterized by H_{pair} is opened up at T < Tc. (*U(1)* spin liquid → Z_2 spin liquid)

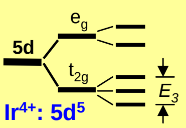
◆ Spinon pairing gives rise to line nodes at Fermi surfaces -

◆ Because of *broken inversion symmetry*, the spin-singlet and spin-triplet pairing states can mix together in the presence of *spin-orbit coupling* → *line nodes*.

◆ {General Condition for line nodal gap**: *The pairing must be pure spin singlet or singlet with triplet admixture in order to have nodal lines.***}

Magnetic interactions in $Na_3Ir_4O_8$





◆ ***Ir-Ir*** → isotropic exchange.

◆ ***Ir-O-Ir*** → anisotropy exchange and DM interaction.

◆ t_{2g} levels → *L=1* multiplet.

◆ Spin-orbit coupling → pseudospin ***J=L+S***, *J=1/2 or 3/2.*

◆ *g≈2 (J=1/2)*.

Validity of our model

◆ Provided that the exchange path is dominated by Ir-Ir direct exchange, our starting point with isotropic Heisenberg model remain valid both in weak and strong coupling limits, if the spin ***S*** is interpreted as pseudospin ***J=1/2***.

◆ The correction terms are anisotropy Heisenberg exchange and DM interaction, of order *(g-2)²*.

◆ These corrections spoil the conservation of total ***J***, give rise to a decay rate *1/* τ_s. In the limit *1/* τ_s>>Δ, therefore the spin susceptibility is not much affected by the onset of pairing.

Spin orbit interaction

◆ Spin orbit interaction will result in

$$\chi_s/\chi_n = 1 - O(\Delta\tau_s)$$

In the limit *1/* τ_s>>Δ, spin susceptibility changes only slightly across T_c.

Summary

◆ **A variational approach to emergent phenomena:** We study fermionic spin liquid states describe by trial Hamiltonian on a 3D hyperkagome lattice.

◆ **Symmetric spin liquid states on 3D hyperkagome lattice:** Assuming the spin liquid states have the the full point group symmetry and translational symmetry of lattice, we classify all the possible flux states and show that Fermi surfaces exist in all these states.

◆ ***U(1)* to Z_2 transition at 20K:** Above Tc~20K, the spin liquid is a Fermi liquid of spinons. Below T_c, the pairing between spinons will open a gap at spinon spectrum.

◆ **How the line nodal gap forms:** Broken inversion symmetry will lead in general mixing of spin singlet and spin triplet states, resulting in formation of line nodal gaps, C_V~T^2.

◆ **Why the spin-susceptibility does not change across T_c:** The presence of strong spin-orbit coupling in this material also provides a natural explanation to the observed spin-susceptibility which is more or less temperature independent below Tc~20K.