Due to unusual spinlike properties, electrons in graphene—despite scattering—exhibit a small increase in their conductivity.

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The pseudospin for the counterpropagating paths is then rotation is \( \pi \) anticlockwise path (red line), the angle of pseudospin rotates by an angle of \( -\pi \) in the graphene plane; for an antiparallel direction (black arrows), whereas scattering in the forwards or backwards direction (lower right) is allowed [15].

A long-range potential, due, for example, to charges trapped in the substrate, is not able to differentiate between neighboring atoms and thus it does not affect the pseudospin. Owing to the conservation of pseudospin, such a potential is unable to scatter chiral quasiparticles in the backwards direction [15], Fig. 1 (c), and this suppression of backscattering is associated with weak antilocalization of electrons in graphene [9]. As electrons propagate around closed paths, Fig. 1 (b), the pseudospin remains parallel to the momentum. For a clockwise path [blue line in Fig. 1 (b)], the pseudospin rotates by an angle of \(-\pi\) in the graphene plane; for an antitotal spin rotation is \( \pi \). The difference in the angle of rotation of the pseudospin for the counterpropagating paths is then \( 2\pi \). In analogy to the rotation of a spin-1/2 fermion, for which a rotation by \( 2\pi \) doesn’t return the wave function to its original state, net rotation of the pseudospin by \( 2\pi \) induces a phase difference of \( \pi \) between the counterpropagating paths. The returning electrons are now out of phase. This leads to destructive interference that suppresses backscattering, producing an increase of conductivity called weak antilocalization [2, 9]. Suppression of antilocalization by a perpendicular magnetic field will then be seen as positive magnetoresistance.

Graphene has two copies—known as valleys—of the gapless Dirac-like spectrum. In the absence of intervalley scattering, the interference of counterpropagating electrons from the same valley is sensitive to intravalley symmetry-breaking perturbations that affect the pseudospin. Counterpropagating electrons accumulate different phases, suppressing any (negative or positive) magnetoresistance effect. Intervally scattering, on the other hand, allows the counterpropagating electrons to occupy different valleys [16, 17]. As the two valleys have opposite chirality, the phases acquired by the electron and its time-reversed partner around a closed loop are equal, resulting in constructive interference and a restoration of the weak localization effect [10–13, 16, 17].

The tendency of symmetry-breaking perturbations, either intra- or intervalley, to destroy weak antilocalization suggests that it shows up only in relatively clean samples. Not only did Tikhonenko and coauthors [14] improve sample quality, they were also able to tune the ratio of the dephasing length to the symmetry-breaking length. They did this by (a) increasing temperature to reduce the dephasing length and (b) employing an applied gate voltage to decrease carrier density—thus increasing the intervalley scattering length. In this work they exploited behavior established by them in earlier experiments [13].

At low temperature, when the dephasing length exceeds the symmetry-breaking length, weak localization is observed, as in previous experiments [10–13]. However, by decreasing the ratio of the dephasing length to the symmetry-breaking length, it was possible to enter the regime when decoherence suppresses the influence of symmetry-breaking perturbations. In this case, Tikhonenko et al. observe positive magnetoresistance, a clear signature of weak antilocalization arising from phase-coherent paths short enough to preserve the chiral nature of counterpropagating electrons. Surprisingly, they find that weak antilocalization persists up to a relatively high temperature of around 200 K, owing to weak electron-phonon scattering in graphene, so that the main source of dephasing over a broad range of temperature remains electron-electron scattering.

The observation of weak antilocalization in graphene arises from a phase difference of \( \pi \) acquired by counterpropagating chiral electrons. One does not expect this in bilayer graphene where the chirality of low-energy quasiparticles is different [8, 18]. In bilayers, pseudospin is linked to the direction of momentum, but...
turns twice as quickly as momentum does. The acquired phase difference of counterpropagating chiral electrons would be a multiple of \( \pi \), resulting in weak localization [12, 16, 19]. So far, the story of weak localization in graphene involves the interplay of additional spinlike quantum numbers, related to lattice and valley degrees of freedom, but not electronic spin itself. Spin-orbit coupling may be an alternative way to induce weak antilocalization in graphene and bilayer graphene, as in conventional conductors [2, 3], but its observation is likely to be challenging in view of the predicted weakness [20] of the spin-orbit interaction in graphene.

References


About the Author

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Edward McCann received his Ph.D. from the University of Birmingham, UK, for theoretical work on mesoscopic fluctuations in disordered conductors. He was a postdoctoral researcher at the Max-Planck-Institut für Physik komplexer Systeme, Dresden, Germany, before moving to Lancaster University, UK, initially as an EPSRC Junior Research Fellow and later as a Lecturer in Condensed Matter Physics. His recent research has focused on the electronic properties of graphene, a single-atom-thick layer of carbon atoms, and of few-layer graphene films.