

Layer Coherent Phase in Double Layer graphene at $\nu_1 = \nu_2 = 0$

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In the recent advancement in graphene heterostructures, it is possible to create a double layer tunnel decoupled graphene system that has a strong interlayer electronic interaction. In this work, we restrict the parameters in the low energy effective Hamiltonian using simple symmetry arguments. Then, we study the ground state of this system in the Hartree-Fock approximation at $\nu_1 = \nu_2 = 0$. In addition to the phases found in monolayer graphene, we found an existence of layer coherent phase which breaks the layer $U(1)$ symmetry. At non-zero Zeeman coupling strength (E_z), this layer coherent state has a small magnetization, that vanishes when E_z tends to zero. We discuss the bulk gapless modes using the Goldstone theorem. We also comment on the edge structure for the layer coherent phase.

I. INTRODUCTION

After the discovery of the quantum Hall effect in two dimensional electron gas (2DEG)¹, the interest started to build towards bilayer 2DEG's² (and for general systems with internal quantum number³). In the quantum Hall regime the ground state of double layer 2DEG has been explored theoretically^{2,4,5} and later experimentally⁶ (and the references therein). It has been observed that in 2DEG (in this case GaAs), when the interlayer distance is small, the system at total filling fraction $\nu_T = \nu_1 + \nu_2 = \frac{1}{2}$ (ν_1, ν_2 being the filling fraction of each layer) and 1 forms an incompressible QHS⁷⁻⁹. The individual layers at $\nu_T = 1$ and $\frac{1}{2}$ has even denominator filling fractions of $\frac{1}{2}$ and $\frac{1}{4}$ respectively which are known to be compressible states. This phase is a layer coherent phase in which the electron of one layer forms a bound state with the holes of the other layer forming excitons and spontaneously breaks the layer $U(1)$ symmetry. We can think of layer coherent states as either easy plane layer pseudospin ferromagnet or electron-hole bound exciton⁶. This arises from the conservation of particle number in the individual layers. Developments in graphene technology have boosted the interest in quantum Hall effect in graphene^{10,11}. Some recent experiments in the quantum Hall regime in double layer graphene systems has been found to exhibit layer coherent states¹²⁻¹⁴. Experimentally it is possible to fabricate double layer graphene with very small interlayer distance d ($\sim 2\text{nm}$) where $d/l < 1$ (l being the magnetic length)¹²⁻²⁰ which was earlier difficult to achieve in GaAs systems. The separator between the graphene layers is made out of stacked hBN layers. Thus by changing the number of stacked hBN layers the interlayer interaction can be tuned from weak to strong. This induced a huge interest in the understanding and testing of the double layers of graphene, Bernal-stacked bilayer graphene^{12,18}, twisted magic angle bilayer graphene²¹ etc. There has been some theoretical²²⁻²⁶ and experimental²⁷ studies to understand the Coulomb drag in double layer graphene in zero magnetic field. Ref. 28 predicted that at higher temperature at the zero magnetic field there can be a normal to superfluid transition

in double layer graphene.

In the presence of a ultra short-range (compared to the magnetic length l) interaction, the Hamiltonian projected to the $n = 0$ Landau level manifold for monolayer graphene (MLG) has $SU(2)_{\text{spin}} \times (U(1) \times \mathbb{Z}_2)_{\text{valley}}$ symmetry in the absence of a Zeeman field²⁹. There exists four different possible phases namely ferromagnet (F), charge density wave (CDW), Kekulé distorted phase (KD) and anti-ferromagnet (AF), which becomes canted anti-ferromagnet (CAF) in presence of Zeeman coupling³⁰. The predicted phase transition from CAF to F³¹⁻³⁶ has been verified in the experiment³⁷. This understanding of symmetry has been used to study the ground state at fractional fillings as well³⁸.

In the case of double monolayer graphene electron fillings of each layer (ν_1 and ν_2) can be controlled independently. For this system many interesting quantum states have been found. Some of those states can be explained using interlayer Jain composite fermion states⁴, proposed for double layer two-dimensional electron gas¹³. In this manuscript we propose the relevant symmetry in double monolayer graphene which restricts the interacting Hamiltonian to three parameters. Within the scope of this letter, we restrict ourselves to understand the mean field ground state when two layers of graphene are at $\nu_1 = \nu_2 = 0$. We show that for certain values of the parameters, the system goes into a layer coherent phase, which has a small magnetization in presence of a Zeeman field. Increasing the Zeeman field strength one can drive a second order phase transition from magnetized layer coherent phase to the ferromagnetic phase.

Here we would like to emphasize that we want to find a low energy Hamiltonian that is restricted by symmetry. We also focus on the translation invariant ground state solutions of this low energy Hamiltonian in the allowed parameter space. Our method does not talk about the details of the microscopic model but only the low energy effective model.

We describe our assumptions, method and findings in a few sections. In section II we describe the assumptions and our Hamiltonian. After that we describe the results and the Goldstone modes in section III and IV respec-

tively. We also have some discussion over possible lattice models, experimental signatures in section V. Then in section VI we summarize our findings and describe possible application of this work.

II. ASSUMPTIONS AND MODEL

We restrict our calculations to the $n = 0$ Landau level. When the interaction strength is much smaller than the cyclotron energy gap the Landau level mixing can be ignored. In the strong interaction strength regime the form of the effective theory gets dictated by the symmetry (discussed below) when we integrate out the higher Landau levels. When the layers are far enough from each other, we should get two MLG with no interlayer interaction. The valley $U(1)$ for each layer is conserved in order to conserve the translational symmetry in each layer separately. Here we make an additional assumption that the global spin $SU(2)$ symmetry can be enhanced to spin $SU(2)$ symmetry for each layer separately. For this to be the symmetry of this theory we assume that interlayer spin-spin interaction is zero (or negligible). In the absence of the inter layer tunneling it is justified that the Heisenberg term ($\vec{S} \cdot \vec{S}$) will be absent. Other than the Heisenberg a long range spin dipole-dipole interac-

tion between layers can break the spin $SU(2)$ symmetry in each layer to a global $SU(2)$ symmetry. However, the spin dipole-dipole interaction falls as r^{-4} . As the distance between the layers is a few nanometers, we choose to ignore this interaction. Thus under these assumptions the only term that is allowed is the $\vec{S} \cdot \vec{S}$ on each layer which has the spin $SU(2)$ symmetry in each layer.

From this understanding and keeping in mind that the number of particles in each layer is fixed we propose our symmetry of the continuum model to be (in the absence of Zeeman coupling) $[SU(2)_{\text{spin}} \otimes U(1)_{\text{valley}}]$ for each layer, a global $(\mathbb{Z}_2)_{\text{valley}}$ and $(U(1) \otimes \mathbb{Z}_2)_{\text{layer}}$ for the layers. symmetry for each layer. This restricts the interacting part of the Hamiltonian to only three parameters. We can write the Hamiltonian as,

$$H = H_0 + H_{\text{int}}. \quad (1)$$

where H_0 is the one body term coming from Zeeman coupling such that,

$$H_0 = -E_z \left(\sigma^z \otimes \tau^0 \otimes \gamma^0 \right). \quad (2)$$

H_{int} , the 2 body interaction term which obeys the above mentioned symmetry, is given by

$$\begin{aligned} H_{\text{int}} = \frac{\pi l^2}{A} \sum_{\vec{q}} e^{-iq_x(k_1 - k_2 - q_y)l^2 - \frac{q^2 l^2}{2}} \left[K_{xy} \sum_{i=1,2} : \vec{c}_{k_1 - q_y}^\dagger \left(\sigma^0 \otimes \tau^i \otimes P_L \right) \vec{c}_{k_1} \vec{c}_{k_2 + q_y}^\dagger \left(\sigma^0 \otimes \tau^i \otimes P_L \right) \vec{c}_{k_2} : \right. \\ \left. + K_z : \vec{c}_{k_1 - q_y}^\dagger \left(\sigma^0 \otimes \tau^3 \otimes P_L \right) \vec{c}_{k_1} \vec{c}_{k_2 + q_y}^\dagger \left(\sigma^0 \otimes \tau^3 \otimes P_L \right) \vec{c}_{k_2} : \right. \\ \left. + L_z : \vec{c}_{k_1 - q_y}^\dagger \left(\sigma^0 \otimes \tau^0 \otimes \gamma^3 \right) \vec{c}_{k_1} \vec{c}_{k_2 + q_y}^\dagger \left(\sigma^0 \otimes \tau^0 \otimes \gamma^3 \right) \vec{c}_{k_2} : \right] \end{aligned} \quad (3)$$

Here $\vec{c}_k = (c_{k,\uparrow,K,1}, c_{k,\downarrow,K,1}, c_{k,\uparrow,K',1}, c_{k,\downarrow,K',1}, c_{k,\uparrow,K,2}, c_{k,\downarrow,K,2}, c_{k,\uparrow,K',2}, c_{k,\downarrow,K',2})^T$ presents the column vector of fermionic annihilation operators, A is the area of the sample, and l is the magnetic length. The index k_i represents the guiding centers in the Landau gauge. We use the convention where $\sigma^i, \tau^i, \gamma^i$ represents the Pauli matrices in spin, valley, and layer respectively. Here, $P_L = \frac{(\gamma^0 - (-1)^L \gamma^3)}{2}$ is the layer projection operator to layer L . The parameters K_z and K_{xy} arises from the intralayer interactions and are same as the parameters u_z and u_\perp respectively as defined by Kharitonov in the monolayer graphene case²⁶. The parameter L_z is a function of the distance between the layers (d) which should go to zero as d becomes very large (disjoint MLG limit). Here we would like to comment that we also added a capacitance term which is zero when both layers have equal fillings³⁹,

$$H_{\text{cap}} = \frac{g_{es} \pi l^2}{A} (\rho_1(\mathbf{q} = 0) - \rho_2(\mathbf{q} = 0))^2. \quad (4)$$

where $\rho_L(\vec{q})$ is the Fourier transformed electron density operator of L th layer and g_{es} is the coupling strength of the capacitance term.

We define an order parameter Δ matrix which specifies the HF states $|HF\rangle$,

$$\langle HF | c_{k,s,\alpha,L}^\dagger c_{k,s',\alpha',L'} | HF \rangle = \delta_{\vec{k},\vec{k}'} \Delta_{s'\alpha',L',s\alpha L}. \quad (5)$$

where s being the spin, α being the valley and L being the layer index. This Δ matrix can also be thought of as a sum of projection operators of the four filled states at each momentum. The Δ matrix completely determines the single Slater determinant states and any order parameters e.g. electron density, magnetization etc. can be calculated using it. We assume that the HF states preserve translation symmetry i.e. the guiding centers are a good quantum number. Hence, we drop the guiding center label from Δ matrix. Since the capacitance term is a classical term, we only keep the Hartree term and drop the Fock term. In the next section, we discuss the Δ matrix of the different HF states.

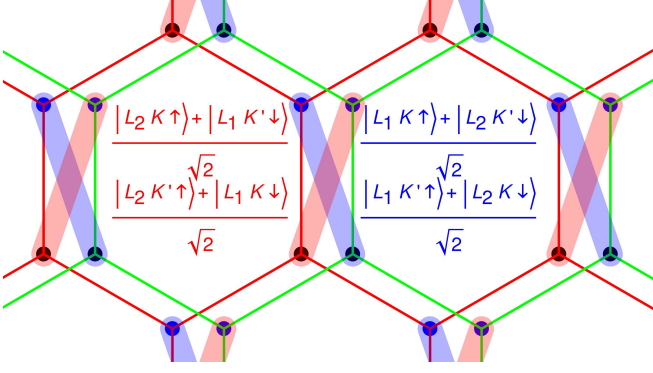


FIG. 1. Here we represented the Layer coherent (LC) phase. The layers here are color coded (green lines and red lines). As shown here the states are linear combination of different layer indices. The corresponding states are also color coded as blue and light red.

III. RESULTS

At $\nu_1 = \nu_2 = 0$ there are four occupied single particle states in the spin-valley-layer space. For $L_z \geq 0$ we find that the phase diagram is exactly the same as the phase diagram found for MLG in Ref. 30. The energies of the phases (defined as $E_{gs} = \langle HF | H_{int} | HF \rangle$ for the proposed HF ground state)) depend on L_z . For these phases, the layer $U(1)$ is not broken and the Δ matrix is block diagonal in the layer index. Each of this block is a four dimensional matrix in the space of valley and spin. The four phases are,

1. Charge Density Wave (CDW): CDW breaks the valley \mathbb{Z}_2 symmetry. At the zero Landau level, different valley indices are pinned to the sublattices. In this phase in each layer the alternate sites (A) in the lattice are occupied and the other sites (B) are left unoccupied. The Δ matrix for this phase is

$$\Delta_{CDW} = \sigma^0 \otimes (\tau^0 + \tau^3) \otimes \gamma^0, \quad (6)$$

and the energy is

$$E_{CDW} = 2(K_z - L_z). \quad (7)$$

2. Kekulé Distorted (KD): This is a bond order phase where the valley $U(1)$ symmetry is broken. In lattice limit the spontaneous breaking of the valley $U(1)$ symmetry leads to the translation symmetry breaking in each layer. This phase doesn't have any Goldstone modes. The Δ matrix for this phase will be

$$\Delta_{KD} = \frac{1}{2} \sigma^0 \otimes (\tau^0 + \tau^1) \otimes \gamma^0, \quad (8)$$

with energy,

$$E_{KD} = 2(K_{xy} - L_z). \quad (9)$$

3. Ferromagnet (F): This phase breaks the spin $SU(2)$ symmetry in each layer. Similarly, the Δ matrix and energy will be

$$\Delta_F = \frac{1}{2}(\sigma^0 + \sigma^3) \otimes \tau^0 \otimes \gamma^0 \quad (10)$$

$$E_F = -4E_z - 2(2K_{xy} + K_z + L_z). \quad (11)$$

4. Canted Anti-Ferromagnet (CAF): This phase breaks the spin $U(1)$ symmetry in each layer. The Δ matrix is,

$$\Delta_{CAF} = \frac{1}{2} \left[\sin \phi (\sigma^1 \otimes \tau^3 \otimes \gamma^0) + \cos \phi (\sigma^3 \otimes \tau^0 \otimes \gamma^0) + \sigma^0 \otimes \tau^0 \otimes \gamma^0 \right] \quad (12)$$

where ϕ is given by

$$\cos \phi = \frac{E_z}{2|K_{xy}|}, \quad (13)$$

with energy,

$$E_{CAF} = -4E_z - 2(2K_{xy} + K_z + L_z). \quad (14)$$

At $E_z = 0$ the states become a pure anti-ferromagnetic state. Increasing the Zeeman field E_z beyond $2|K_{xy}|$ can drive a continuous phase transition from canted anti-ferromagnetic phase to ferromagnetic phase.

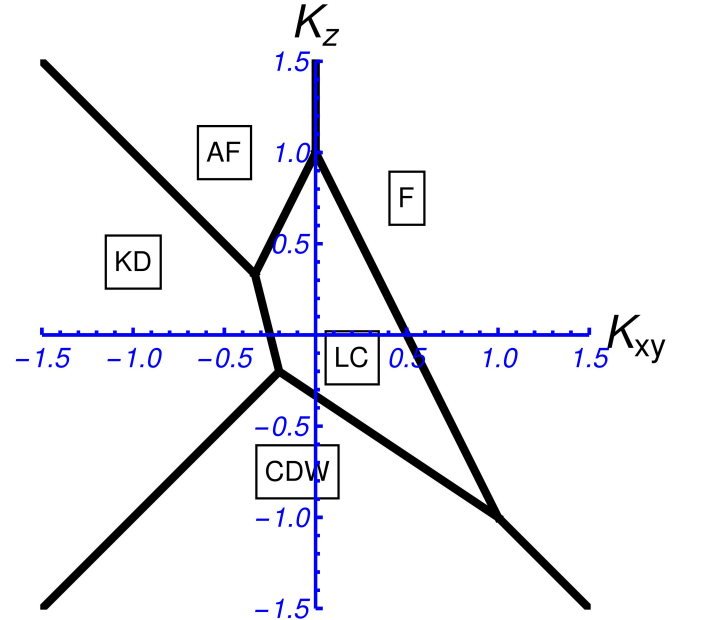


FIG. 2. Here we present the Phase diagram of for $L_z = -0.5$ in the absence of Zeeman coupling. The phase LC Phase appears near $K_{xy} = K_z = 0$. All the phase transitions here are First order.

Next we come to the special phase of the double layer graphene. For $L_z < 0$, we find there exists a layer coherent phase which breaks the Layer $U(1)$ symmetry (see 3).

We find the layer coherent phase both in the presence and absence of the Zeeman energy. For a non-zero Zeeman coupling, there are two parameters (and operators which are connected by the left over ground state symmetry) that,

$$\Phi_L = \sigma^1 \times \tau^1 \times \gamma^1 \quad (15a)$$

$$S^z = \frac{\sigma^3 \times \tau^0 \times \gamma^0}{2}. \quad (15b)$$

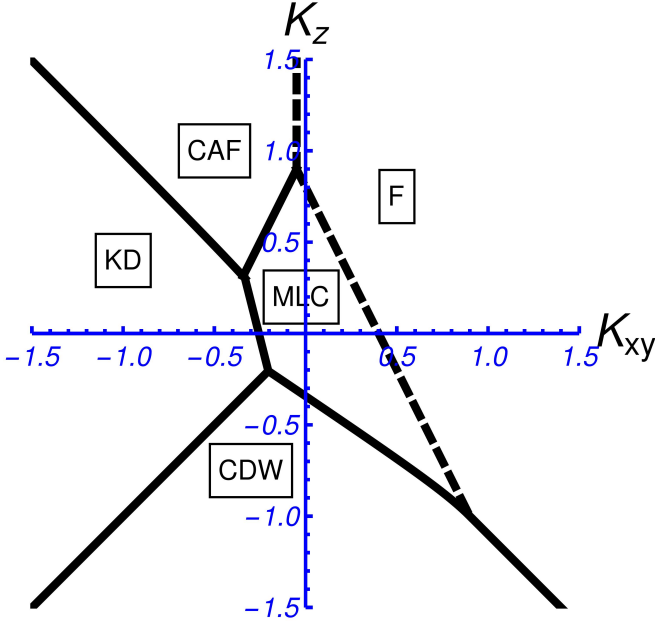


FIG. 3. Here we present the Phase diagram of for $L_z = -0.5$ and $E_z = 0.1$. As we can see that the MLC phase appears and there is a second order transition from MLC to F as marked by the broken line.

The magnetic layer coherent phase occurs at $E_z \neq 0$ with $\langle S^z \rangle \neq 0$. At $E_z = 0$ we find $\langle S^z \rangle = 0$, we call it layer coherent phase (LC) (see fig. 1). We can write the Δ matrix for the MLC phase as,

$$\Delta_{\text{MLC}} = \frac{1}{2} \left[\sin \theta (\sigma^1 \otimes \tau^1 \otimes \gamma^1) + \cos \theta (\sigma^3 \otimes \tau^0 \otimes \gamma^0) + \sigma^0 \otimes \tau^0 \otimes \gamma^0 \right] \quad (16)$$

with $\cos \theta$ defined as,

$$\cos \theta = \frac{2E_z}{|2K_{xy} + K_z + 2L_z|}. \quad (17)$$

The energy of the phase is

$$E_{\text{MLC}} = -2K_{xy} - K_z - \frac{4E_z^2}{|2K_{xy} + K_z + 2L_z|}. \quad (18)$$

Here $\langle \Phi_L \rangle = 4 \sin \theta$ and $\langle S^z \rangle = 2 \cos \theta$. For $2E_z \geq |2K_{xy} + K_z + 2L_z|$ with $\theta = 0$, this Δ will represent

a ferromagnetic ground state and for any other value of θ the Δ matrix represents a magnetic layer coherent state (MLC). For the zero Zeeman coupling, we have $\cos \theta = 1 \Rightarrow \langle S^z \rangle = 0$, a purely layer coherent state. The phase transition from MLC to F is a second order transition (see Fig. 3). However, similar to the AF to F phase transition, the LC to F phase transition is a first order transition. Thus all phase transitions are first order at $E_z = 0$ (see Fig. 2). The Phase boundary between MLC and F changes, as we change the total Zeeman couplings at a fixed L_z . Here in Table I we represent all different phase boundaries.

Phases	Boundary equation
KD,CAF	$K_z = -K_{xy} + E_z^2/K_{xy}$
KD,CDW	$K_z = K_{xy}$
F,CDW	$K_z = -K_{xy} + E_z$
F,MLC	$K_z = -2K_{xy} - 2L_z - 2E_z$
MLC,CDW	$-\frac{3K_z}{2} = \left(L_z + 2K_{xy} - \sqrt{(2L_z + K_{xy})^2 + 3E_z^2} \right)$
CAF,MLC	$K_z = 2(K_{xy} - L_z)$
KD,MLC	$K_z = -3K_{xy} - \sqrt{(K_{xy} - 2L_z)^2 + 4E_z^2}$
F,CAF	$K_{xy} = -E_z/2$

TABLE I. Phase boundary equations as a function of the parameters

IV. GOLDSTONE MODES

The Hamiltonian in the presence of Zeeman term has five different $U(1)$ symmetries coming from $U(1)_{\text{spin}} \otimes U(1)_{\text{valley}}$ for the two layers and a layer $U(1) \times \mathbb{Z}_2$ symmetry. For the layer diagonal phases, the presence of gapless bulk Goldstone mode is known. The CDW phase has no gapless bulk mode. In the continuum limits it seems that KD phase breaks a continuous symmetry but as valley indices are momenta, it breaks lattice symmetry. Hence in this phase we will have no Goldstone modes. The F phase has spin wave mode and at long wavelength, it's gap is proportional to the Zeeman coupling strength (E_z). As the CAF phase breaks the spin $U(1)$ symmetry there will be a pair of gapless neutral modes in the bulk³⁴.

Next we discuss the new layer coherent phase and its bulk modes. From Eq. 16 one can easily see that the ground state has the two leftover $U(1)$ symmetries defined by operators $\sigma^3 \otimes \tau^3 \otimes \gamma^0$ and $\sigma^3 \otimes \tau^0 \otimes \gamma^3$. These operations can be understood as opposite spin rotations at different valleys or different layers. In other words, these are relative valley and layer spin twists respectively. Thus out of five different continuous symmetries, three are broken by the ground states giving rise to three different Goldstone modes in the bulk. However, these modes will be neutral as there is a charge gap in the bulk and these excitations are similar to spin waves. We remind the readers here that the breaking of the valley part of the symmetry breaks the lattice C_3 rotation about a site. This happens as the $n = 0$ manifold the \mathbf{K}, \mathbf{K}' of each

layer maps to the A, B sublattice of each layer³⁰. This means we will count one extra Goldstone mode in the continuum analysis.

V. DISCUSSION

In this manuscript, we constructed the Hamiltonian using symmetry principles without discussing the nature and details of the interaction at the lattice scale. The model only assumes the lattice interactions are local and thus their Fourier transform is a function independent of momentum.

In principle we can reproduce the interactions in the continuum model by projecting the microscopic Hamiltonian to the lowest Landau Level. We present a simplified example which includes the onsite Hubbard interaction (U_1), nearest neighbor interlayer electron density-density interaction (U_2) and a intralayer nearest neighbor spin-spin interaction (J),

$$H_{\text{lat}} = U_1 \sum_{\substack{s_1, s_2 \\ r, L}} : n_{s_1, r, L} n_{s_2, r, L} : + U_2 \sum_{\substack{s_1, s_2 \\ r, r' \\ L_1 \neq L_2}} : n_{s_1, r, L_1} n_{s_2, r', L_2} : \\ + J \sum_{\langle r, r' \rangle, L} : \vec{S}_{r, L} \cdot \vec{S}_{r', L} : \quad (19)$$

Here n is the fermion number operator and \vec{S} is the local spin operator. Though we assumed ultra-short interactions, adding finite range to these interactions do not change the symmetry of the continuum model when we project the hamiltonian in the zero Landau level manifold. We can write the relation between the continuum parameters in Eq. 3 in terms of the parameters of Eq. 19 as $K_{xy} \propto -J$, $K_z \propto U_1$ and $L_z \propto U_1/2 - U_2$.

We would like to emphasise here that the Hamiltonian presented here is just an example to show that even at the simplest model at the lattice level, we can achieve the Hamiltonian in Eq. 3. Here we are not concerned with the values/signs of different parameters K_{xy}, K_z, L_z but showing the phases that is determined by these parameters. Modeling a generic lattice theory with physically motivated parameters and their values is an interesting study but out of the scope for the current manuscript. We hope to study a lattice model of a double layer graphene in the future.

From Eq. 16 we can see that as the states are mixture of \vec{K}, \vec{K}' of different layers, near the edge the dispersion will contain two pairs of particle-like bands and another two pairs of hole-like bands due to the breaking of the translation symmetry⁴⁰. There will be a pair of counter propagating modes only if we have identical layers near the edge of the system. Near the edge, both the valley $U(1)$ symmetry and the layer $U(1)$ will be broken generically. Thus the edge of a double layer graphene will be gapped if the bulk is in MLC phase. As the states are superposition of two different layers, there will be a

drag in the two terminal measurements at least for finite temperature¹⁶. However, we know that there will be two pair of counter propagating modes at the edge for each layer in the F phase^{33,37,40}. Thus by changing the Zeeman energy with respect to the interaction energies, one can make a transition from MLC to F. This should show up in the two terminal conductance measurement³⁷. It will also be interesting to measure the lattice scale structure using both spin resolved and spin unresolved⁴¹ tunneling electron microscope to confirm the phase directly.

VI. SUMMARY AND OUTLOOK

Here we argued that the continuum limit of the double layered graphene at $\nu_1 = \nu_2 = 0$ has a big symmetry group that restricts the interacting part of the Hamiltonian severely to only three parameters at $n = 0$ Landau Level. Further, we find a candidate ground state using the HF approximation that breaks the layer $U(1)$ symmetry. We also find a second order phase transition from MLC to F as a function of Zeeman energy. We argued for a general system, the edge of the MLC will be gapped. This leads to the possible experiment to find two terminal conductance that will change when we go from the MLC to F.

This study is just the beginning of understanding the double layer graphene ground state in the quantum Hall regime. It was previously shown that the phase transition from CAF to F connects the bulk gapless modes of the CAF to the gapless edge modes of F³⁴. We hope to study the edge theory of double layer graphene in future to answer the question of the phase transition from MLC to F.

It has been shown that if we have finite range interactions in monolayer graphene then we can have coexistence of phases⁴². Similarly, in a lattice model coexistence can also be shown by doing HF calculation in the lattice limit⁴³. This explains the experimental results⁴⁴, where bond order was observed using Scanning Tunnelling Microscope. This question may also be important in double layer graphene case, as we might have a similar coexistence. To understand that possibility one needs to study that lattice Hamiltonian similar to the one mentioned in Eq. 19. Furthermore, this theory can be used to explore the phase diagrams at other filling fractions in the parameter space of K_{xy}, K_z and L_z similar to the MLG case³⁸. There is also a surge of interest in understanding the BCS/BEC condensation^{6,17,18,45} in double layer graphene systems. As previously mentioned this state breaks the layer $U(1)$ symmetry just like a superfluid state. At low enough temperatures these excitons can form a superfluid state where the interaction between the electron and hole can be tuned by tuning the L_z parameter (which depends on the interlayer separation d).

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Appendix A: Details of the technique

The interacting Hamiltonian in Eq. 3 can be written in a simplified form as,

$$H_{int} = \frac{\pi l^2}{A} \sum_{\substack{\mathbf{q}, k_1, k_2 \\ a, b, c, d}} e^{-iq_x(k_1 - k_2 - q_y)l^2 - \frac{q^2 l^2}{2}} V_{a,b,c,d} : c_{k_1 - q_y, a}^\dagger c_{k_1, b} c_{k_2 + q_y, c}^\dagger c_{k_2, d} : \quad (\text{A1})$$

where

$$V_{a,b,c,d} = K_{xy} \sum_{i=1,2} \left(\sigma^0 \otimes \tau^i \otimes P_L \right)_{a,b} \left(\sigma^0 \otimes \tau^i \otimes P_L \right)_{c,d} + K_z \left(\sigma^0 \otimes \tau^3 \otimes P_L \right)_{a,b} \left(\sigma^0 \otimes \tau^3 \otimes P_L \right)_{c,d} \\ + L_z \left(\sigma^0 \otimes \tau^0 \otimes \gamma^3 \right)_{a,b} \left(\sigma^0 \otimes \tau^0 \otimes \gamma^3 \right)_{c,d}. \quad (\text{A2})$$

To calculate the total HF energy $E = \langle HF | H_0 + H_{int} | HF \rangle$ we write the average of the four-fermion term that arises in the interacting Hamiltonian H_{int} as

$$\langle HF | c_{k_1 - q_y, a}^\dagger c_{k_1, b} c_{k_2 + q_y, c}^\dagger c_{k_2, d} | HF \rangle = \Delta_{b,a} \Delta_{d,c} \delta_{q_y, 0} - \Delta_{d,a} \Delta_{b,c} \delta_{q_y, k_1 - k_2}. \quad (\text{A3})$$

The first term gives the Hartree term and the second term is the Fock term. Using this, we can calculate the energy from the electron-electron interaction given by $E_{int} = \langle HF | H_{int} | HF \rangle$

$$E_{int} = \frac{\pi l^2}{A} \sum_{\substack{a, b \\ c, d}} \sum_{\substack{\mathbf{q} \\ k_1, k_2}} e^{-iq_x(k_1 - k_2 - q_y)l^2 - \frac{q^2 l^2}{2}} V_{a,b,c,d} (\Delta_{b,a} \Delta_{d,c} \delta_{q_y, 0} - \Delta_{d,a} \Delta_{b,c} \delta_{k_1 - q_y, k_2}) \\ = \frac{\pi l^2}{A} \sum_{a, b, c, d} V_{a,b,c,d} \left(\sum_{\substack{q_x \\ k_1, k_2}} e^{-iq_x(k_1 - k_2)l^2 - \frac{q_x^2 l^2}{2}} \Delta_{b,a} \Delta_{d,c} - \sum_{\mathbf{q}, k_1} e^{-\frac{q^2 l^2}{2}} \Delta_{d,a} \Delta_{b,c} \right) \\ = \frac{1}{2N_\Phi} \sum_{\substack{i \\ a, b, c, d}} V_{a,b,c,d} \left(N_\Phi^2 \Delta_{b,a} \Delta_{d,c} - \frac{N_\Phi A}{(2\pi)^2} \int_{\mathbf{q}} d\mathbf{q} e^{-\frac{q^2 l^2}{2}} \Delta_{d,a} \Delta_{b,c} \right) \\ = \frac{1}{2N_\Phi} \sum_{a, b, c, d} V_{a,b,c,d} \left(N_\Phi^2 \Delta_{b,a} \Delta_{d,c} - \frac{N_\Phi A}{2\pi l^2} \Delta_{d,a} \Delta_{b,c} \right) \quad (\text{A4a})$$

$$E_{int} = \frac{N_\Phi}{2} \sum_{\substack{i \\ a, b, c, d}} V_{a,b,c,d} (\Delta_{b,a} \Delta_{d,c} - \Delta_{d,a} \Delta_{b,c}) \quad (\text{A4b})$$

where A is the area of the system and $N_\Phi = A/(2\pi l^2)$ is the number of guiding centers in the system. Hence the total energy of the system per guiding center is

$$\frac{E}{N_\Phi} = E_z (\sigma_3 \otimes \tau_0 \otimes \gamma_0)_{ab} \Delta_{b,a} + \frac{1}{2} \sum_{a, b, c, d} V_{a,b,c,d} (\Delta_{b,a} \Delta_{d,c} - \Delta_{d,a} \Delta_{b,c}). \quad (\text{A5})$$

The first term is the Zeeman contribution and the second term comes from the electron-electron interaction.

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