GRAPHENE

Charges driving under the influence

An investigation of Coulomb drag in graphene integrated into a stacked heterostructure unveils unexpected electron–hole symmetry-breaking in two-dimensional electronic crystals.

Vincent Bouchiat

Suppose you live in a noisy multi-storey building. When your neighbours upstairs party at night, it is highly likely your agitation will be directly related to the excitement overhead. A similar remote influence can occur for moving charges in electronic systems. Imagine two stacked conductors separated by a thin and electrically insulating buffer layer. The buffer is thick enough that no tunnelling effects occur, but still so thin that charge carriers within a given layer can feel any charge fluctuations in the other. An electrical current passing through the active layer can then influence the charge carriers within the passive layer by a frictional effect associated with Coulomb interactions. This is 'Coulomb drag'. Charges of similar polarity acquire opposite momentum, and electrons and holes couple to form so-called excitons, which can follow the drive direction. This bilayer system acts as a sort of one-to-one electrical transformer[1] that operates down to zero frequency. Roman Gorbachev and his colleagues now report in *Nature Physics* an experimental demonstration of Coulomb drag in graphene–boron nitride heterostructures and find a number of novel features[2].

Pogrebinsky predicted Coulomb drag would occur in multi-layered semiconductors 35 years ago[3]. It was first observed in 1989 using gallium arsenide heterostructures[4] by measuring the open-circuit voltage induced in the passive layer when a current is driven in the active one. The effect has since become a valuable tool for studying the interactions between charge carriers in many low-dimensional systems. More recently, Coulomb drag has been explored both theoretically[5] and then experimentally[6] in graphene. Such an atomically-thin, two-dimensional gas of high-mobility fermions is an ideal system for studying interlayer charge interactions, which are known to play a crucial role in scattering in graphene[7]. It could also lead to new effects such as the condensation of the remotely interacting excitons into a superfluid state[8,9].

Part of the novelty of the work by Gorbachev *et al.* is the innovative fabrication techniques they used. They obtained their samples[10] by repeatedly stacking hexagonal boron nitride (h-BN) and exfoliated graphene flakes on top of each other using micromanipulation, stamping and careful annealing of the sandwich (Fig. 1a). Hexagonal boron nitride is a flat, high-bandgap semiconductor; its two-dimensional crystalline structure almost perfectly matches that of graphene. Gorbachev and his co-workers used h-BN thin-films both as the insulating spacing material between the double graphene layers and also as the substrate and the capping layer of the heterostructure. Thus, h-BN acted as a gate dielectric and also embedded the electronic system in an environment known to preserve the high electronic mobility of both graphene layers[11]; a feature lacking in the seminal experiments[8] on Coulomb drag in graphene.

Beyond optimizing the graphene mobility and ensuring that the two graphene layers were parallel, exfoliated layers of h-BN also enabled control of the spacing between the graphene sheets from about 12 nm down to 1 nm (they could have gone even thinner, down to a single boron-nitride atomic layer, but in this case tunnelling through the spacer becomes a parasitic effect). As expected, the net drag-current magnitude and direction were linked to the sign and density of charge carriers in the active layer, but also to the charge imbalance in the passive layer; both of these conditions could be precisely tuned independently using the top and bottom gates.

An intriguing regime arises, however, when the spacer reaches its lower limit. In this case, the distance between the layers is much smaller than the characteristic separation of the carriers in graphene. In this regime of strong coupling between remote carriers, one would expect the Coulomb drag to vanish when both graphene layers are made neutral (in the absence of any magnetic field) for symmetry reasons. The authors, however, observe the exact opposite: a large and positive Coulomb drag was measured in all strongly coupled samples at zero doping, whereas a sharp inversion of the drag was seen when a moderate magnetic field was applied. Moreover, in this strong limit, charge–charge interactions across layers were so large that mesoscopic fluctuations, related to charge interference, did not obscure the drag unless the device was cooled below 40 K.

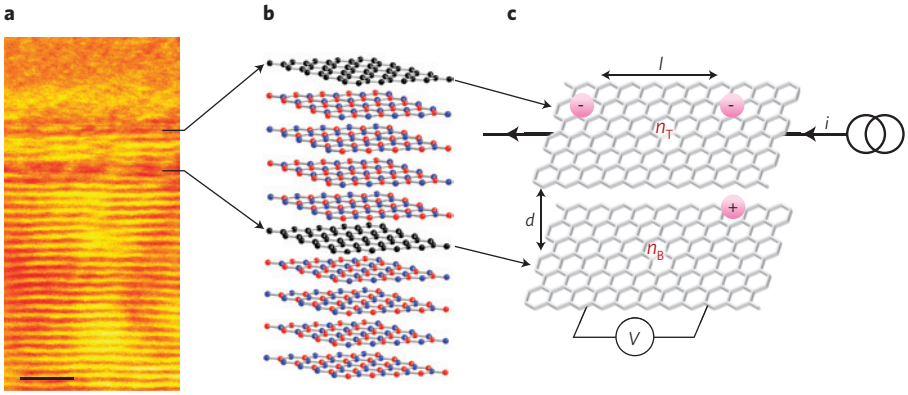

Figure 1 | Graphene–boron nitride heterostructures. **a**, A high-resolution scanning transmission electron microscopy image of the nearly perfect stacking of graphene over h-BN. The scale bar is 2 nm long. **b**, The atomic-layer sequence of the heterostructure. The carbon, boron and nitrogen atoms are represented as black, blue and red respectively. **c**, Schematic of the Coulomb drag experiment in graphene. The voltage, *V*, across the passive bottom layer is measured as a current, *i*, is passed through the top layer. The two stacked graphene layers act as atomically thin electrically conducting plates in which the sign and density of charge carriers (n_T and n_B respectively) can be independently tuned with gate voltages. The control of the boron nitride thickness *d* down to 1 nm allows investigation of the strong-coupling limit, where $d \ll l$, the characteristic distance between charges. Parts **a** and **b** reproduced with permission from ref. 10 © 2012 NPG.

Several recent theoretical works have attempted to provide an explanation for this charge symmetry breaking and the strong Coulomb drag found in proximal coupled neutral bilayers[12,13], but the one supported by Gorbachev *et al.* seems convincing as well. It relies on a specific property of graphene whereby the coherence of charge transport near charge neutrality is limited by a rough landscape of electron and hole puddles induced either by interfacial charge disorder[14,15] or by mechanical strain. When the spacing between layers becomes small, mutual polarization effects lead to hole puddles in one layer to be predominantly aligned on top of electron puddles of the other layer and *vice versa*. Such an anti-correlation favours electron–hole interaction that gives rise to the observed positive drag. These puddles are likely to generate other unusual effects in double layers, such as the observed strong reversal of drag voltage on application of a moderate magnetic field.

This experiment marks the emergence of a new class of hybrid devices obtained by stacking two-dimensional crystals and exploiting the richness of 'flat' conductors. Further refinements to the stacking technique, such as intercalating other types of 2D crystals or controlling the relative lattice orientation of the stacked layers, could make this method an original way of producing artificial heterostructures that are beyond even more sophisticated techniques such as molecular-beam epitaxy in an ultrahigh-vacuum environment. ❐

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QUANTUM SPIN LIQUIDS

Tell-tale topology

Quantum spin liquids have long eluded detection, despite nearly forty years of investigation. Now, a topological property unique to the quantum-spin-liquid state has emerged as a viable method of detection.

Steven R. White

How can you identify something when you only know what it is not? This question has puzzled many condensed-matter physicists trying to find and characterize quantum spin liquids (QSLs)[1]. But now, writing in *Nature Physics*, Hong-Chen Jiang and colleagues[2] have succeeded in using an idea from quantum-information theory to identify a QSL in a simple, realistic model system.

At low enough temperature, almost all solids containing interacting local magnetic moments order in some fashion, becoming ferromagnets or antiferromagnets, for example. This ordering is used to classify phases of matter, and almost always results in clear experimental signatures: in a crystal, for example, sharp peaks in X-ray diffraction result from the broken translational symmetry associated with crystalline order. QSLs, by definition, do not order, even in the limit of zero temperature — any tendency to do so is destroyed by quantum fluctuations. Thus, in addition to being rare, QSLs are hard to identify experimentally and difficult to classify, once found.

Topological order has long been hailed as a solution to this problem — a subtle property that provides both a framework for classifying some QSLs and possible means to detect them[3]. But topological order cannot be detected by local measurement, including any form of microscopy or scattering. (This immunity from detection also makes QSLs with topological order excellent candidates for holding qubits in quantum computers: the same property makes them almost immune to decoherence.) So how can topology enable QSL detection? For two-dimensional QSLs, the degeneracies of the states of the system are reflected in the topological genus of the surface on which the QSL lives.

It is easy to understand this relationship, at least in the case of a $\mathbb{Z}_2$ QSL, in terms of the earliest QSL — the resonating-valence-bond state first proposed by Philip Anderson in 1973[4]. Anderson's theory assumes that strong frustration of the magnetic interactions

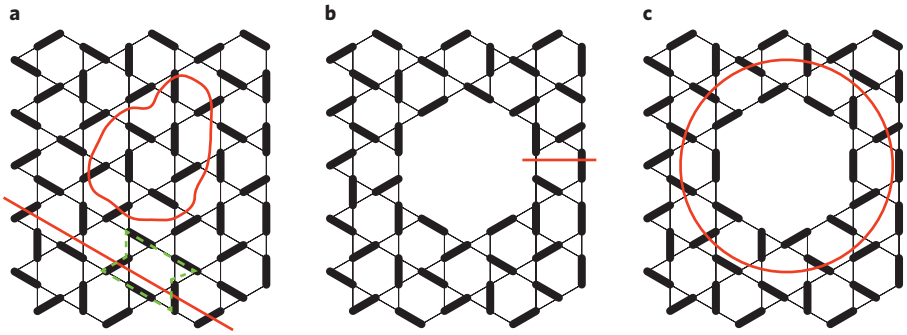

Figure 1 | Valence-bond configurations on a kagome lattice. a, For each red line, the parity is set by the number of bonds crossing the line. Short loops of bonds (in green) can resonate by shifting the bonds by one site along the line, leaving the associated parity unchanged. **b**,**c**, A surface with genus 1 has one topologically distinct line for which the parity can be either even or odd, leading to distinct topological sectors. The two valence-bond patterns in **b** and **c** have different parities for the line in **b**, but the same parity for the line in **c**. Both surfaces are topologically equivalent to an open-ended cylinder.