Title

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Pseudospin Magnetism in Graphene

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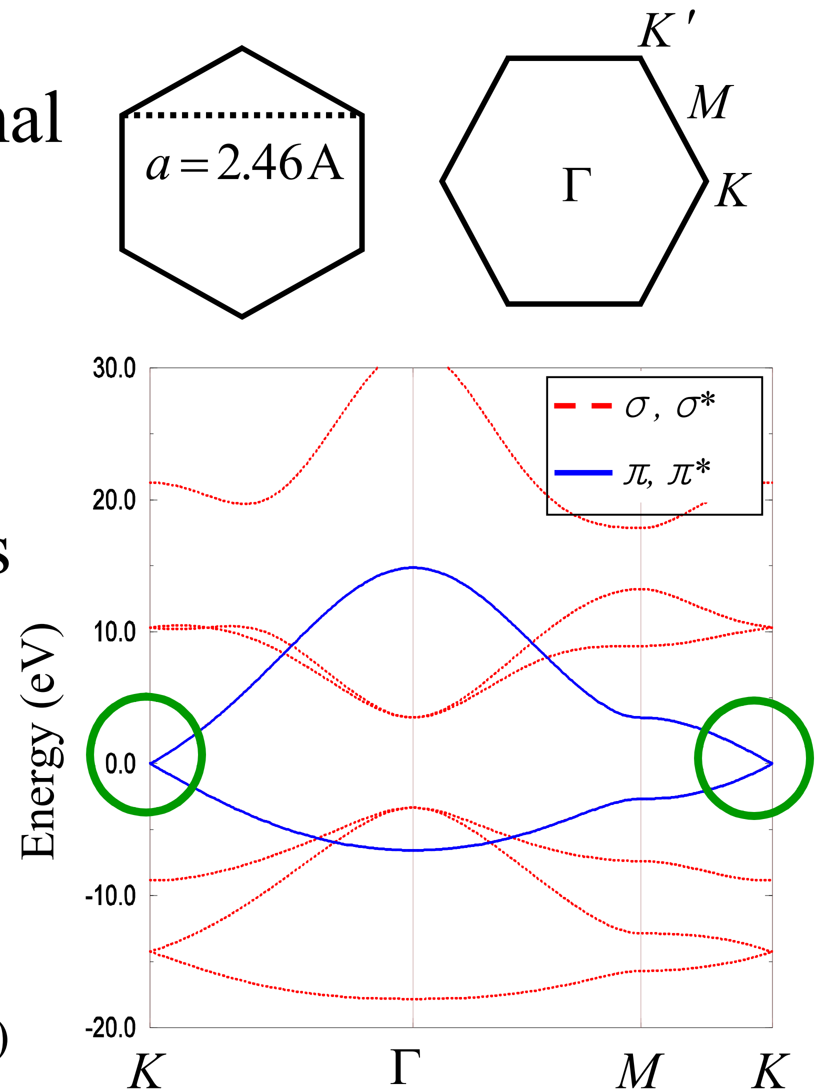
We predict that neutral graphene bilayers are pseudospin magnets in which the charge density contribution from each valley and spin spontaneously shifts to one of the two layers. The broken symmetry state has a momentum-space vortex, which is responsible for unusual competition between interaction and kinetic energies leading to symmetry breaking in the vortex core. We discuss the possibility of realizing a pseudospin version of ferromagnetic metal spintronics in graphene bilayers based on hysteresis associated with this broken symmetry.

1. Introduction (1)

1) Graphene

- Graphene is a two-dimensional honeycomb lattice of carbon atoms.

- Energy bands at low energies are described by a 2D Dirac-like equation with linear dispersion near K/K'.



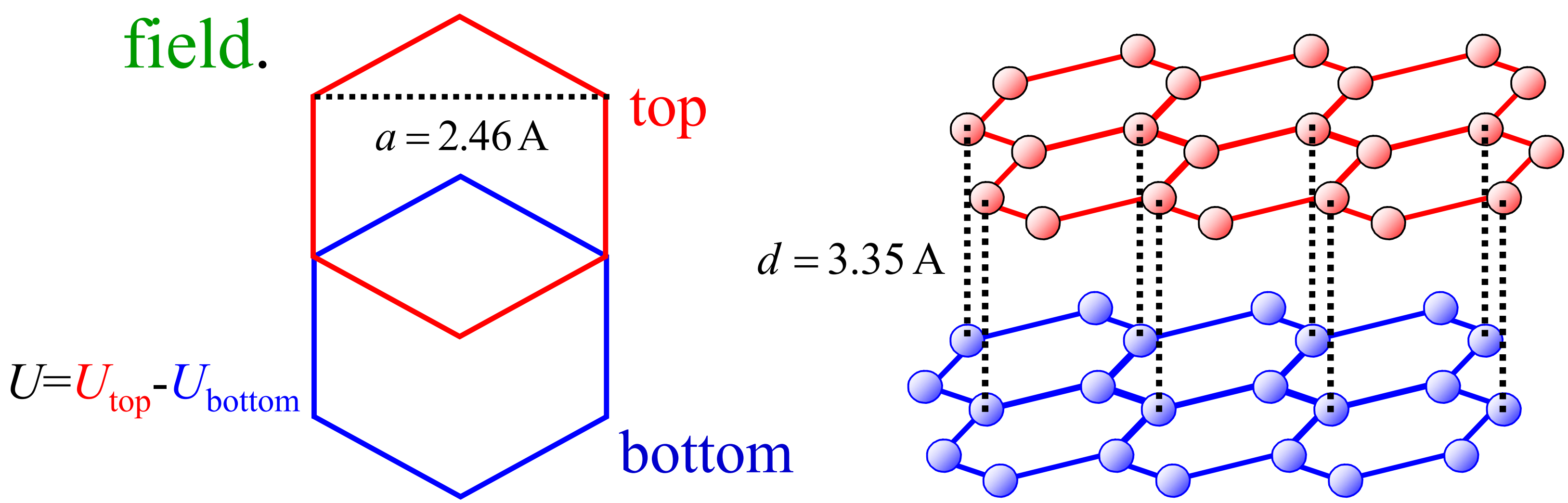
Min et al., PRB **74**, 165310 (2006)

1. Introduction (2)

2) Graphene bilayer

Min et al., PRB **75**, 155115 (2007)

- Graphene bilayer is composed of a pair of coupled graphene monolayers.
- A band gap opens if on-site energy difference U between two layers is non-zero.
- U can be controlled by doping or an external electric field.



2. The Model (1)

1) Band Hamiltonian

$v_F =$ in-plane velocity
$\pi = p_x + ip_y$
$m = \gamma_1 / 2v_F^2$

- Low energy band Hamiltonian matrix

$$H_B^{mono} = v_F \begin{pmatrix} 0 & \pi^+ \\ \pi & 0 \end{pmatrix}$$

$$H_B^{bi} = -\frac{1}{2m} \begin{pmatrix} 0 & (\pi^+)^2 \\ (\pi)^2 & 0 \end{pmatrix}$$

- Chiral two-dimensional electron system

$$H_B = -\varepsilon_0(k_c) \left(\frac{k}{k_c} \right)^J \left[\cos(J\phi_{\mathbf{k}})\tau_x + \sin(J\phi_{\mathbf{k}})\tau_y \right]$$

$J =$ chirality
$\boldsymbol{\tau} =$ Pauli matrices
$k_c =$ cutoff
$\phi_{\mathbf{k}} = \tan^{-1}(k_y / k_x)$

J=1 : monolayer $\quad \varepsilon_0(k_c) = \hbar v_F k_c$

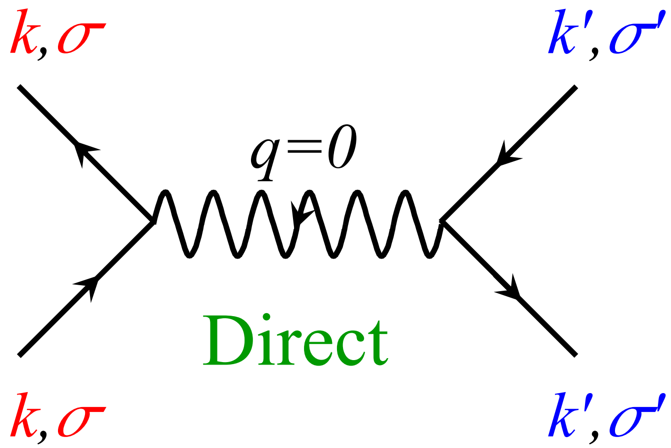
J=2 : bilayer $\quad \varepsilon_0(k_c) = \hbar^2 k_c^2 / 2m$

2. The Model (2)

2) External gate potential

$$H_g = -\frac{V_g}{2}\tau_z$$

3) Interactions



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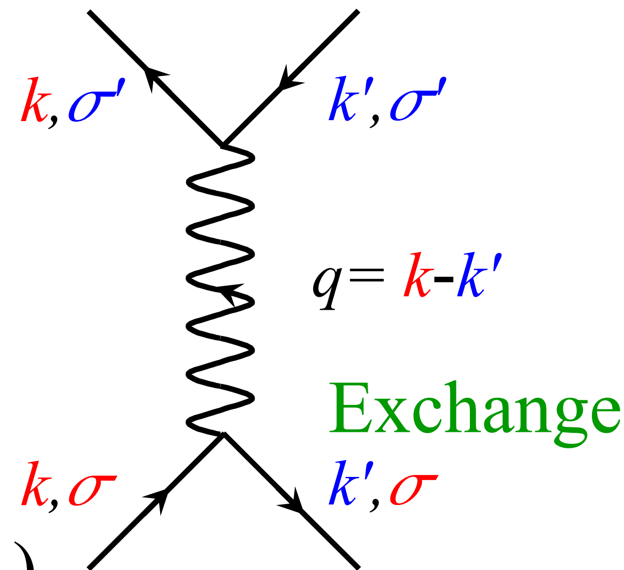


4) Coupling constant $\alpha = e^2 k_c / \varepsilon_r \varepsilon_0 (k_c)$

J=1 : monolayer $\quad \alpha = e^2 / \varepsilon_r \hbar v_F$

J=2 : bilayer $\quad \alpha = 2e^2 / \varepsilon_r \hbar v_c$

J = chirality
$\boldsymbol{\tau}$ = Pauli matrices
k_c = cutoff
ε_r = dielectric constant

3. Mean-field Theory (1)

1) Hartree-Fock mean-field theory

$$\boxed{H_{MF} = -\left(B_0(\mathbf{k}) + \mathbf{B}(\mathbf{k}) \cdot \boldsymbol{\tau}\right)}$$

$\boldsymbol{\tau}$ = Pauli matrices representing pseudospin degrees of freedom

$\mathbf{B}(\mathbf{k})$: effective magnetic field

2) Self-consistent solution

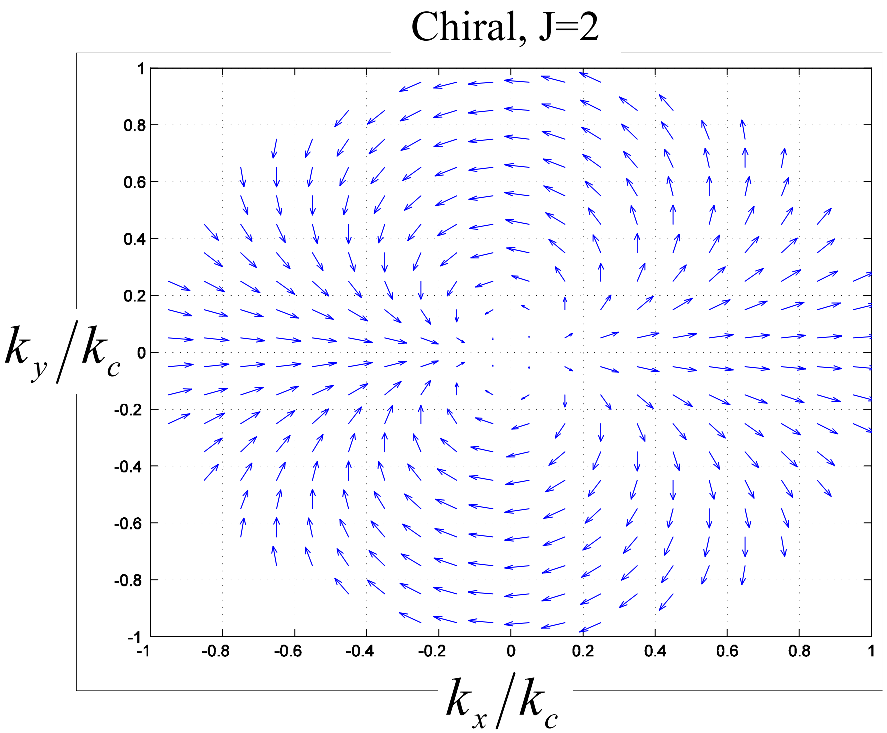
- In-plane effective magnetic field is parallel to the band Hamiltonian effective field.

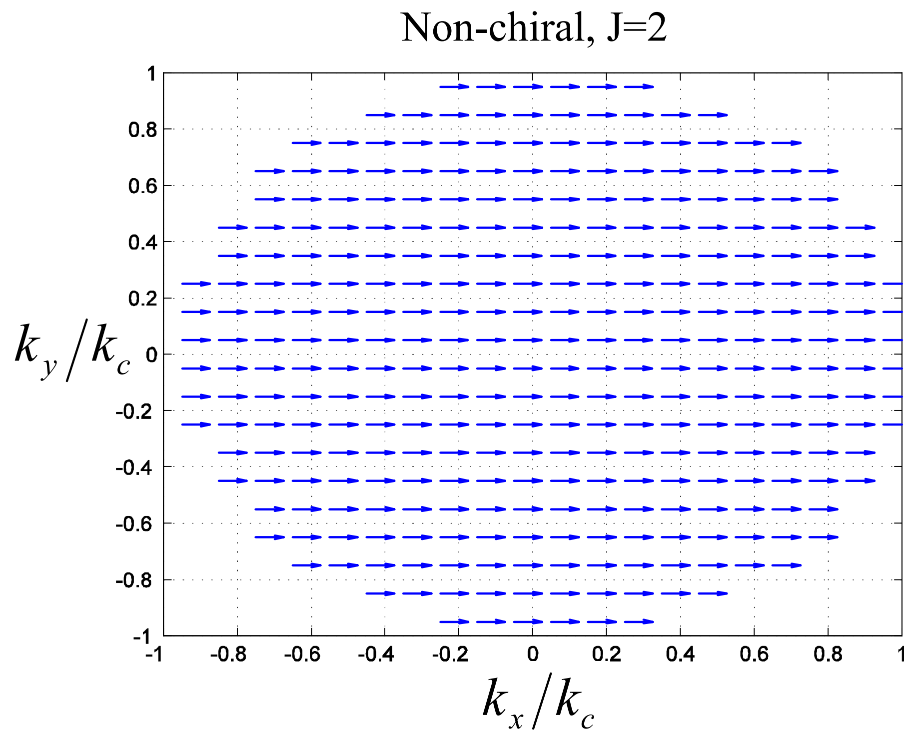
$$\boxed{\mathbf{B}(\mathbf{k}) = (B_\perp(k)\cos(J\phi_{\mathbf{k}}), B_\perp(k)\sin(J\phi_{\mathbf{k}}), B_z(k))}$$

- Out-of-plane pseudospin orientation corresponds to the charge transfer between layers.

3. Mean-field Theory (2)

3) In-plane pseudospin orientation



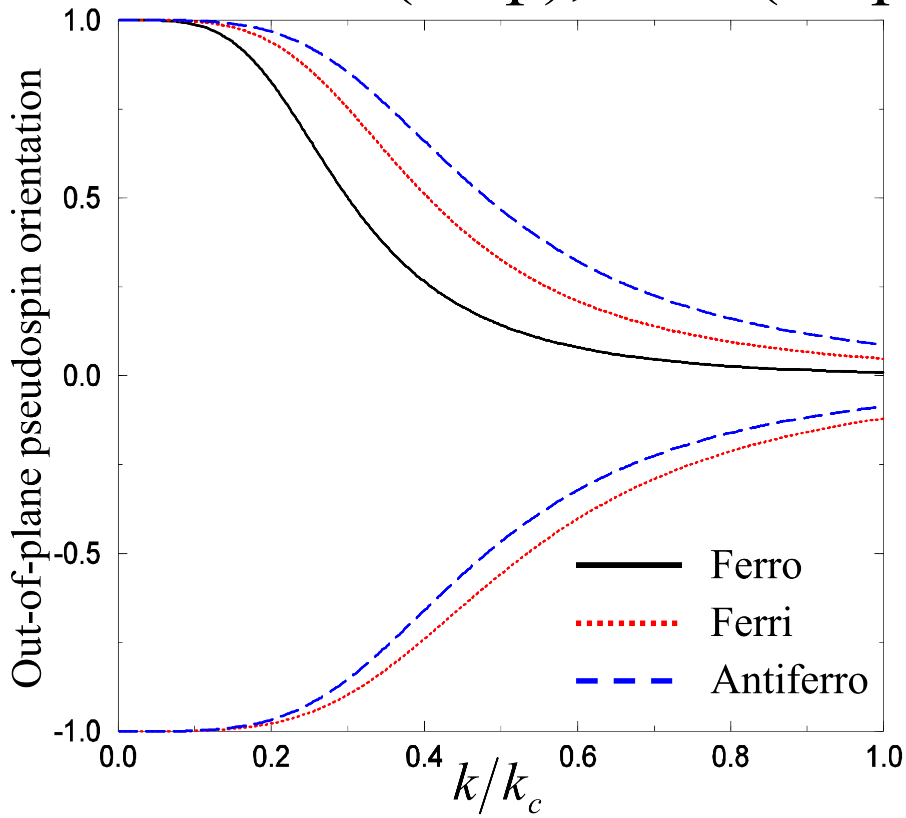


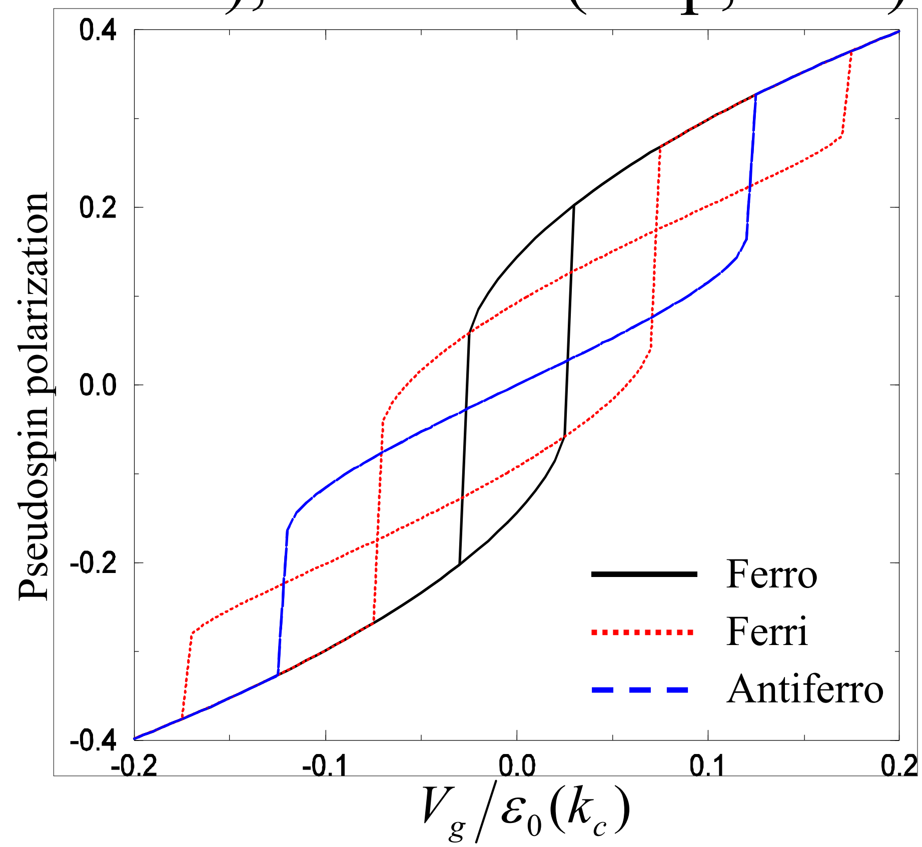
- Due to the frustration of in-plane exchange by the chiral character, pseudospin spontaneously rotates to out-of-plane in the chiral model.

3. Mean-field Theory (3)

4) Out-of-plane pseudospin orientation

- Spin (↑/↓) and valley (K/K') degeneracy
- Ferro (4 up), ferri (3 up, 1 down), antiferro (2 up, 2 dn)





3. Phase Diagram (1)

1) Stability of the normal state

- Stability test for a small $n_z(k) \approx 0$ at $V_g = 0$

$$\boxed{\frac{n_z(k)}{n_\perp(k)} = \frac{B_z(k)}{B_\perp(k)}}$$

$\mathbf{n}$ = orientation of $\mathbf{B}$

$$\Rightarrow \boxed{n_z(k) = \int_0^1 dk' \, M(k,k') n_z(k')}$$

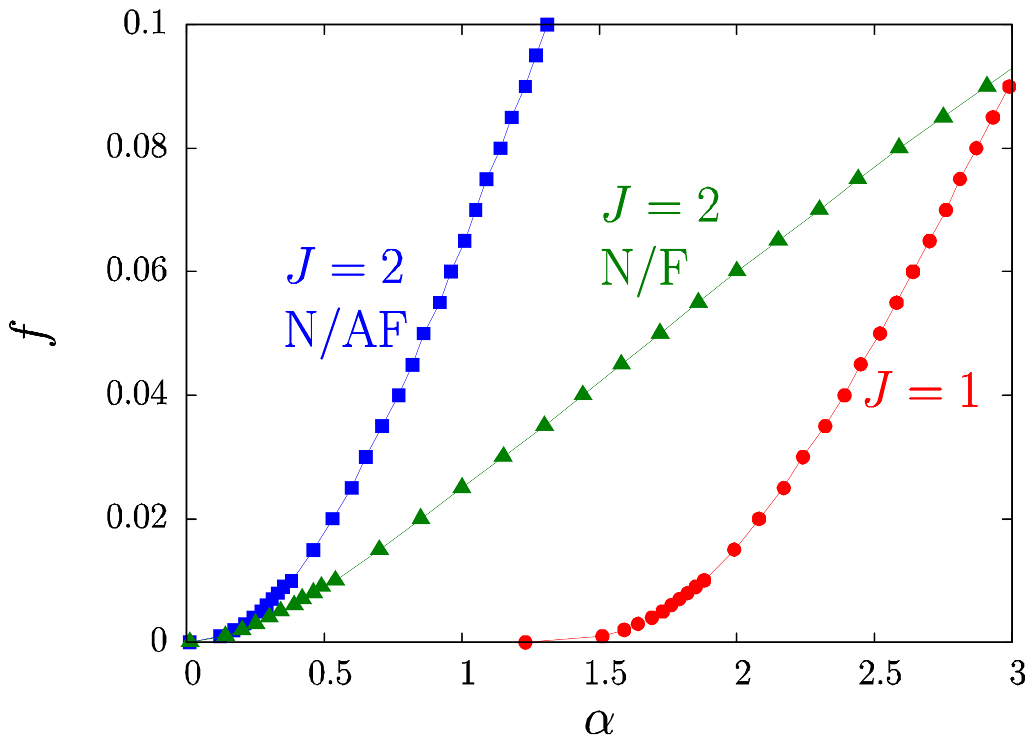
constructed from the normal state solution

in units of k_c for k

- If the largest eigenvalue of the linear integral operator M is larger than 1, the normal state becomes unstable.

3. Phase Diagram (2)

2) Phase diagram from the stability test



J : chirality

α : coupling constant

f : doping

N : normal state

F : ferro state

AF: antiferro state

- Magnetic order is stable for larger coupling constant, for larger J, for smaller doping.

4. Discussion (1)

1) Chirality sum rule

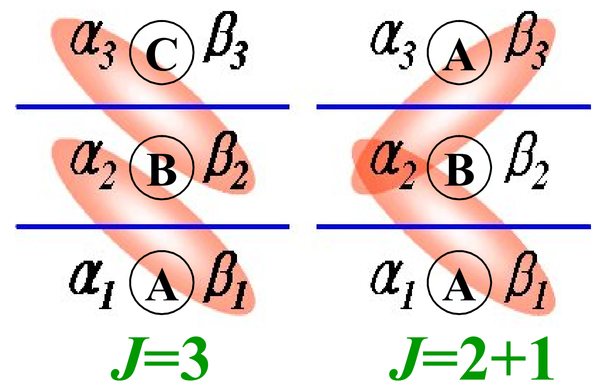
Min et al. PRB **77**, 155416 (2008)

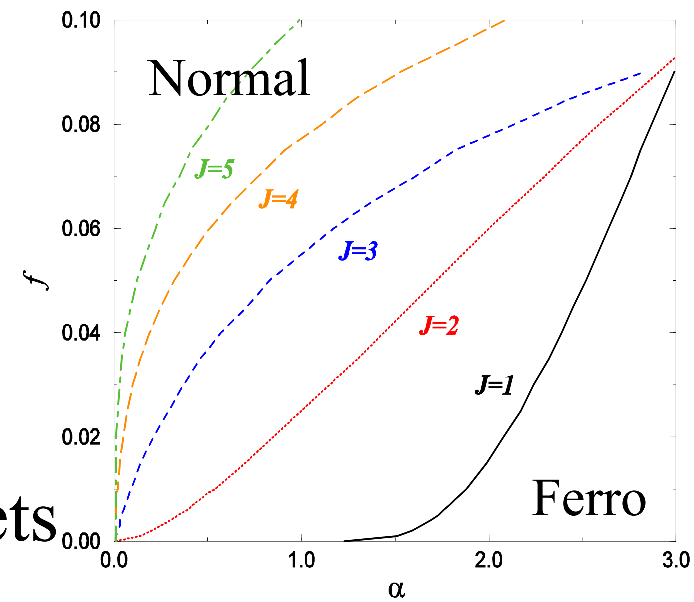
- Arbitrarily stacked graphene multilayers are described by a set of chiral systems.

$$H_N^{eff} = H_{J_1} \otimes H_{J_2} \otimes \cdots \otimes H_{J_{N_D}}$$

$$\sum_{i=1}^{N_D} J_i = N$$

$N_D =$ Number of doublets





2) Pseudospin magnets

- ABC stacked N-layer graphene is described by N-chiral system.

$\Rightarrow$ Candidate for pseudospin magnets

4. Discussion (2)

3) Pseudospintronics

- Similar to behavior for an easy-axis ferromagnet in an external magnetic field along the hard axis.
- The pseudospin ferromagnet can be switched between metastable states with gate voltages much smaller than thermal energies, similar to standard CMOS but uses much less power .

$\Rightarrow$ Can exhibit a pseudospin version of giant magnetoresistance and spin-transfer torque.

4) Future work

- Influence of electronic correlation