Stability of time-reversal symmetry breaking spin liquid states in high-spin fermionic systems

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Outline

- Part I
  - Fundamentals of high spin systems
  - Spin wave description
  - Valence bond picture
- Part II
  - Competing spin liquid states of spin-3/2 fermions in a square lattice
  - Competing spin liquid states of spin-5/2 fermions in a honeycomb lattice
    - Properties of chiral spin liquid state
    - Stability of the spin liquid states beyond the mean-field approximation
    - Finite temperature behavior
    - Experimentally measurable quantities

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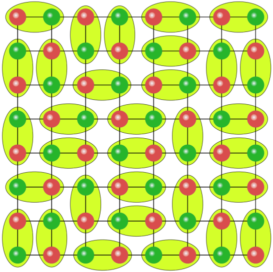
EPL 93, 66005 (2011)

Part II

Spin liquid phases



$$H = J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

$J > 0$	antiferromagnetic coupling

Schwinger fermions

$$\vec{S}_i = \sum_{\alpha,\beta} c^\dagger_{i,\alpha} \, \vec{F}_{\alpha,\beta} \, c_{i,\beta}$$

$$\{c_{i,\alpha}, c^\dagger_{j,\beta}\} = \delta_{i,j}\delta_{\alpha,\beta}$$

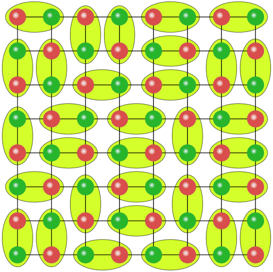
1 particle / site

Bond operators

$$\chi_{i,j} = c^\dagger_{i,\sigma} c_{j,\sigma} = \chi^\dagger_{j,i}$$

$$H = -J \sum_{\langle i,j \rangle} c^\dagger_{i,\alpha} c_{j,\alpha} c^\dagger_{j,\beta} c_{i,\beta} + \sum_i \varphi_i \left(c^\dagger_{i,\alpha} c_{i,\alpha} - 1 \right)$$

Spin liquid phases



Local gauge invariance

$$c_{j,\alpha} \to e^{i\theta_j}\, c_{j,\alpha}$$

$$c^\dagger_{j,\alpha} \to e^{-i\theta_j}\, c^\dagger_{j,\alpha}$$

$$\chi_{i,j} \to \chi_{i,j} e^{i(\theta_j - \theta_i)}$$

$$\varphi_i \to \varphi_i - i\partial_t \varphi_i$$

Bond operators

$$\chi_{i,j} = c^\dagger_{i,\sigma} c_{j,\sigma} = \chi^\dagger_{j,i}$$

Plaquette operator

$$\Pi = \chi_{i,j}\chi_{j,k}\cdots\chi_{l,i}$$

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Spin liquid phases

Mean-field bonds: $\chi_{i,j} \to \bar{\chi}_{i,j}$

Plaquette operator

$$\Pi = \bar{\chi}_{i,j}\bar{\chi}_{j,k}\ldots\bar{\chi}_{l,i} = \mathrm{Abs}[\Pi]e^{i\Phi}$$

- $\Phi = n\pi$ (n integer): no time reversal symmetry breaking.
- With nontrivial Φ: time reversal symmetry breaking.
  - Low lying excitations composite particle (spinon $+$ an elementary flux) $\to$ anyons.
  - Effective gauge theory.

$F = \frac{3}{2}$ system on a square lattice

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Let us recall the n.n. Hamiltonian in the limit of strong repulsion:

$$H_{eff}^{F=3/2} = \sum_{\langle i,j\rangle} \left[g_0 \mathscr{P}_0^{(i,j)} + g_2 \mathscr{P}_2^{(i,j)} \right]$$

where $\mathscr{P}_S^{(i,j)} = c_{i,\sigma_1}^\dagger c_{j,\sigma_2}^\dagger c_{j,\sigma_3} c_{i,\sigma_4} \hat{P}_S$, and $\hat{P}_S$ are antisymmetric.

Hamiltonian with 2 parameters.

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Hamiltonian with 2 parameters.

$$H_{eff}^{F=3/2} = \sum_{\langle i,j \rangle} \left[a_0\, n_i n_j + a_1 \mathbf{S}_i \mathbf{S}_j + a_2 (\mathbf{S}_i \mathbf{S}_j)^2 + a_3 (\mathbf{S}_i \mathbf{S}_j)^3 \right]$$

Hamiltonian with 4 parameters

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Hamiltonian with 4 parameters

One can exploit the fact that $\hat{P}_0$ and $\hat{P}_2$ are antisymmetric with respect to the exchange of the spin of the colliding particles leading to a new effective Hamiltonian:

$F = \frac{3}{2}$ system on square lattice

$H_{eff} = \sum_{\langle i,j \rangle} \left[g_0 \mathscr{P}_0^{(i,j)} + g_2 \mathscr{P}_2^{(i,j)} \right]$

$$H_{eff} = \sum_{<i,j>} \left[a_n \left(n_i n_j + \chi^\dagger_{i,j} \chi_{i,j} - n_i \right) + a_s \left(\mathbf{S}_i \mathbf{S}_j + \mathbf{B}^\dagger_{i,j} \mathbf{B}_{i,j} - \frac{15}{4} n_i \right) \right]$$

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Site- and bond-centered operators

- $n_i = c^\dagger_{i,\alpha} c_{i,\alpha}$ (particle number at site *i*)
- $\mathbf{S}_i = c^\dagger_{i,\alpha} \mathbf{F}_{\alpha,\beta} c_{i,\beta}$ (spin at site *i*)
- $\chi_{i,j} = c^\dagger_{i,\alpha} c_{j,\alpha}$ (scalar valence bonds)
- $\mathbf{B}_{i,j} = c^\dagger_{i,\alpha} \mathbf{F}_{\alpha,\beta} c_{j,\beta}$ (vector valence bonds)

Nonuniform bond centered orders

- $\langle |\chi_{i,j}|^2 \rangle \propto \langle \mathbf{S}_i \mathbf{S}_j \rangle \rightarrow$ spin-Peierls distortion B. Marston and J. Affleck PRB (1989)
- $\langle |\mathbf{B}_{i,j}|^2 \rangle \propto \langle \mathbf{Q}_i \mathbf{Q}_j \rangle \rightarrow$ quadrupole-Peierls distortion

SU(2) bond-ordered states

The nonlocal part of the mean-field Hamiltonian:

$$\left(a_n \langle \chi_{j,i} \rangle \delta_{\alpha,\beta} + a_s \langle \mathbf{B}_{j,i} \rangle \mathbf{F}_{\alpha,\beta}\right) c^\dagger_{i,\alpha} c_{j,\beta} + H.c.$$

- A more suitable new link parameter: $U_{i,j} = \langle \mathbf{B}_{i,j} \rangle \mathbf{F}$, with the usual inner product in the 3 dimensional space of the generators **F**.
  - $U_{i,j}$ is a member of SU(2)
  - 4×4 matrix for $F = 3/2$ fermionic atoms
- The SU(2) plaquette: $\Pi^{SU(2)} = U_{i,j} U_{j,k} U_{k,l} U_{l,i}$.
- The SU(2) plaquette $\Pi^{SU(2)}$ is also invariant under the U(1) gauge transformation defined above: $c_{i,\sigma} \to c_{i,\sigma} e^{i\phi_i}$, $\langle \chi_{i,j} \rangle \to \langle \chi_{i,j} \rangle e^{i(\phi_j - \phi_i)}$, and $U_{i,j} \to U_{i,j} e^{i(\phi_j - \phi_i)}$.

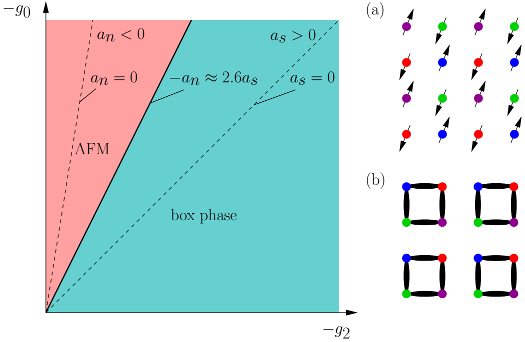
Mean-field phase diagram: $F = 3/2$, 1/4 filling, square lattice

Parameters

$$a_n = \frac{5g_2 - g_0}{4}$$

$$a_s = \frac{(g_2 - g_0)}{3}$$

$$g_S = -\frac{4t}{U_S}$$



Nonzero order parameters

- AFM: $\langle \mathbf{S}_i \rangle$
- box phase: $\langle \chi_{i,j} \rangle$
  - valence bond solid state
  - plaquettes with flux $\Phi = 0$, or $\pm\pi$

For the SU(4) line: C. Wu MPL (2006)
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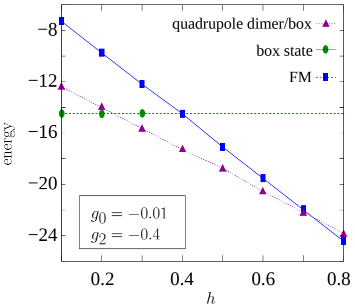
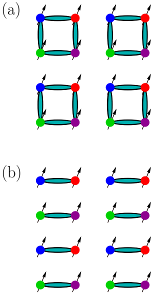
In presence of magnetic field

Hamiltonian with magnetic field:

$$H^h = H^{MF} + h \sum_i \mathbf{S}_i .$$





Order parameters

- SU(2) dimer/ Quadrupole dimer: $\langle \mathbf{S}_i \rangle$, $\langle \chi_{i,j} \rangle$, $\langle \mathbf{B}_{i,j} \rangle$
- SU(2) plaquette/ Quadrupole plaquette: $\langle \mathbf{S}_i \rangle$, $\langle \chi_{i,j} \rangle$, $\langle \mathbf{B}_{i,j} \rangle$

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In presence of magnetic field

Linear Zeeman energy: $\omega_L = g_F \mu_B B$

Quadratic Zeeman energy: $\omega_q = \frac{\omega_L^2}{\omega_{hf}}$.

- ω_{hf}: hyperfine splitting (1-10 GHz)
- g_F: gyromagnetic factor
- μ_B: Bohr magneton

The quadratic Zeeman term can be neglected if $\frac{\omega_L}{\omega_q} \gg 1 \Rightarrow \frac{\omega_{hf}}{\omega_L} \gg 1$

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Magnetic field was considered in units of t.

t has a maximum at
$V_0 \approx \omega_R$,
where $t \sim \omega_R \sim 1 - 100$ kHz.
($\omega_R / 2\pi \sim 400.98$ kHz for ^{9}Be)

In optical lattice: $t = \omega_R \frac{2}{\pi} \xi^3 e^{-2\xi^2}$

- $\xi = (V_0/\omega_R)^{1/4}$
- V_0 potential depth,
- ω_R recoil energy

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Result: the SU(2) plaquette state has the lowest enegy at $\omega_L \sim 0.1 - 1t$ (0.1-100 kHz)

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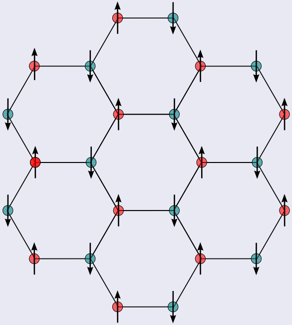
$$\omega_{hf}/\omega_L \sim 10^4 - 10^7$$

Competing spin liquid states of SU(6) symmetric spin-5/2 fermions on a honeycomb lattice

Néel state vs. spin liquid state

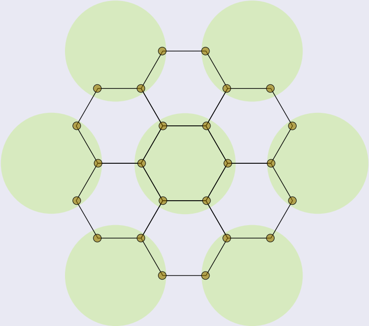
Néel state



Néel state is not energetically favorable.

M. Hermele, V. Gurarie, A. M. Rey, PRL (2009).

Spin liquid - VB state



The ground state expectedly consists SU(6) singlets (6 atoms with $F = \frac{5}{2}$ can form an SU(6) singlet)

Finite temperature field theory

$$H[c, c^\dagger] = -J \sum_{\langle i,j \rangle} c^\dagger_{i,\alpha} c_{j,\alpha} c^\dagger_{j,\beta} c_{i,\beta}$$

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$$H[c, c^\dagger] = -J \sum_{\langle i,j \rangle} c^\dagger_{i,\alpha} c_{j,\alpha} c^\dagger_{j,\beta} c_{i,\beta}$$

Partition function: $Z = \int [\mathrm{d}c][\mathrm{d}\bar{c}] \exp(-\int_0^\beta \mathrm{d}\tau \, L[c, \bar{c}])$

$L[c, \bar{c}] = \sum_i \bar{c}_{i,\alpha} \partial_\tau c_{i,\alpha} + H$ and #atoms= #sites

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Decoupling procedure:

Hubbard-Stratonovich transformation: $L[c, \overline{c}] \to L[c, \overline{c}; \varphi, \chi]$

auxiliary fields: φ_i (on-site, real), and $\chi_{i,j}$ (link, complex)

$$Z = \int [\mathrm{d}\varphi][\mathrm{d}\chi][\mathrm{d}c][\mathrm{d}\overline{c}] \exp(-\int_0^\beta \mathrm{d}\tau \, L[c, \overline{c}; \varphi, \chi]) = \int [\mathrm{d}\varphi][\mathrm{d}\chi] Z[\varphi, \chi]$$

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$$Z[\varphi,\chi] = \exp\left(-\int_0^\beta \mathrm{d}\tau \sum_{\langle i,j\rangle}\left[\tfrac{1}{J}|\chi_{i,j}|^2 + \ln\det\mathscr{G}_{i,j}(\tau)\right]\right)$$

Saddle-point $\to$ and beyond...

Ground state spin liquid states — Technical details

Partition function and free energy

$$Z = \int D[c,\bar{c}] e^{-S[c,\bar{c}]}$$

$$S[c,\bar{c}] = \int_0^\beta \mathrm{d}\tau \Big[\sum_i \bar{c}_{i,\alpha}(\partial_\tau + \varphi_i) c_{i,\alpha} - J \sum_{\langle i,j \rangle} \bar{c}_{i,\alpha} c_{j,\alpha} \bar{c}_{j,\beta} c_{i,\beta} + \sum_i \varphi_i (\bar{c}_{i,\alpha} c_{i,\alpha} - 1)$$

$$F = -k_B T \ln Z$$

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Partition function after a Hubbard-Stratonovich transformation

$$Z = \int D[c,\bar{c},\chi,\chi^*] e^{-S_{\mathrm{HS}}[c,\bar{c},\chi,\chi^*]}$$

$$S_{\mathrm{HS}}[c,\bar{c}] = \int_0^\beta \mathrm{d}\tau \Big[\sum_i \bar{c}_{i,\alpha}(\partial_\tau + \varphi_i) c_{i,\alpha} - \sum_{\langle i,j \rangle} \left(\chi_{i,j} \bar{c}_{j,\alpha} c_{i,\alpha} + \chi^*_{i,j} \bar{c}_{i,\alpha} c_{j,\alpha} - \frac{1}{J} |\chi_{i,j}|^2 \right) \Big]$$

Ground state spin liquid states — Technical details

Integrating out the fermion fields:

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finite temperature Green's function

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finite temperature Green's function

Saddle-point approximation:

$$\chi_{i,j}(\hat{q}) = \beta V \bar{\chi}_{i,j} \delta_{\hat{q},0} + \delta\chi_{i,j}(\hat{q}),$$
$$\varphi_i(\hat{q}) = \beta V \bar{\varphi}_i \delta_{\hat{q},0} + \delta\varphi_i(\hat{q}).$$

$$\left. \frac{\delta S_{\text{eff}}[\{\delta\psi\}]}{\delta\psi} \right|_{\{\delta\psi\}=0} = 0$$

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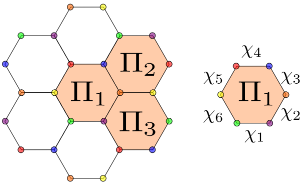
$$\left. \frac{\delta S_{\text{eff}}[\{\delta\psi\}]}{\delta\psi} \right|_{\{\delta\psi\}=0} = 0$$

$$\operatorname{tr}\log(\beta \mathscr{G}^{-1}) = \operatorname{tr}\log\left[\beta(\mathscr{G}_{(0)}^{-1} - \Sigma)\right] = \operatorname{tr}\log\left(\beta \mathscr{G}_{(0)}^{-1}\right) + \sum_{n=1}^{\infty} \frac{\operatorname{tr}(\mathscr{G}_{(0)}\Sigma)^n}{n}.$$

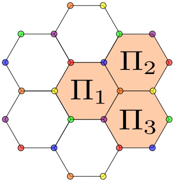
Ground state spin liquid states

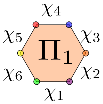


$$\chi_{i,j} = J\,\mathrm{tr}\left(\mathscr{G}_0 \frac{\partial \Sigma}{\partial \chi^*_{i,j}}\right)$$

$$\Pi_1 = \chi_1\chi_2\chi_3\chi_4\chi_5\chi_6 = |\Pi_1| e^{i\phi_1}$$

Ground state spin liquid states





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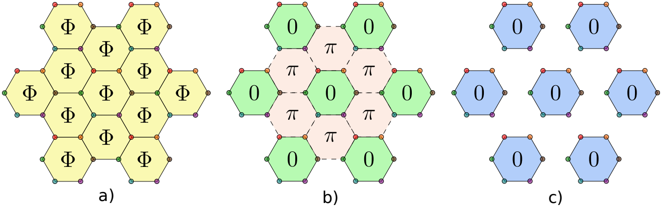
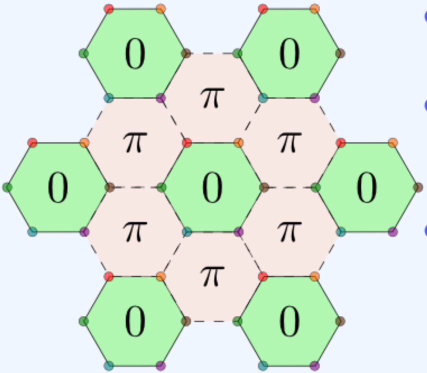
	E
a) Chiral spin liquid state	-6.148
b) Straggered flux state	-6.062
c) Valence bond crystal	-6

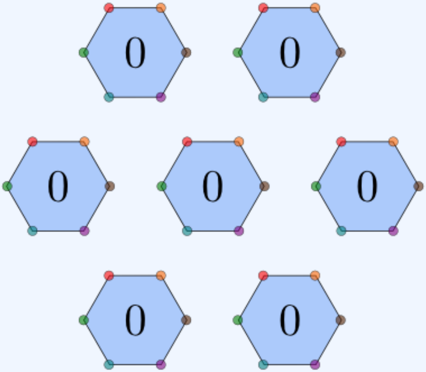


Staggered flux state



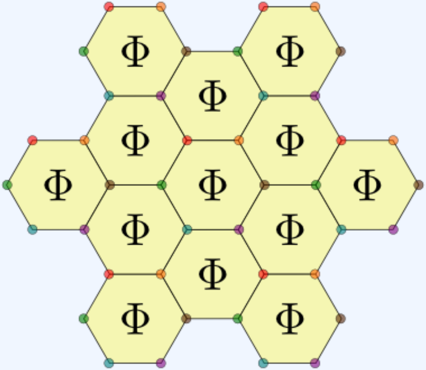
- has a triple degeneracy,
- is the honeycomb analog of the pi-flux phase
- due to the frustrated nature of the dual lattice alternating fluxes are unfavorable here.

Box state



- also has a triple degeneracy,
- has zero fluxes for every plaquette,
- is composed of disjoint plaquettes,
- is the honeycomb analog of the box phase

Chiral spin liquid state

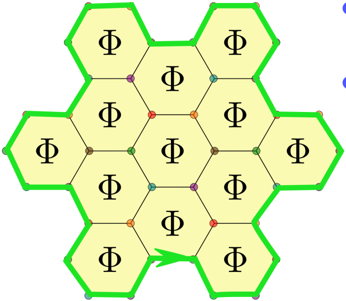


- uniform, lattice and SU(6) rotational symmetric,
- has a mean-field generated flux:

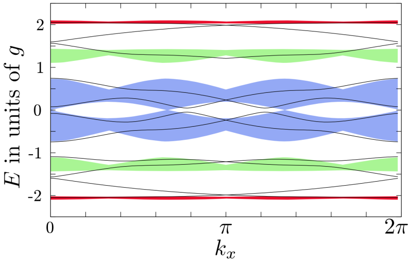
$$\Phi = \frac{2\pi}{3},$$

- violates time reversal symmetry.

Chiral spin liquid state



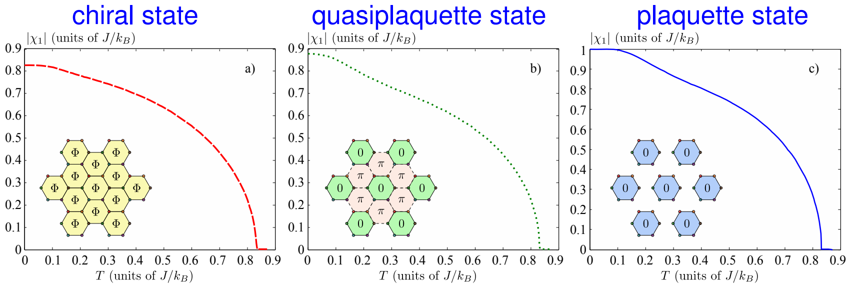
- chiral edge states appear,
- there is a nonzero transverse conductivity: $C = 6$,
- quasiparticle statistics is fractionalized, each spinon carries a $\Phi_0 = \pi/3$ elementary flux.



Chiral spin liquid state

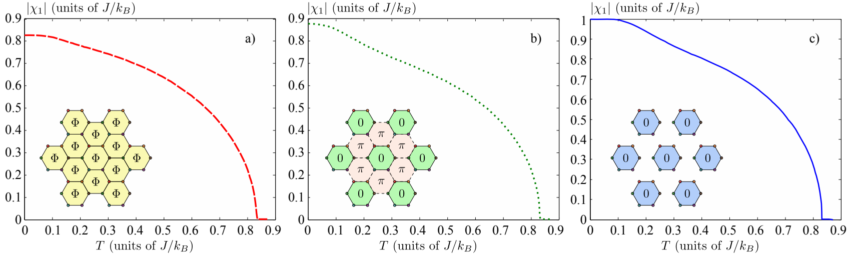
- The low energy fluctuations are phase fluctuations of the mean field, $\chi_{i,j} = \chi_{i,j}^{\rm mf}\, e^{ia_{i,j}}$, and the lowest energy spinon excitations.
- $a_{i,j}$ is a gauge field, with the transformation property:
$$a_{i,j} \to a_{i,j} + \theta_i - \theta_j .$$
- The effective theory is then a U(1) Chern-Simons theory coupled to 6 spinon fields
$$\mathcal{L} = \frac{1}{8\pi q^2}(\mathbf{e}^2 - v b^2) - \frac{C}{4\pi}\epsilon^{\mu\nu\lambda} a_\mu \partial_\nu a_\lambda + \sum_{l=1}^{6}\left[-i c_{l,\alpha}^\dagger (\partial_t - i a_0) c_{l,\alpha} + \frac{1}{2m_s} c_{l,\alpha}^\dagger (\partial_i + i a_i)^2 c_{l,\alpha} \right].$$
- Detection through the magnetic structure factor:
$$S^{zz}(i,j;t) = \langle S_i^z(t) S_j^z(0) \rangle$$

Finite temperature behavior



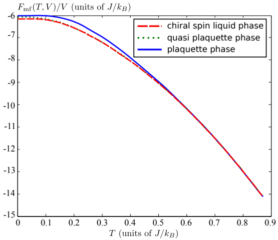
All the spin liquid phases "melt" around the same critical temperature.

chiral state quasiplaquette state plaquette state



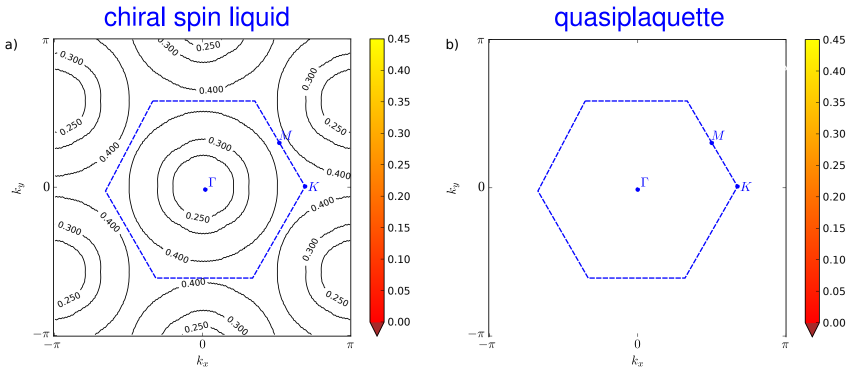
All the spin liquid phases "melt" around the same critical temperature.

- No new state occurs as lowest free energy SP solution.
- The SP free energies approach each other without crossing.
- The chiral state remains the lowest free energy solution even at $T > 0$.



Stability analysis

$$\text{Stability matrix}: \quad C_{\mu,\nu} \sim \frac{\partial^2 (\mathscr{G}_0 \Sigma)^2}{\partial \chi_\mu \partial \chi_\nu}$$



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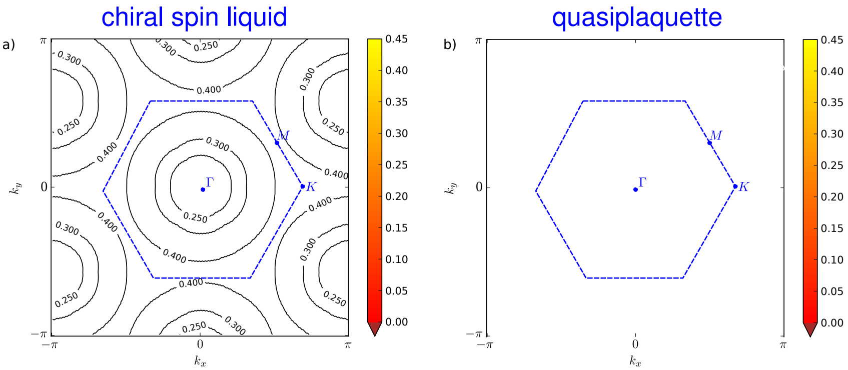
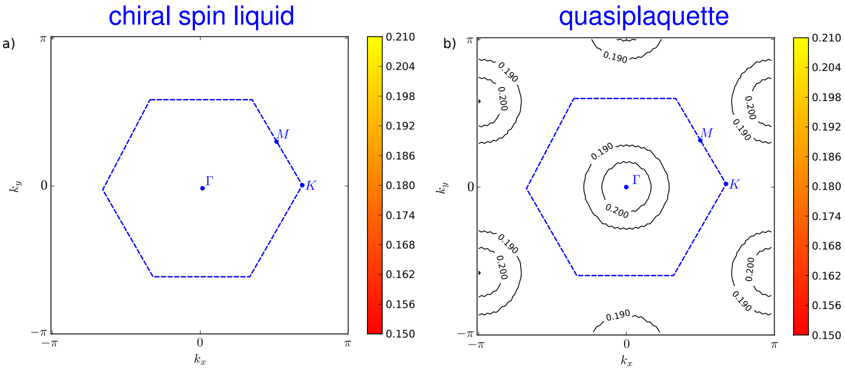


The quasiplaquette state collapses into the lower free energy chiral spin liquid state.

Experimentally measurable quantities

Structure factor: $S(\mathbf{r},\tau;\mathbf{r}',0) = \langle S_z(\mathbf{r},\tau) S_z(\mathbf{r}',0) \rangle$



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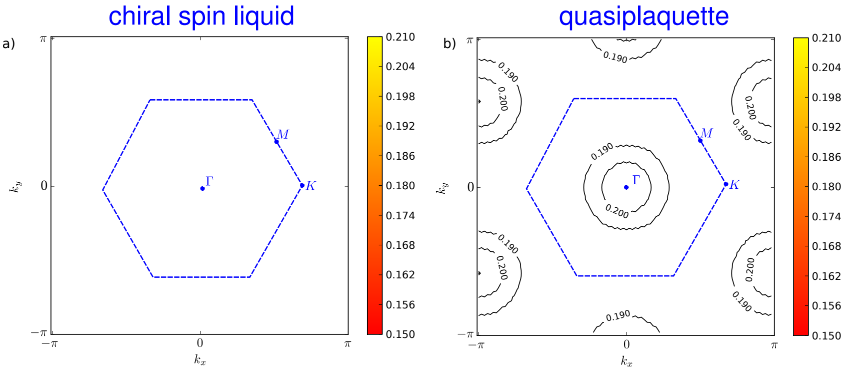
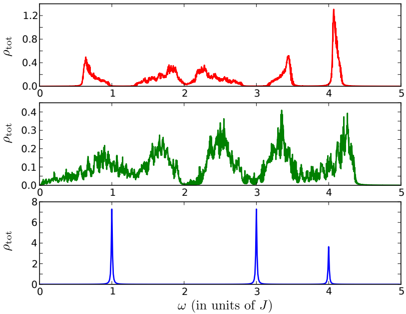


Unambiguous features $\longrightarrow$ Suitable tool to distinguish the phases.

Experimental measurable quantities

Spectral density: $\rho_{\rm tot}(\omega) = \sum_{\mathbf{k}} {\rm Im} S(\mathbf{k}, \omega)$



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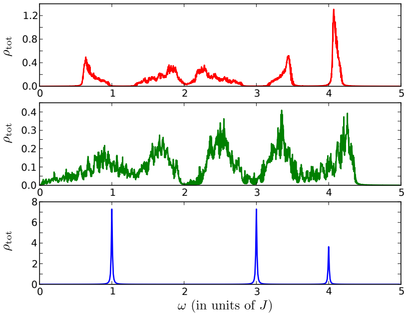

Unambiguous features $\longrightarrow$ Suitable tool to distinguish the phases.

Thank you for your attention