Optical properties of Wigner crystal and helical state in bilayer graphene

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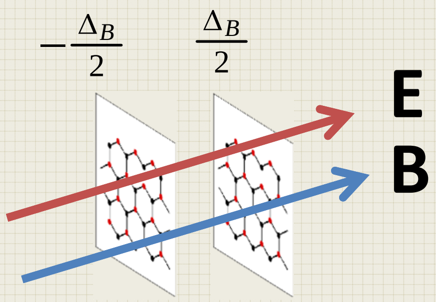
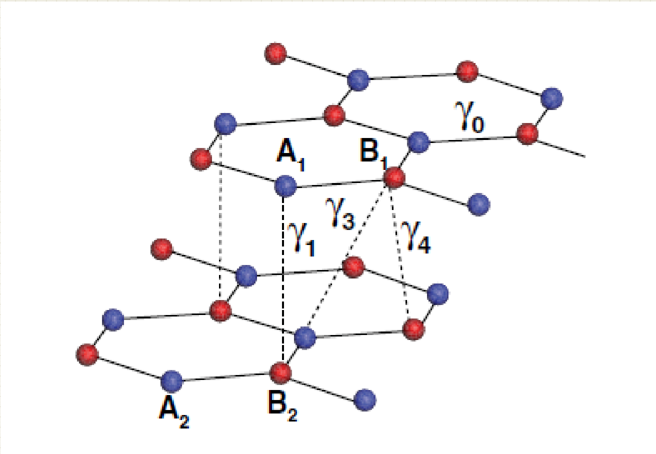
Outline

Non-collinear orbital pseudomagnetic states can exist in Landau level N=0 of a **biased** graphene bilayer in a magnetic fied. They can be detected by optical experiments.



- Origin of the orbital pseudospin in biased bilayer graphene.
- Phase diagram for non-collinear pseudomagnetic states.
- Optical properties: absorption and Kerr effect.

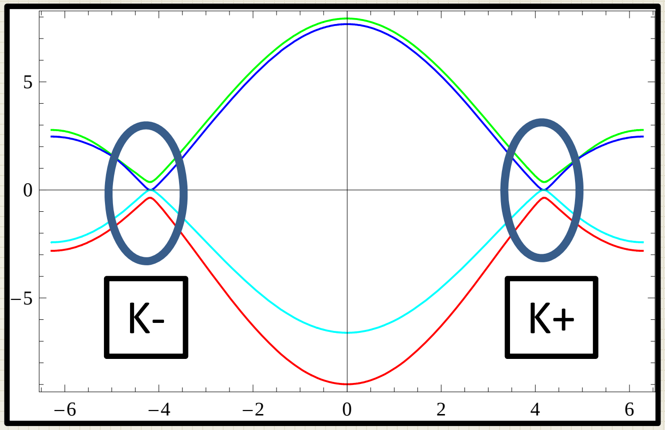
Bernal-stacked graphene bilayer



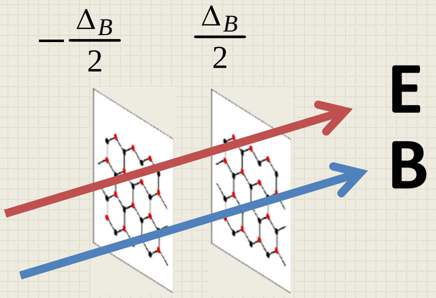
A1-B2: high-energy sites
A2-B1: low-energy sites

$\gamma_0 = 3.12$ eV n.n intralayer hopping

$\gamma_1 = 0.38$ eV n.n interlayer hopping

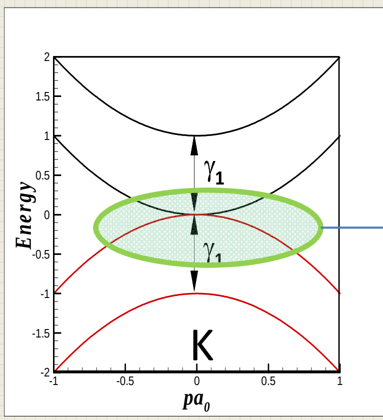


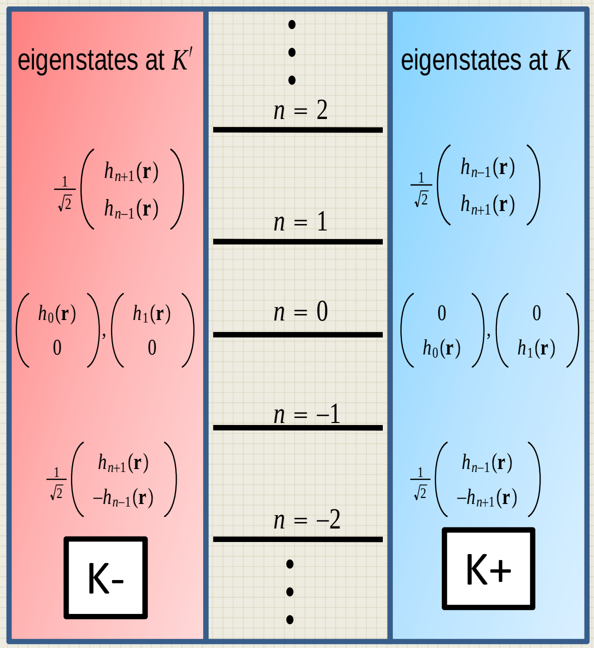
Band structure and the two valleys



BLG in a magnetic field: Landau levels

NO BIAS





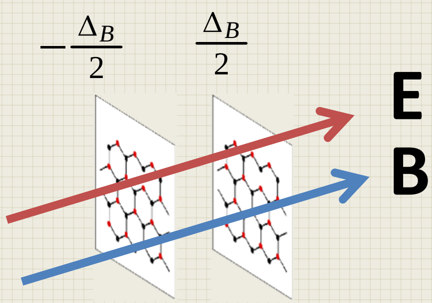
$$\begin{pmatrix} A_2 \\ B_1 \end{pmatrix} \begin{matrix} \textit{Bottom layer} \\ \textit{Top layer} \end{matrix}$$

<u>Two-component model amplitudes on low-energy sites</u>

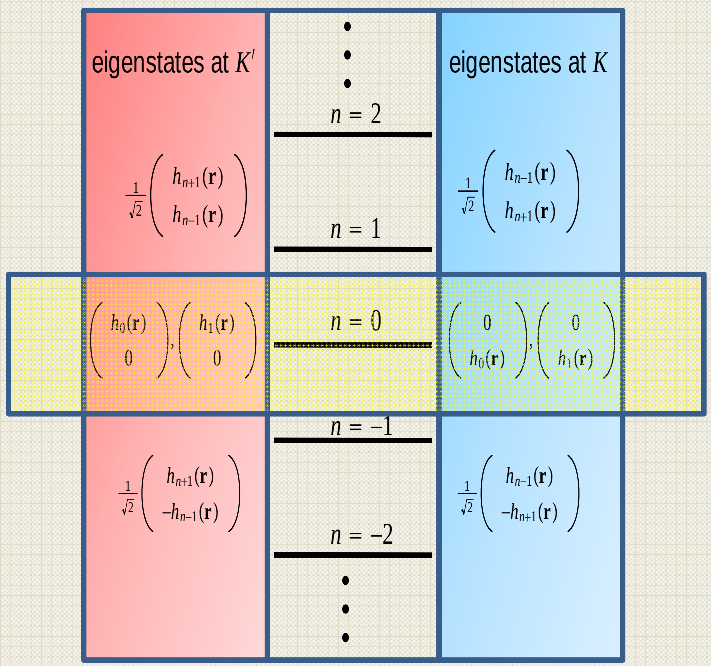
$$E_n = \pm\hbar\omega_c^* \sqrt{|n|(|n|+1)}$$

$$n = \ldots, -3, 2, -1, 0, 1, 2, 3, \ldots$$

N=0 Landau level degeneracy



$$h_n(\mathbf{r}) = \frac{1}{\sqrt{L_y}} e^{-iXy/\ell^2} \boxed{\varphi_n(x-X)}$$ orbital

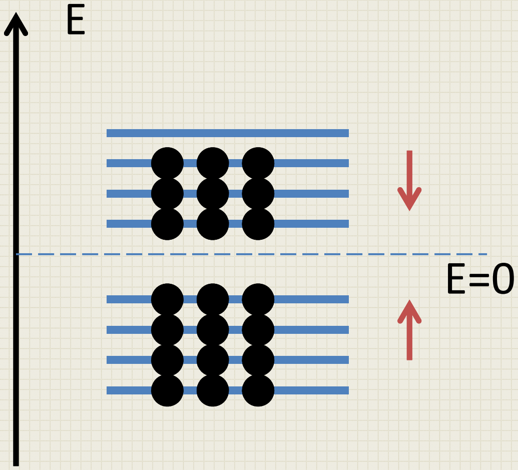


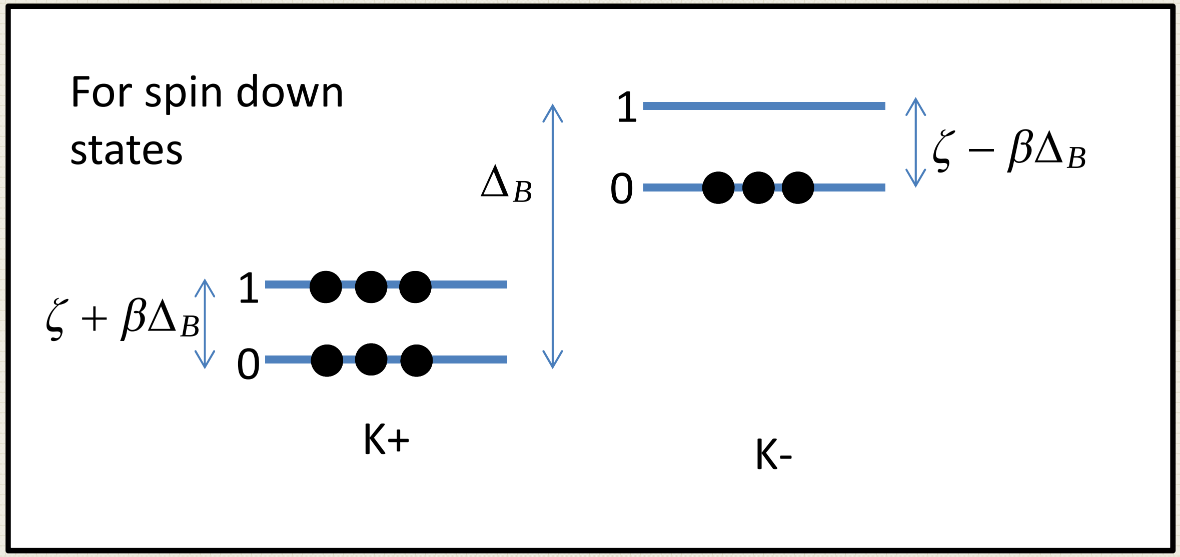
$$\begin{pmatrix} A_2 \\ B_1 \end{pmatrix} \begin{matrix} \textit{Bottom layer} \\ \textit{Top layer} \end{matrix}$$

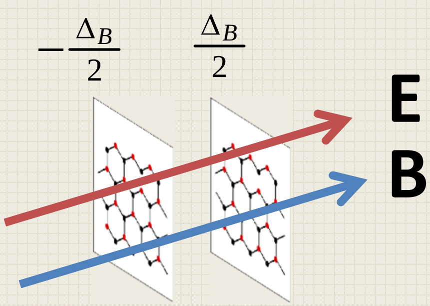
Valley and layer indices are related in N=0

Landau level N=0 has 8 sub-levels: 2(spin) X 2(valleys) X 2(orbitals)

Special case: N=0 and ν=3





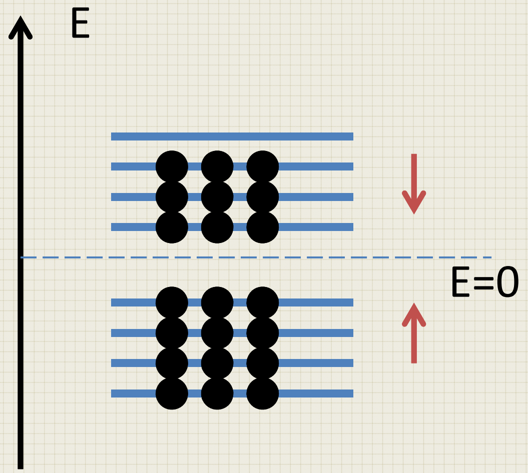


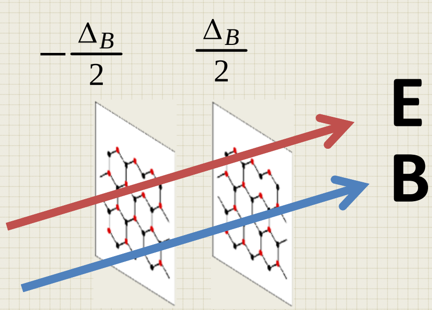
$$\zeta = \beta\left(2\frac{\gamma_1\gamma_4}{\gamma_0} + \delta_0\right),$$

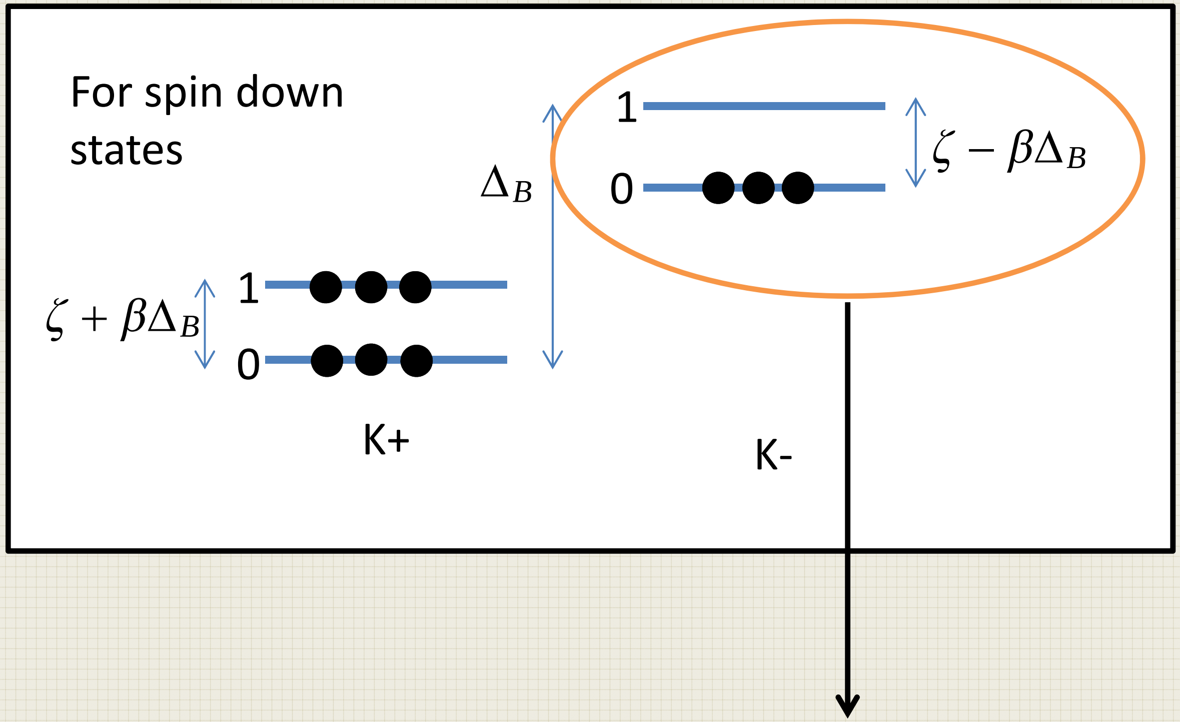
$$\beta = \frac{\hbar\omega_c^*}{\gamma_1} = 7.24\times10^{-3}B[\mathrm{T}],$$

$$\zeta = 0.39B[\mathrm{T}]\ \mathrm{meV},$$
$$\Delta_Z = 0.12B[\mathrm{T}]\ \mathrm{meV}.$$

A two-level system



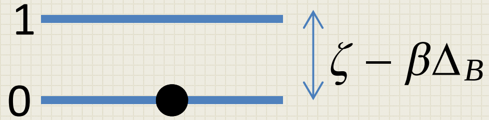


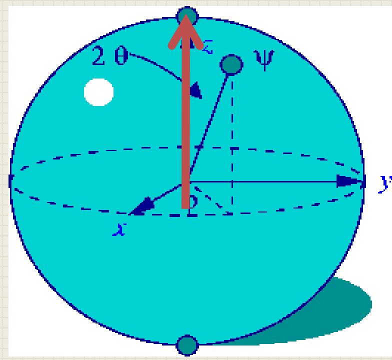


The 0-1 gap can be made negative !

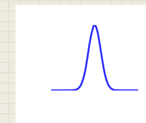
Our two-level system:
the gap is controlled by the electric field between the layers.

Orbital pseudospin

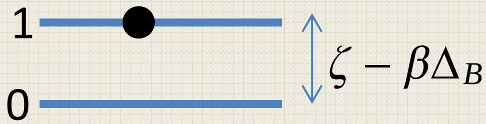


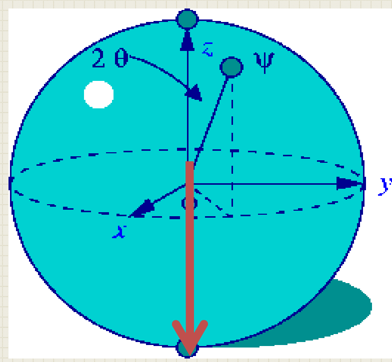


orbital n=0

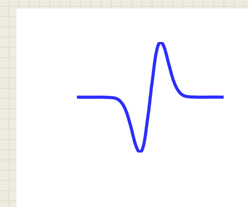


$$\begin{pmatrix} 0 \\ \varphi_0 \end{pmatrix}$$





orbital n=1



$$\begin{pmatrix} 0 \\ \varphi_1 \end{pmatrix}$$

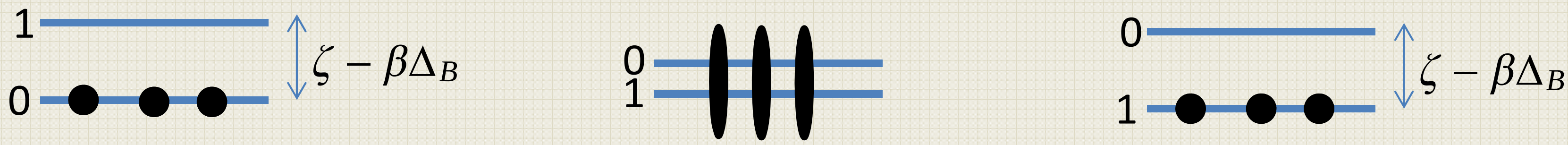
Quantum mechanics allows any linear combinations of these two states so that the orbital pseudspin can point anywhere on the Bloch sphere.

Quantum Hall ferromagnetism with orbital pseudospin

small bias $\beta\Delta_B < \zeta$

$\beta\Delta_B \gtrsim \zeta$

large bias $\beta\Delta_B >> \zeta$



$|\uparrow\uparrow\uparrow\uparrow \cdots\rangle$

$|\nearrow\nearrow\nearrow\nearrow \cdots\rangle$

$|\downarrow\downarrow\downarrow\downarrow \cdots\rangle$

Broken-symmetry state (like an XY ferromagnet)

Coulomb exchange interaction is more negative for electrons in n=0 than for electrons in n=1

General Hartree-Fock Hamiltonian

$$E_{HF} = -\frac{11}{32}\sqrt{\frac{\pi}{2}} - \frac{1}{2}\beta\Delta_B + \frac{1}{\sqrt{2}\,\ell e}\beta\left(\Delta_B - \frac{1}{2}\Delta_B^{(1)}\right)p_z(0)$$ **« Zeeman » coupling**

$$+ \frac{1}{4e^2\ell^2}\sum_{\mathbf{q}} \mathbf{p}_{\parallel}(-\mathbf{q}) \cdot [a(q)\mathbf{I} + b(q)\mathbf{\Lambda}(\mathbf{q})] \cdot \mathbf{p}_{\parallel}(\mathbf{q})$$

$$+ \frac{1}{4e^2\ell^2}\sum_{\mathbf{q}} c(q)p_z(-\mathbf{q})p_z(\mathbf{q})$$

a and c: nonlocal exchange interactions
b: dipole-dipole electrostatic interaction

$$+ \frac{i}{8e^2\ell^2}\sum_{\mathbf{q}} d(q)(\hat{\mathbf{z}} \times \hat{\mathbf{q}}) \cdot (\mathbf{p}(-\mathbf{q}) \times \mathbf{p}(\mathbf{q})).$$

$$\sim D\int d\mathbf{r}(\mathbf{p} \cdot (\nabla \times \mathbf{p}))$$

p= orbital pseudospin

Dzyaloshinski–Moriya interaction
(from Coulomb interaction, not spin-orbit)

Phase diagram for ν=3

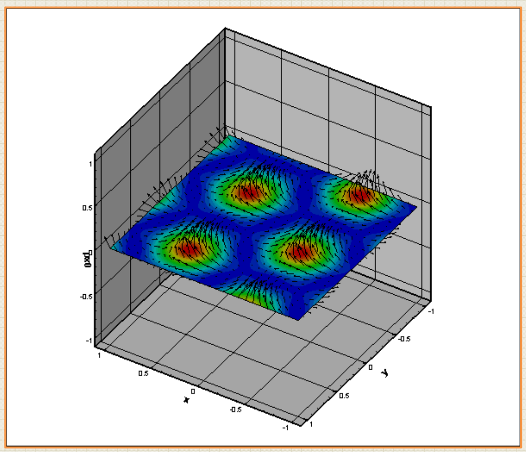
$|\uparrow\uparrow\uparrow\uparrow\cdots\rangle$ $|\nearrow\nearrow\nearrow\nearrow\cdots\rangle$ $|\searrow\searrow\searrow\searrow\cdots\rangle$ $|\downarrow\downarrow\downarrow\downarrow\cdots\rangle$

Uniform state | Uniform tilted state | Triangular Wigner crystal | Helical state | Triangular Wigner crystal | Uniform tilted state | Uniform state

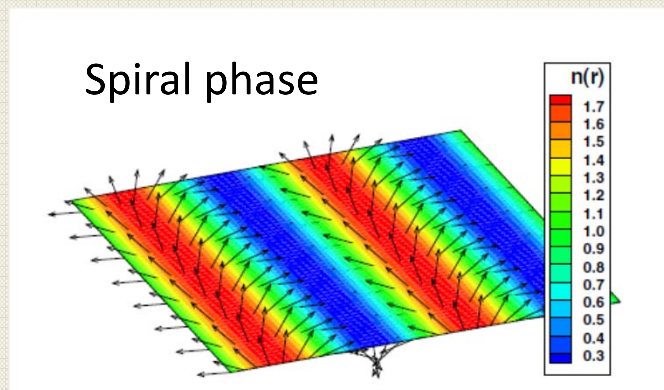
0 53 56 76 $\Delta_M = 130$ 184 204 207 Δ_B (meV)

$B = 10$ T

$\varepsilon = 5$

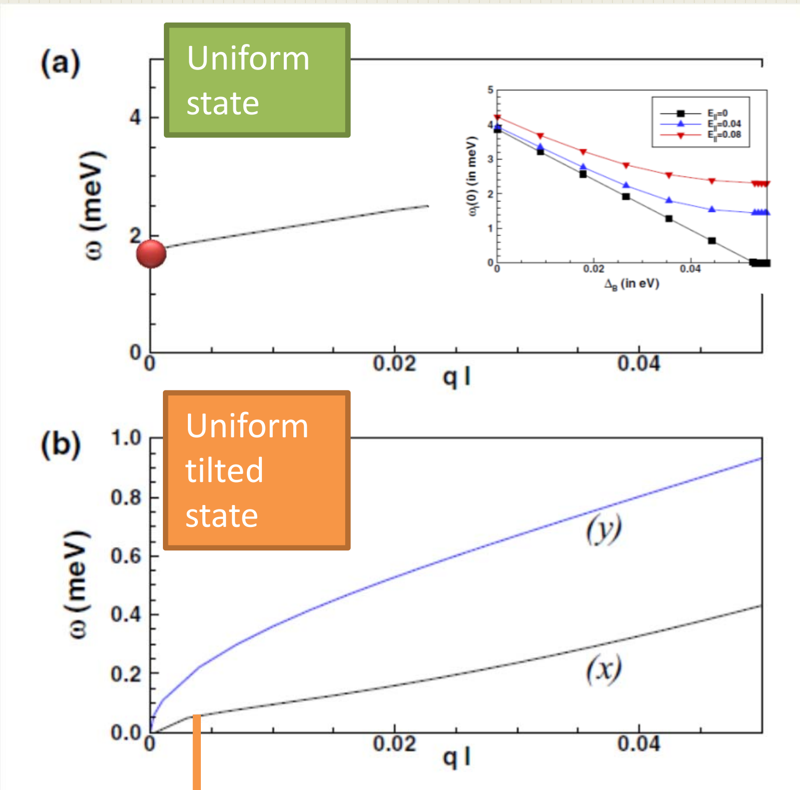


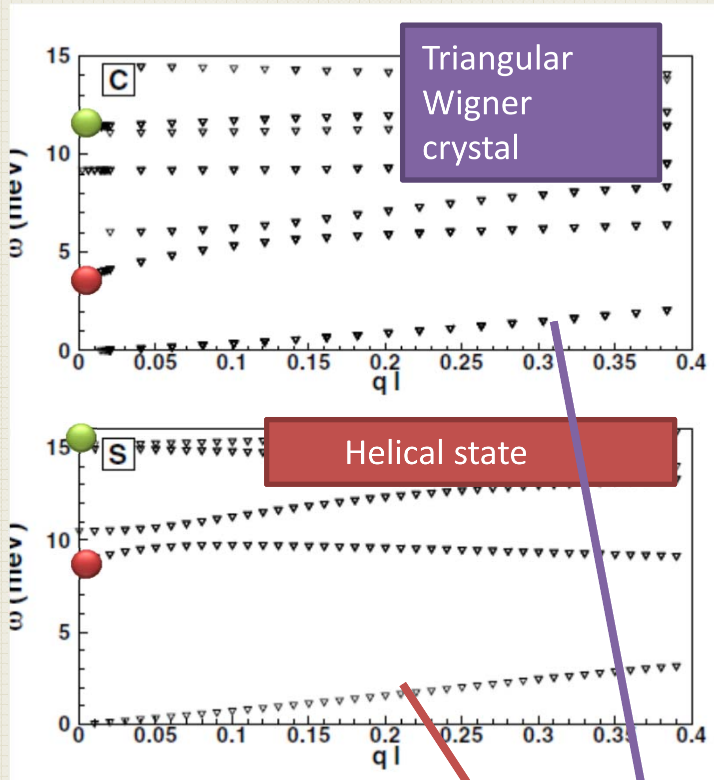
Wigner crystal
with meron-like
pseudospin texture



The electronic density
is also modulated
in space.

Magnetoexciton modes



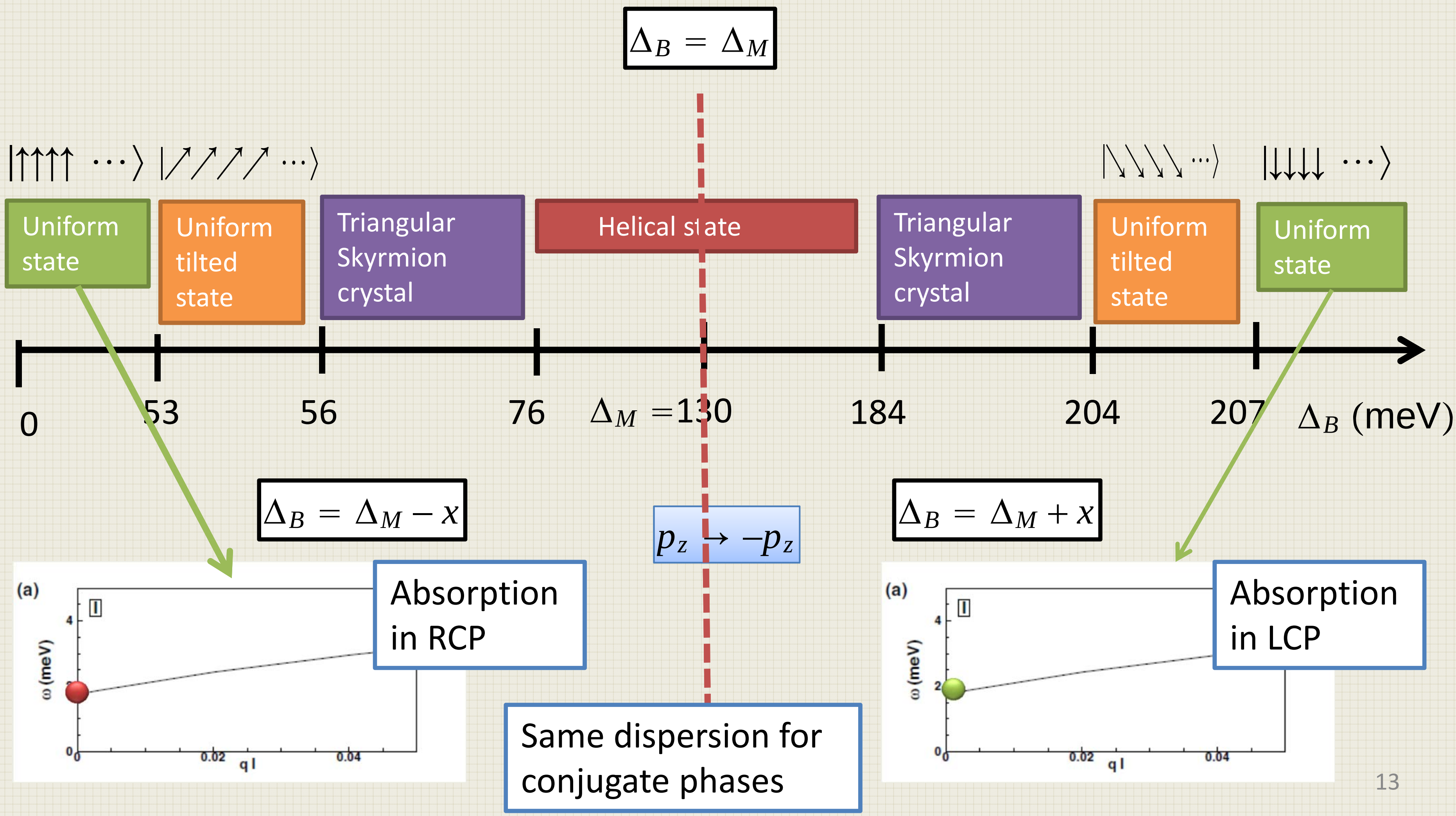


Goldstone mode with anisotropic dispersion

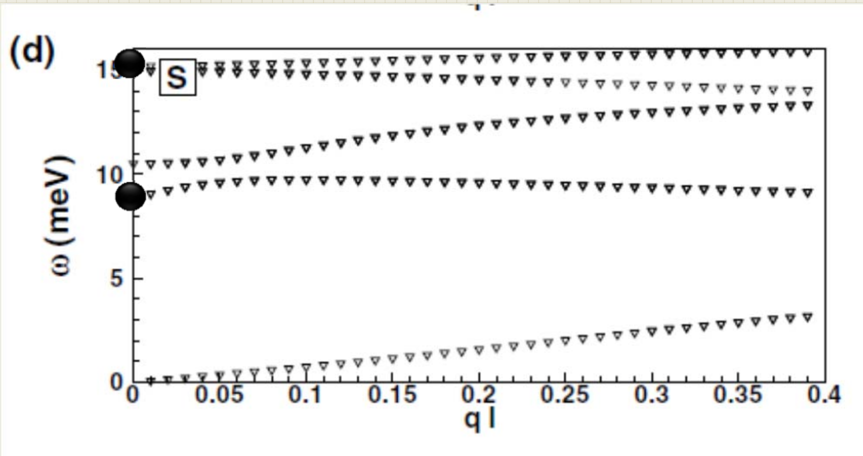
$3.85\ \text{meV} \Rightarrow 9.3\times 10^{11}\ \text{Hz}$

Gapless phonon mode in the WC and helical phases

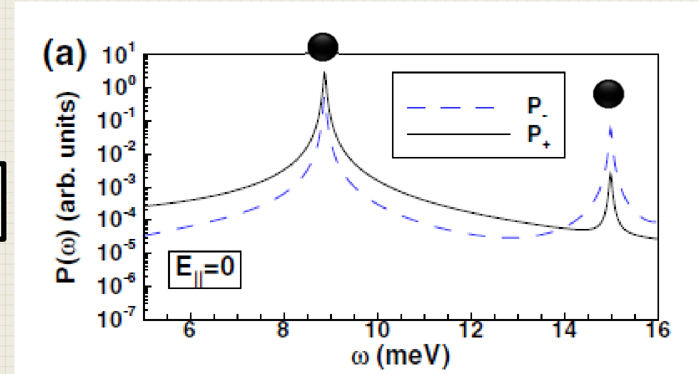
Symmetry of the phase diagram:conjugate states



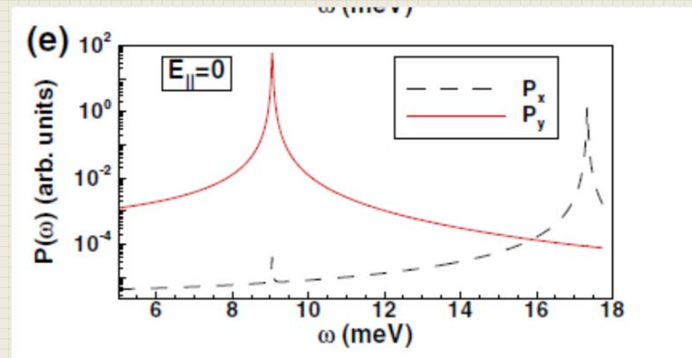
Optical absorption in helical state



$\Delta_B = \Delta_M - x$



$\Delta_B = \Delta_M$

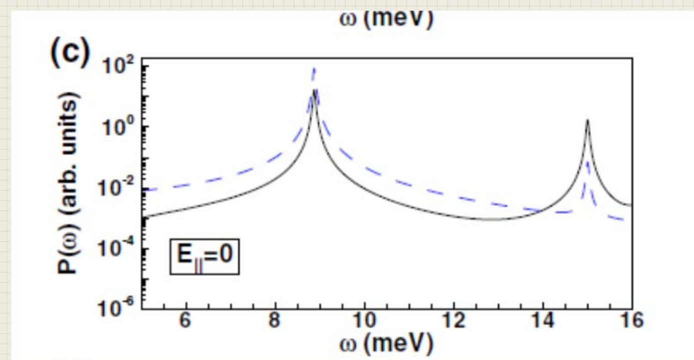


Modes are not fully circularly polarised. in helical state

linear polarisation for $\Delta_B = \Delta_M$

Symmetry RCP-LCP for conjugate phases

$\Delta_B = \Delta_M + x$



Kerr effect

Modes that are active in absorption also show a Kerr effect

Uniform state

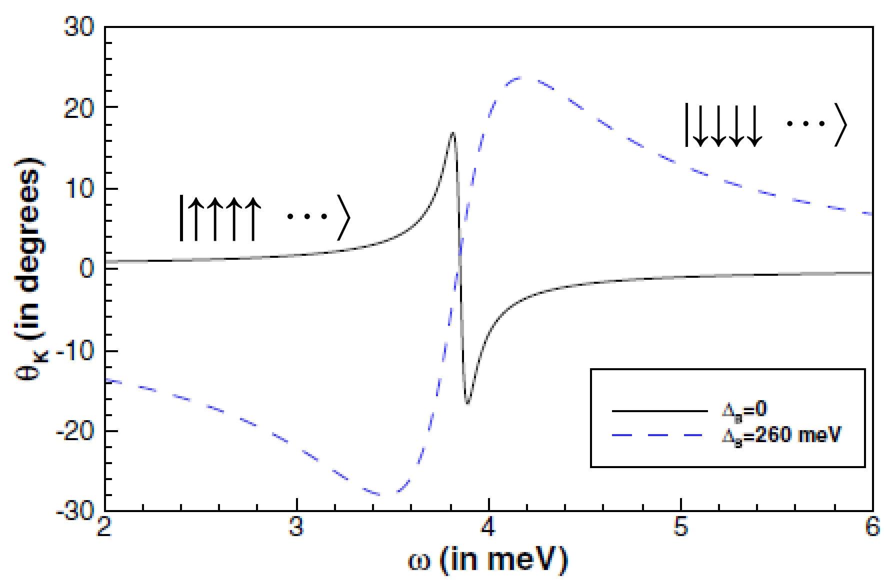


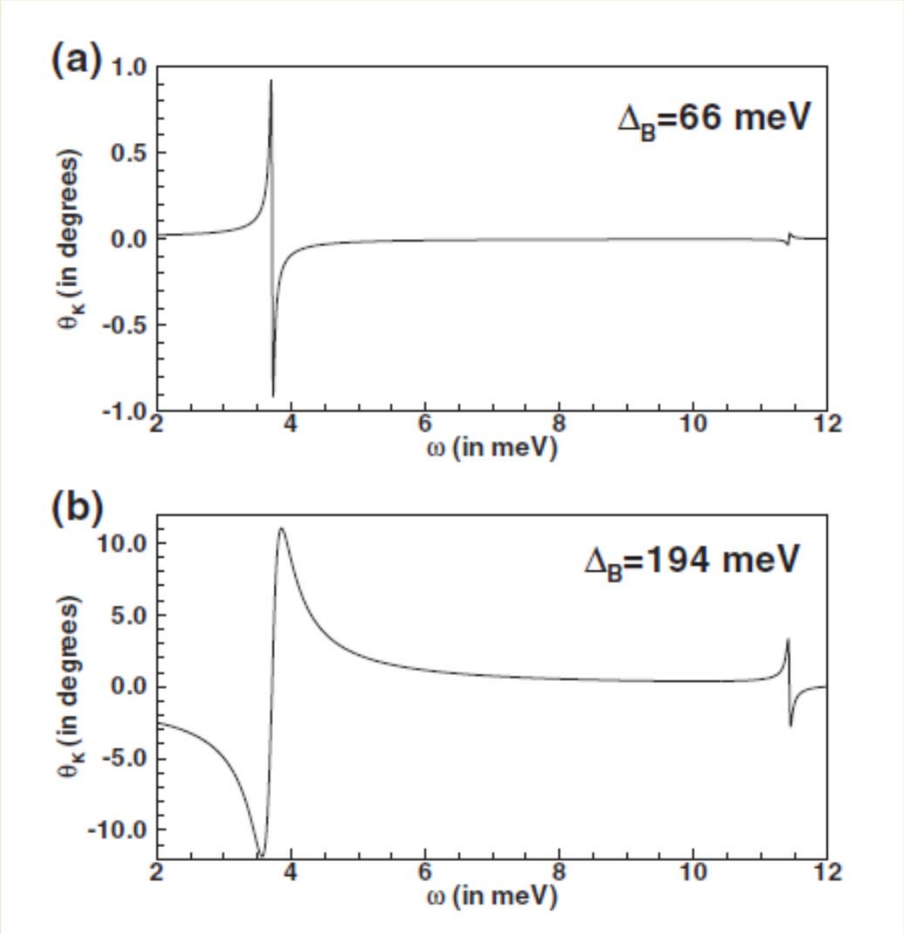
FIG. 12. (Color online) Kerr angle for conjugate biases $\Delta_B = 0$ and $\Delta_B = 260$ meV in the I and I^* phases.

Polarisation angle rotates in opposite directions for conjugate phases.

Also in the WC and helical phases.

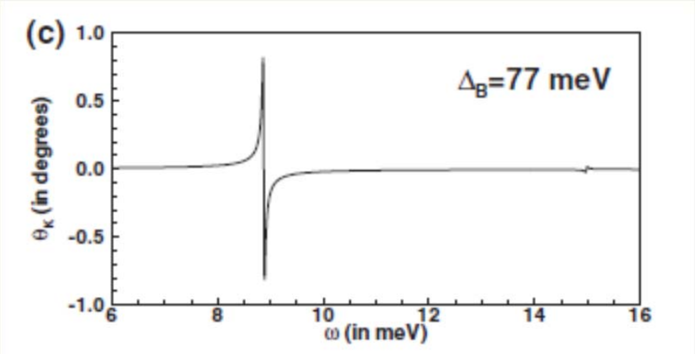
We have not included disorder so that we cannot obtain the numerical value of the Kerr angle.

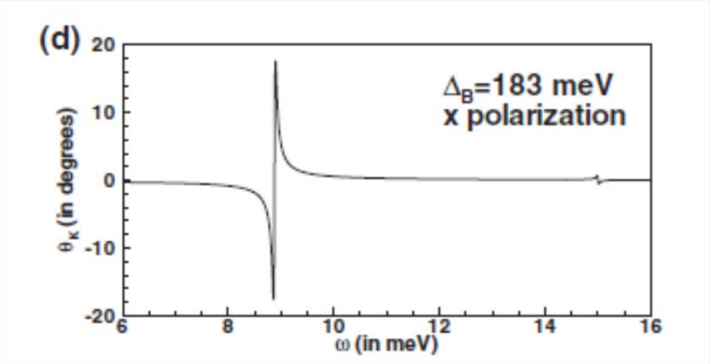
Kerr effect: skyrmion crystal



Polarisation angle rotates in the opposite direction in the conjugate phase.

Kerr effect: helical state





Polarisation angle rotates in opposite directions for conjugate phases.

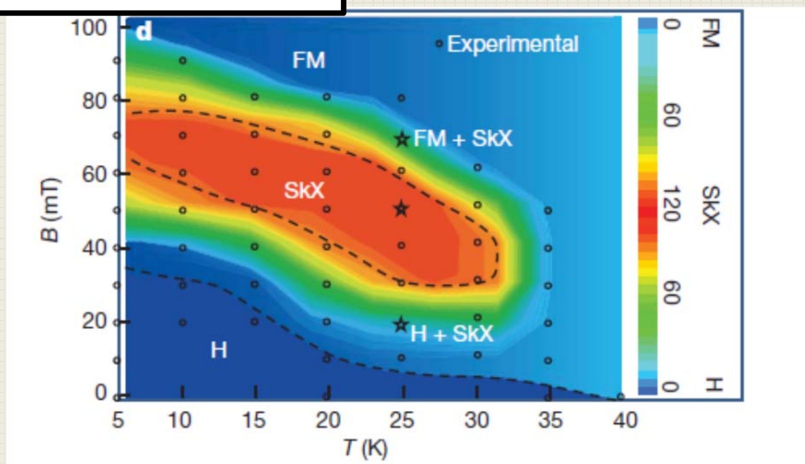
No Kerr effect at $\Delta_B = \Delta_M$

Conclusion

- At some special filling factors, the biased Bernal-stacked bilayer graphene behave as an helical ferromagnet.
- Several nonuniform phases are obtained as the bias is increased.
- All phases but one (the tilted state) have gapped magnetoexcitonic states, some of which are active in optical absorption and Kerr rotation. Conjugate phases are active in opposite circular polarisations and their Kerr angle rotate in opposite directions.

Non-collinear spin configurations in helical ferromagnets

Magnetic field perpendicular to thin film plane



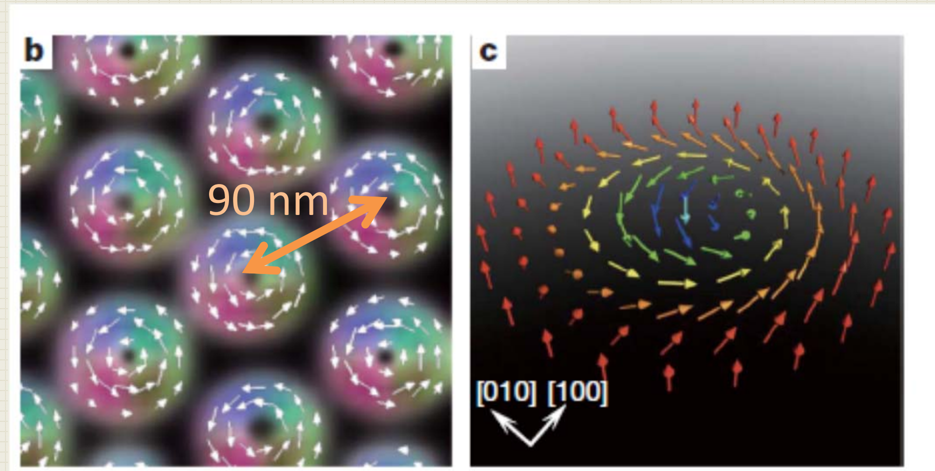


Figure 3 | Phase diagrams of magnetic structure and spin textures in a thin film of $Fe_{0.5}Co_{0.5}Si$. a–c, Spin textures observed using Lorentz TEM

Real-space imaging using
Lorentz transmission electron microscopy

$$H = \int \mathrm{dr}\left[\frac{J}{2}(\nabla \mathrm{M})^2 + \alpha \mathrm{M}\bullet(\nabla \times \mathrm{M})\right]$$

Ferromagnetic exchange
+ Dzyaloshinskii
-Moriya interaction

From X. Z. Yu et al., Nature Letters, 465, 901 (2010).

We find a similar behavior with bias in Bernal-stacked bilayer graphene : an effective DM interaction arises from the Coulomb interaction and the magnetic moments are replaced by electric dipoles. The different phases are detectable in optical (absorption, Kerr) experiments.