Transport gap in suspended bilayer graphene at zero magnetic field

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We report a change of three orders of magnitude in the resistance of a suspended bilayer graphene flake which varies from a few kΩ in the high-carrier-density regime to several MΩ around the charge neutrality point (CNP). The corresponding transport gap is 8 meV at 0.3 K. The sequence of quantum Hall plateaus appearing at filling factor \( \nu = 2 \) followed by \( \nu = 1 \) suggests that the observed gap is caused by the symmetry breaking of the lowest Landau level. Investigation of the gap in a tilted magnetic fields indicates that the resistance at the CNP shows a weak linear decrease for increasing total magnetic field. Those observations are in agreement with a spontaneous valley splitting at zero magnetic field followed by splitting of the spins originating from different valleys with increasing magnetic field. Both the transport gap and \( B \) field response point toward the spin-polarized layer-antiferromagnetic state as the ground state in the bilayer graphene sample. The observed nontrivial dependence of the gap value on the normal component of \( B \) suggests possible exchange mechanisms in the system.

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I. INTRODUCTION

Following on the isolation of single-layer graphene, the study of bilayer graphene (BLG) became a separate direction of research in the study of two-dimensional materials. Charge carriers in bilayer graphene have a parabolic dispersion with an effective mass of about 0.054\( m_e \), but also possess a chirality. The latter manifests itself in an unconventional quantum Hall effect with the lowest Landau level (LLL) being eightfold degenerate. Compared to single-layer graphene, bilayer graphene has, in addition to spin and valley degrees of freedom, an orbital degree of freedom, where Landau levels with numbers \( n = 0 \) and 1 (each four fold degenerate) have the same energy. Recent advances in obtaining suspended bilayer graphene devices with charge carrier mobility exceeding \( \mu > 10000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \) gave access to the investigation of many-body phenomena in clean bilayer graphene at low charge carrier concentration (\( n < 10^{10}\text{cm}^{-2} \)).

Due to the nonvanishing density of states at the charge neutrality point (CNP), bilayer graphene is predicted to have a variety of ground states triggered by electron-electron interaction. There are two competing theories describing the ground state of BLG: a transition (i) to a gapped layer-polarized state (excitonic instability) or (ii) to a gapless nematic phase. Excitonic instability is a layer polarization in which the charge density contribution from each valley and spin spontaneously shifts to one of the two graphene layers. This redistribution is caused by an arbitrarily weak interaction between charge from the conduction and valence band states. Since each bilayer flavor (spin or valley) can polarize toward either of the two layers, there are 16 possible states, which can be classified by the total polarization as being layer ferromagnetic (all degrees of freedom choose the same layer), layer ferrimagnetic (three of the four valley-spin flavors choose the same layer), or layer antiferromagnetic (with no overall polarization). To make it clear, the term “magnetic” should be associated with flavor (not only spin) orientation between two layers. These states are considered as analogous to the biased bilayer in the sense that the charge transfer can be attributed to the (wave-vector-dependent) exchange potential difference between low-energy sites on the opposite layers. The total energy of the system is lowered by the gain in the exchange interaction via breaking of the inversion symmetry, i.e., introducing a gapped state. Antiferromagnetic polarization is electrostatically favorable due to the absence of a net charge on both layers; however, the actual ground state is theoretically undefined. Recent experiments have suggested evidence of the possible existence of two of the antiferromagnetic states—the anomalous quantum Hall (AQH) state and the spin-polarized layer-antiferromagnetic (LAF) state. To avoid possible confusion we note that in earlier literature the LAF state is also called the quantum valley Hall state. The AQH state has electrons that are polarized in the same layer for both spins and in opposite layers for opposite valleys. This state has spontaneously broken time-reversal symmetry and therefore possess a substantial orbital magnetization exhibiting the quantized Hall effect (at zero magnetic field), while its spin density is everywhere zero. Due to its magnetization the AQH state can be favored over other ground states in a perpendicular magnetic field. The LAF state has opposite spin polarization for opposite layers. In contrast to the AQH state, the LAF state does not have topologically protected edge states, which brings its minimum conductance to zero. For both states the theoretical estimations of the gap \( \Delta \) give the value of 1.5–30 meV. However, the intervalley exchange weakly favors the LAF state. One of the ways to determine the character of the bilayer ground state experimentally is to investigate the response of the gap value to a magnetic field \( B \) (which couples to spin) and electrical field \( E \) (which couples to layer pseudospin). When Zeeman coupling is included, the AQH-state quasiparticles simply spin split, leaving the ground state unchanged but the charge gap reduced. It was calculated...
that for a 4 meV spontaneous gap at zero field, a field of \( B = 35 \) T drives the gap to zero. On the other hand, the gap in the LAF state is weakly \( B \) field dependent.

The second possible description for the ground state of BLG is based on a nematic phase caused by the renormalization of the low-energy spectrum.\(^{18,19}\) Detailed tight-binding-model studies showed that inclusion of next-neighbor interlayer coupling changes the band structure in the bilayer, producing a Lifshitz transition in which the isoenergetic line about each valley is broken into four pockets with linear dispersion.\(^{2,23}\)

At energies higher than 1 meV the four pockets merge into one pocket with the usual quadratic dispersion. Moreover, electron-electron interactions might result in further energy spectrum transformation, where the number of low-energy cones can be reduced to 2 near each of the two different valleys with increase of \( B \). There is an essential change of about 6 M\( \Omega \) in the unit capacitance of the system at \( \alpha \approx 0.5 \times 10^{10} \text{ cm}^{-2} \). The typical current we use is around 1 nA. See the Appendix.

### III. TEMPERATURE DEPENDENCE AND QUANTUM TRANSPORT

Our pristine samples are strongly \( p \) doped with the CNP situated beyond 60 V and a metallic resistance of a few hundreds of ohms over the entire voltage range. Therefore we perform the current annealing technique in order to obtain high-quality devices. In contrast to previous samples, in which each successive step of current annealing tended to cause a sharper change in the resistance values within the scanned region of \( V_g \), the bilayer sample discussed here already shows after the first current annealing step a highly resistive region around the CNP (not shown). The next annealing step (1.1 mA) moves the charge neutrality point down to \( V_g = 1.2 \) V. However, surprisingly, the resistance around the CNP becomes 14 M\( \Omega \) and is reduced down to 5 k\( \Omega \) in the metallic regime at \( V_g = -60 \) V [Fig. 1(a), inset]. This fact points toward opening of a gap. The temperature dependence of the membrane from 4.2 K to 300 mK is shown in Fig. 1(a).

There is an essential change of about 6 M\( \Omega \) in the maximum resistance \( (R_{\text{max}}) \) from 4.2 down to 1.3 K; however, further lowering of the temperature does not change \( R_{\text{max}} \) much. From an Arrhenius plot of the resistance at the CNP [Fig. 1(c)] we can extract a thermal excitation gap of 0.33 meV.\(^{26}\) The saturation of resistance at lower \( T \) can be explained by variable-range hopping with different temperature dependence. We would like to point out that our excitation current value of 1 nA gave a voltage drop around 10 mV at the CNP, which is much higher than the energy \( kT \) at measured temperatures (0.3 meV). Therefore one has to be careful in comparing transport and thermal excitation gaps.

There might be several scenarios for the observed gap formation in the gate voltage dependence: (i) A lateral confinement in the membrane, where the energy levels are

\[
E_n = \frac{\hbar^2 k^2}{2m} = \frac{\hbar^2 \pi^2}{2m W^2} l^2,
\]

where \( W = 2.3 \) \( \mu \text{m} \) is the width of the flake and \( l \) is an integer. However, the first two levels have energies of \( E_1 = 1.3 \) \( \mu \text{eV} \) and \( E_2 = 5.3 \) \( \mu \text{eV} \), which are much lower than \( k_bT \) at measured temperatures. (ii) True gap formation with zero density of states within the gap and available states at the conduction and valence bands. (iii) A transport gap, accompanied by observation of reproducible conductance oscillations in the region of suppressed conductance. In such a...
The transport gap in suspended bilayer graphene... 

**FIG. 1.** (Color online) Four-probe resistance of the suspended bilayer graphene. (a) Gate dependence of the sample at the temperatures of 4.2 (black), 1.3 (red), 0.7 (green), and 0.3 K (blue). Inset: Resistance at 4.2 K on a logarithmic scale showing the dramatic change from the CNP to the metallic regime. (b) Transport gap extraction at 4.2 and 0.3 K. The energy gap in the bias direction is highlighted by the conductance crossover (fitted with dashed lines) at zero. The values of the transport gap are 3 meV (4.2 K) and 8 meV (0.3 K). (c) An Arrhenius plot of the resistance. The value of the extracted thermal gap is 0.33 meV.

regime transport is limited by the quantum confinement effect along the width (mainly originating from the impurities). A more complicated case, when the gap value depends on the charge carrier density, i.e., the energy of the levels changes while they are being filled with carriers. This situation might happen when the gap is induced by charge redistribution between layers, which would be influenced by the applied back gate voltage. At the moment, we cannot determine the exact gap type; therefore, further analysis is performed assuming a transport gap scenario, but keeping in mind that this gap value might happen when the gap is induced by charge redistribution on the charge carrier density, i.e., the energy of the levels.

(iv) A more complicated case, when the gap value depends on the density (\(\mu = 1/(eR_{sq}n)\)), where \(R_{sq}\) is the square resistance of the sample and \(e\) is the elementary charge. The mobility value \(\mu \propto 20 000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}\) at \(n = 3.5 \times 10^{11} \text{ cm}^{-2}\) corresponds to the value of high quality bilayer graphene devices. Due to the symmetry of resistance change around the CNP [Fig. 1(b)] and the fact that the CNP itself is situated around zero gate voltage (\(V_g = 1.2 \text{ V}\)), which corresponds to the density of \(n = 0.77 \times 10^{10} \text{ cm}^{-2}\) at 0 V, we can also exclude the low-quality “p-doped” regions close to the contacts (which can form after current annealing) as the cause of the reported gap. In the meantime, we cannot exclude a charge inhomogeneity in the sample bulk which might lead to the observed order of magnitude difference between electrical and transport gaps, in analogy to the nanoribbon case.

Given the fact that the resistance reaches MΩ values at the CNP, it is already hard to establish quantum Hall plateaus in our suspended bilayer device. However, we have achieved the observation of quantum Hall transport shown in Figs. 2(a) and 2(b). The first quantum Hall plateau appears at 5 T on the hole side (red curve), which we attribute to the filling factor \(v = 2\). This plateau is followed by the appearance of \(v = 1\) at 7 T [Fig. 2(b)]. The conductance values of the observed plateaus deviate from the expected ones of \(2e^2/h\) and \(e^2/h\), since they are affected by charge inhomogeneity. Therefore, we determine the exact values of the corresponding plateaus by the scaling of their positions in the graph of density (\(V_{gr}\)) vs magnetic field \(B\) [Fig. 2(d)]. As expected from \(v = n/(eB/h)\) the scaling is linear with the leverage factor of \(\alpha = 0.64 \times 10^{10} \text{ cm}^{-2} \text{ V}^{-1}\) for \(v = 2\) and 1. In order to use the same \(\alpha\) for both filling factor sets [see Fig. 2(d)] the slopes of \(V_{gr}\) versus \(B\) and the \(v\) values, respectively, have to be a factor of 2 different. Therefore, we have to point out that the linear scaling will hold as well for a leverage factor of \(1.1 \times 10^{10} \text{ cm}^{-2} \text{ V}^{-1}\) if we assume \(v = 4\) and 2 as the observed sequence of plateaus. From previous studies we know that the capacitance probed by the quantum Hall effect (QHE) in graphene devices (especially in suspended samples) can be higher than the geometrical value, due to the deviation from the plane capacitor model. However, we attribute the observed plateaus to the filling factors 2 and 1. As we noticed before, most of the time the current annealing procedure leads to the formation of high-quality annealed regions connected in series with low-mobility “p-doped” regions close to the contacts. Therefore higher values of the conductance plateaus can be explained by a “p-doped” slope, which increases with magnetic...
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\[ \nu = 4 \]
\[ \nu = 0 \]
\[ \nu = -4 \]
\[ \nu = 2 \]
\[ \nu = -2 \]
\[ \Delta \nu = -1 \]
\[ \nu = 1 \] g*µ BB

\[ B (T) \]

\[ E \]

FIG. 2. (Color online) Quantum transport at 1.3 K. (a) Quantum Hall conductance of the suspended bilayer at \( B = 0 \) and 5 T. (b) Quantum Hall conductance of the suspended bilayer at \( B = 7 \) and 11 T. The exact filling factors \( \nu \) corresponding to the observed plateaus are shown. (c) Resistance of the sample in the quantum Hall regime. (d) Scaling of the filling factor positions in graph of gate voltage (\( V_g \)) vs magnetic field. (e) LL hierarchy of the symmetry breaking of the lowest LL in bilayer graphene. Suggested scenario of spontaneous valley splitting followed by spin splitting at high field \( B \). This might also be the reason for the absence of resistance quantization on the electron side [Fig. 2(c)]. Assuming \( \mu B \gg 1 \) for the formation of QHE plateaus,\(^{30}\) our observation implies a lower bound for the mobility of 2000 cm\(^2\) V\(^{-1}\) s\(^{-1}\).

To summarize our QH transport results: At this point we have shown that a zero-field gap opens at the CNP in the studied graphene bilayer. This observation points to a possible symmetry breaking of the ground state in bilayer graphene. The application of \( B \) does not restore the broken symmetry and brings the system into the QH regime. In Fig. 2(e) we show the hierarchy of the splitting of the eightfold-degenerate lowest Landau level in applied \( B \).\(^{31}\) The development of the level structure with \( B \) will be specified and discussed in Sec. IV. Meanwhile, if we assume that at \( B = 0 \) T one of the degeneracies is already lifted, then, with increasing field, one can expect quantization at the filling factors \( \nu = 0 \) and 4 followed by \( \nu = 2 \) and 1. However, if the initial symmetry breaking is strong enough and the scanned window in energy is limited (\( V_g \)), then one can expect quantization at \( \nu = 2 \) followed by \( \nu = 1 \). This described hierarchy of level splitting and sequence of plateaus will be observed independent of whether valley or spin splitting occurs first.

IV. RESISTANCE AT THE CNP IN TILTED MAGNETIC FIELD

In order to clarify the nature of the gapped ground state of bilayer graphene and its evolution in a magnetic field we perform a tilted-magnetic-field experiment. In tilted experiments the total magnetic field (\( B_{\text{tot}} \)) can be separated from its normal (to the plane of the sample) component: \( B_n = B_{\text{tot}} \cos \theta \), where \( \theta \) is the angle between these two vectors [Fig. 3(c)]. This procedure allows us to distinguish between the orbital effect (QHE) and pure Zeeman energy, which has to scale with the \( B_{\text{tot}} \) value.\(^{22,31,32}\)

All measurements presented below were performed at a temperature of 1.3 K. The application of the magnetic field perpendicular to the sample plane leads to an increase in the resistance at the CNP, as expected for QH transport in the case of broken-symmetry states. To distinguish between the normal component and total \( B \) we perform a series of experiments keeping \( B_n \) fixed and gradually increasing \( B_{\text{tot}} \). As an example, in Fig. 3(a) we show the change in the normal component and total \( B \) we perform a series of experiments keeping \( B_n \) fixed and gradually increasing \( B_{\text{tot}} \). As an example, in Fig. 3(a) we show the change in the resistance at the CNP as expected for QH transport in the case of broken-symmetry states. To distinguish between the normal component and total \( B \) we perform a series of experiments keeping \( B_n \) fixed and gradually increasing \( B_{\text{tot}} \). As an example, in Fig. 3(a) we show the change in the resistance at the CNP as expected for QH transport in the case of broken-symmetry states.
in the appearance of the plateau associated with filling factor $\nu = 1$ we expect the value of the ground-state gap $\Delta$ to be lowered by spin splitting coupled to $B_{\text{tot}}$. Here we would like to emphasize that we do observe the appearance of $\nu = 1$ and a minimum of resistance at the CNP in a similar magnetic field $B_{\text{tot}} > 7 \, \text{T}$. In a simplified way we describe the resistance value at the CNP point as

$$\ln R_{\text{max}} \propto \Delta/(kT) - g^* \mu_B B_{\text{tot}}/(kT),$$

where $g^*$ is an effective $g$ factor including exchange electron interaction and a Landau level broadening.\(^3\)\(^,\)\(^2\)\(^,\)\(^3\)\(^3\) The change in $\ln(R)$ versus $B_{\text{tot}}$ at fixed $B_n$ values is shown in Fig. 4(b). This dependence can be best described as linear. The slope and $y$ intercept of the linear fit of Fig. 4(b) give the values of $\Delta$ and $g^* \mu_B$. Surprisingly, both these contributions scale with the $B_n$ component. In Fig. 4(c) we show $g^* \mu_B$ versus $B_n$. Despite the fact that the scaling appears linear, a plot of the slope as a function of $\sqrt{B_n}$ does seem to fit also (not shown). $\Delta$ increases with $B_n$ from 1.4 meV at $B_n = 1 \, \text{T}$ up to 1.7 meV at $B_n = 25 \, \text{T}$ (not shown). This $\Delta$ is of the same order as the measured transport gap (which can overestimate the real energy gap) and also corresponds to the theoretically predicted gap of 1.5–30 meV for the excitonic instability.\(^1\)\(^3\)\(^,\)\(^1\)\(^6\)\(^,\)\(^2\)\(^2\)

In summary, tilted-magnetic-field experiments show that the resistance at the CNP of the studied gapped bilayer graphene decreases linearly with increase of the total magnetic field component. This points to a many-body effect and weak reduction of the gap in an applied magnetic field. The developed minimum in the resistivity in Fig. 3 can be explained by the overlapping of spin-up and spin-down levels from the adjacent Landau levels due to Zeeman splitting in the applied $B$.\(^3\)\(^3\) However, from our experiments the estimated $g^* \mu_B < 0.2$, which is very low for spin splitting. In addition, although the resistance decreases in a parallel field, the $R_{\text{max}}$ value does not change by an order of magnitude. This behavior in $B$ is consistent with the layer-antiferromagnetic state being the ground state of the studied bilayer sample.\(^8\)\(^,\)\(^1\)\(^6\)\(^,\)\(^2\)\(^2\) Since in this state the top and bottom layers host spins with opposite orientations, their interaction with the applied $B$ cannot be described as a simple Zeeman splitting. Our results also open an additional question: What is the role of exchange energy and level broadening $\Gamma$ in the LAF state? Naively, the scaling of $g^* \mu_B$ with $B_n$ can be understood from their dependence on the level broadening $\Gamma$. The $\Gamma$ value scales with $\sqrt{B_n}$, meaning that for bigger $B_n$ a smaller $\Gamma$ is needed to observe overlapping of the levels. In reality the situation can be much more complicated, including possible exchange mechanisms that we do not understand yet. This is also supported by the fact that the ground-state gap $\Delta$ depends on $B_n$ as well.

Based on these results we suggest a possible scenario of symmetry breaking in high-quality bilayer graphene [Figs. 2(e) and 3(c)]. The first splitting is caused by valleys and results in the observed transport gap. Application of a magnetic field induces spin splitting of both $K$ and $K'$ levels. When $B$ is high enough then the energy of the spin-up level from $K$ will start approaching the spin-down level from $K'$. The overlapping of the levels will cause a decrease in the resistance at the charge neutrality point. Since we do observe a transport gap in our sample, we exclude a nematic phase transition. In addition to this, the response of the sample in tilted $B$ fits the LAF state. The cause of the valley splitting can be a combination of two effects: electron-electron interaction (which determines the $B$ field behavior of the middle resistance maximum) and a contamination of the sample surface with charged impurities...
which breaks inversion symmetry (via the introduction of an electrical field). 21

V. CONCLUSIONS

We report a transport gap of 3 meV in suspended bilayer graphene at 4.2 K, which increases with decreasing temperature. The sequence of appearance of the QHE plateaus at the filling factor $\nu = 2$ followed by $\nu = 1$ supports the suggestion that the observed gap is caused by symmetry breaking. Measurements in a tilted magnetic field indicate that the resistance at the CNP shows a weak linear decrease with increase in the total magnetic field. Based on this we propose a possible scenario for the symmetry breaking in the investigated bilayer graphene: spontaneous valley splitting at zero magnetic field followed by the splitting of spins originating from different valleys with increase of $B$. The gap value and weak response of the sample to applied magnetic field correspond to the predicted spin-polarized layer-antiferromagnetic state as the ground state of the investigated sample. The observed non-trivial dependence of the gap value on the normal component of $B$ suggests possible exchange mechanisms in the system.

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APPENDIX

In order to minimize self-heating in graphene at the high-resistance CNP we used the following scheme (Fig. 5). An ac source maintained a fixed voltage amplitude of 45 mV (1.87 Hz frequency) across the sample in series with a 45 MΩ resistor. The current through the sample is monitored by the lock-in 1, whose output $U_1$ is proportional to the current flowing in the circuit ($U_1 = I \times 1 \, \Omega$). Simultaneously, the four-probe voltage across the sample ($U_2$) is phase detected by another lock-in 2 connected through the preamplifier and having an input resistance up to 100 MΩ. Then the resistance of the sample is determined by $R = 1 \, \Omega \times U_2/U_1$. The power dissipating in the sample is $P = U_2^2/R$. Therefore, assuming that the maximum $U_2$ is already reached ($\approx 10$ mV), with increase of $R$ the dissipation in the sample will decrease.

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