Signatures of Quantum Non-Locality in a Graphene Polarizer-Analyzer Experiment

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(Dated: May 19, 2020)

Mesoscopic conductance fluctuations are a characteristic signature of phase-coherent transport in small conductors, exhibiting universal character independent of system details. In this work, however, we demonstrate a pronounced breakdown of this universality, due to the interplay of local and non-local phenomena in phase-coherent transport. Our experiments are performed in a polarizer-analyzer geometry, in which an external spin-orbit coupling is induced in graphene by covering a portion of it with a micromagnet, and probing conductance at some distance from this polarizer. The non-local nature of this measurement is manifested through the appearance of giant conductance fluctuations, with amplitude much larger than $e^2/h$, providing a powerful demonstration of the manner in which transport may be strongly impacted by quantum non-locality.

As the size of conducting systems is reduced from the macroscopic realm, towards the fundamental scales that govern electron transport, their electrical behavior is dramatically modified [1]. In this mesoscopic regime, the wave-mechanical nature of carriers causes Drude conduction to be overwhelmed by quantum-interference phenomena, the most widely studied of which are weak localization [2] and universal conductance fluctuations [3, 4] (UCF). Guided by the framework of the Landauer formalism, a quantitative understanding of these effects was first achieved many decades ago. Most notably, the UCF are a specific signature of interference among the different Feynman paths for transmission through the system and exhibit a maximum amplitude of $e^2/h$, independent of system size or the degree of disorder [3]. This universal character has been confirmed in experiments performed on a variety of metals and semiconductors, long providing the perspective from which our understanding of mesoscopic transport is derived.

Another consequence of phase coherence in mesoscopic systems is quantum non-locality, in the presence of which efforts to probe the conductance of small systems are influenced by processes that arise outside of the region under direct study. Examples range from the non-local detection of Aharonov-Bohm oscillations in small metal rings [4], to Fano-resonance phenomenology in systems of coupled quantum point contacts [5, 6], and giant non-locality due to long-range flavor currents in graphene [7].

In this work, we provide a demonstration of the impact of quantum non-locality on mesoscopic transport in graphene, showing how it can be mixed with more conventional, local signatures to yield conductance characteristics without analog in purely local transport. To generate this interplay of local and non-local conduction, we perform our experiments in a polarizer-analyzer geometry. Here, an extrinsic spin-orbit coupling (SOC) is exerted [8–14] on the carriers of graphene, as they pass underneath a micromagnet that covers a portion of the ultrathin carbon sheet. The weak spin interactions inherent to native graphene [15–18] then allow this coupling to be preserved as carriers diffuse away from the magnetic element. Measurement of the conductance of the latter regions consequently develops a non-local character, which is strongly influenced by the SOC generated by the micromagnet. Evidence for this scenario is provided here by our observation that the normal weak-localization signature of graphene can be transformed into one consistent with antilocalization, a known signature of systems with strong SOC [2]. The quantum-coherent nature of the non-local signature is moreover confirmed by our finding that it causes giant fluctuations in the conductance, with an amplitude that can exceed the normal universal value [3] by well over an order of magnitude. This clear violation of the long-standing universality of mesoscopic physics provides a powerful demonstration of the manner in which transport in graphene may be strongly impacted by quantum non-locality.

An example of our polarizer-analyzer geometry is provided in Fig. 1(a). Here, a large graphene sheet is partially covered by a floating Co element (P), which plays the role of the polarizer and induces an effective SOC in the carbon sheet [8–14]. Insight into this process is provided by the results of electronic structure calculations (see Supplementary Material for more details), performed for the graphene/Co system. In Fig. 1(b) we show strong hybridization of the carbon $p_z$ atomic states with the Co orbitals, an interaction which modifies the bandstructure of the graphene layer, as shown in Fig. 1(c). Here we see how the hybridization opens inequivalent gaps, of around 40 meV or so, at the K and K' points. Also present is an induced spin splitting (indicated by the arrows) in both the conduction and valence bands; this feature represents
a direct signature of the induced SOC, and generates strong spin polarization (> 80%) of carriers near the Fermi level (see Supplementary Material). To probe these features, we perform a measurement of an uncovered section of graphene, located several microns away from the micromagnet. Evidence of non-locally induced SOC is then provided by the appearance of a highly characteristic zero-bias anomaly (ZBA, see Figs. 1(d) – 1(f)) in the differential conductance of this analyzer.

The fabrication, and basic electrical characterization, of the polarizer-analyzer devices is described in the Supplementary Material. While we focus here, for completeness, on the results obtained from a systematic study of one such device (P-A:1), our essential findings are confirmed in measurements of a second structure (P-A:2, see Supplementary Material). The four-probe differential-conductance ($g_d$) of these devices was measured by superimposing a small AC voltage upon a larger DC component ($V_d$), and in the analysis that follows we plot the variation of $g_d$ as a function of the portion of that voltage ($V_{eff}$) that is dropped [19] across the graphene itself. To explore the influence of carrier concentration on the phenomena discussed here, the voltage ($V_g$) applied to the Si substrate of the devices could be used to tune the electron or hole density. All measurements were made with the devices mounted in the vacuum chamber of a closed-cycle cryostat that, unless stated otherwise, was operated at a stable base temperature of 3 K.

The key aspects of our study are highlighted in Fig. 1(d), which shows measurements of the differential conductance of the same section of graphene, performed while either including the polarizer in the current path or excluding it. Black data correspond to the latter case, where the external (AC & DC) voltages are applied across probes 5 & 8 in Fig. 1(a), and the differential conductance is determined from the voltage drop across probes 6 & 7. In this configuration, $g_d$ starts from a local minimum at zero bias, following which it increases monotonically when a DC bias of either polarity is applied. Previously, we have shown that this behavior is a rather general signature of the quantum correction of weak localization, which reduces the conductance of graphene at low temperatures but which is quenched by the application of the DC voltage [19]. While the behavior observed in this configuration is therefore unremarkable, a very different situation arises when the polarizer is included in the current path. In this measurement, we again determine the differential conductance using voltage probes 6 & 7, but now apply the external (AC & DC) voltages across probes 1 & 8 to include $P$ in the current path (albeit several microns away from the section of graphene that we are probing). The form of the differential conductance is dramatically transformed in this geometry, exhibiting a pronounced peak near zero bias and mesoscopic fluctuations over a wider range of voltage. The reproducibility of these features is confirmed by the close overlap of the red and blue data points in the figure, which correspond to the results of experiments performed while sweeping the bias voltage in opposite directions. In contrast to localization, the zero-bias peak implies an enhancement of the conductance at zero-bias, behavior that is instead typical of the anti-localization that arises in systems with strong SOC [2].

With the polarizer included in the current path, the differential conductance exhibits a complex evolution with carrier concentration. This can be seen already in Figs. 1(d) – 1(f), which represent the results of measurements performed at different back-gate voltages. While a zero-bias peak is clearly present in Figs. 1(d) & 1(e), in Fig. 1(f) this feature has transformed into a doublet-like structure that is centered around zero-bias. This dramatic change in the form of the differential conductance is highly suggestive of the role of quantum fluctuations due to mesoscopic interference, a point that we
FIG. 2: (Color online) Gate-voltage dependent evolution of differential conductance for P-A:1, measured with $P$ excluded from the current path (external voltages: probes 5 & 8; $V_{\text{eff}}$: probes 6 & 7). The lower panels labeled (i) – (v) provide representative examples of the differential conductance at different gate voltages. (i) $g_{d\min} = 49.7$. (ii) $g_{d\min} = 50.4$. (iii) $g_{d\min} = 54.6$. (iv) $g_{d\min} = 62.3$. (v) $g_{d\min} = 61.5$.

Further demonstrate in Figs. 2 & 3. Here we plot the variation of differential conductance as a systematic function of carrier (hole) concentration ($p$), with the polarizer both excluded from (Fig. 2), and included in (Fig. 3), the current path. Prominent in the contour of Fig. 2 is a suppression of the conductance around zero bias; this feature is apparent, also, in the line plots of panels (i) – (v) and has previously been identified as a signature of weak localization [19]. The presence of the localization is consistent with the weak native SOC in graphene, and with the fact that the polarizer is excluded from the measurement path. While the localization gives rise to a conductance minimum at zero bias, both the width and amplitude of its bias-dependent lineshape show significant fluctuations. Such variations are well known from the study of weak localization in other mesoscopic systems, such as open quantum dots [20, 21], where they are known to reflect the non self-averaging nature of phase-coherent transport.

Turning now to the behavior exhibited when the polarizer is present in the current path, the contour of Fig. 3 reveals a complicated variation of differential conductance with carrier concentration. This is highlighted in the line plots of panels (i) – (v), in which $g_d$ either exhibits a local peak, or minimum, at zero bias, evolving between these forms in a non-trivial manner as the gate voltage is varied. While differential-conductance measurements have previously been used to explore the influence of carrier heating in graphene [22, 23], these experiments typically reveal a slow variation of $g_d$ as a function of the applied bias. The behavior that we observe in Fig. 3 is very different, with $g_d$ exhibiting rich fine structure and, in many cases, a strongly asymmetric response with regards to the polarity of the DC bias. We attribute this response to the influence of the polarizer, and to the capacity of the applied bias, over the narrow range considered here, to serve as a spectroscopic probe [19] (rather than a source of heating) of the hybrid graphene/magnetic system.

The pronounced conductance changes that we observe when varying carrier concentration (Figs. 1(d) – 1(f), Fig. 3) demonstrate the capacity of the polarizer to strongly modify quantum transport in graphene, even in regions some distance (several microns) away from the source of the induced SOC. The presence of the polarizer in the current path causes the conductance of these regions to be governed by a mixture of local and non-local considerations, a characteristic that leads to the observation of unusual mesoscopic phenomena. Perhaps the most significant manifestation of this is provided by the observation of giant conductance fluctuations, with an amplitude that significantly exceeds that expected for UCF. This phenomenon is demonstrated in Fig. 4(a), the main panel of which plots the variation of the zero-bias conductance ($g_d(V_d = 0)$) as a function of $p$, with and without the polarizer included in the circuit. While reproducible fluctuations are apparent in both types of measurement, with the polarizer absent (black and gray plus symbols) the characteristic amplitude of these features does not vary systematically with gate voltage, remaining close instead to $e^2/h$; such behavior is consistent with that expected from the canonical the-
The difference in the zero-bias conductance \( \delta g_d(V_d = 0) \equiv g_d(0, \mathcal{P} \text{ present}) - g_d(0, \mathcal{P} \text{ absent}) \), determined from the two sets of measurement in the main panel.

The temperature \((T)\) dependence of the ZBA is demonstrated in Fig. 4(b), the upper panel of which is a color contour showing the variation of differential conductance with temperature and bias, measured in the polarizer geometry. The line plots (labeled (i) – (iv)) that appear below the contour represent the results of measurements at the four temperatures identified in that panel. According to these data, we see that the ZBA is largely unchanged up to \( \sim 15 \text{ K} \), a value that compares well to the typical width \((1 - 2 \text{ mV})\) of this feature. With further increase of temperature beyond this scale, the zero-bias peak begins to weaken (see panel (iii)) and ultimately washes out completely around 40 K. By 45 K (panel (iv)), the original peak is now replaced by a clear dip around zero bias, a feature that is very similar to that seen (panel (v)) when the polarizer is excluded from the circuit. The dip has previously been discussed in terms of the influence of weak localization, which suppresses the conductance at zero bias but which is quenched itself by the application of non-zero bias [19]. In other words, the zero-bias peak that is suggestive of SOC-induced weak anti-localization at low temperatures, is replaced at higher temperatures with a localization feature. The latter washes out itself with further increase of temperature, somewhere in the range of 50 – 70 K.

Our experimental observations collectively point to the ability of the magnetic element to exert significant non-local influence on quantum transport. With this element included in the current path, measurements performed on uncovered portions of the graphene, remote from the polarizer, exhibit a ZBA in their differential conductance. This peak-like feature is consistent with weak anti-localization [24], arising from the SOC introduced by the Co layer (Fig. 1(c)). As the carrier concentration is varied, the phase-coherent nature of low-temperature transport leads to significant fluctuations (Fig. 3) in the anti-localization signature (much as is the case for the localization feature, see [20] & Fig. 2), and it is these variations that are responsible for the pronounced conductance oscillations apparent in Fig. 4(a). To understand the strongly non-universal character of these fluctuations, it is worth recalling that the original theory for UCF [3] is essentially a local one, appropriate to two-probe measurement configurations that cut-off non-local contributions to transport [25]. By construction, this theory therefore does not account for the non-local phenomena that arise here.

Non-local measurements have been widely used to study details of spin transport in graphene, most notably via the spin-Hall effect (see [18] for details). Such experiments make use a very different non-local geometry to that employed here, with current being passed through one region and voltage being measured across another. In such experiments, however, the source of the induced SOC is usually present throughout the graphene layer, which is very different to the situation in the polarizer-analyzer geometry that we utilize. In our case, SOC is induced locally by the polarizer, and the non-

\[ \text{FIG. 4}: \quad \text{(Color online) (a) Variation of the zero-bias conductance} \quad (g_d(V_d = 0)) \quad \text{of P-A:1 as a function of hole concentration. Filled symbols (crosses) correspond to measurements performed with the polarizer included in (excluded from) the current path. Red (black) data points correspond to measurements performed while sweeping the bias voltage up; down-sweep data are indicated in blue (gray). The inset plots the difference in the zero-bias conductance} \quad (\delta g_d(V_d = 0)), \quad \text{from measurements performed with and without the polarizer present. Red (blue) data were obtained by subtracting the sweep-up (sweep-down) measurements of the main panel. (b) The upper panel is a color contour showing the variation of \( g_d \) as a function of the effective bias and temperature. Line plots (i) – (iv) correspond to the temperatures (15-, 25-, 35- and 45-K, respectively) denoted by white dotted lines in the contour. Vertical scale is the same in all cases. Panel (v) shows, for comparison, a typical differential-conductance trace obtained (at 3 K) with the polarizer excluded from the current path.} \]
local character of our experiment then arises from weak spin dephasing of the polarized carriers [15–18] once they are injected into the bare graphene.

The influence of temperature on the zero-bias peak is demonstrated in Fig. 4(b). In prior studies of the quantum corrections (weak localization and electron interactions) in native graphene, we have found that these features become most prominent below 50 K [19, 26], in agreement with the scale on which the peak is suppressed in Fig. 4(b). The suggestion, therefore, is that the behavior in Fig. 4(b) is driven primarily by the influence of temperature on the phase coherence required [27] for the (anti-) localization, rather than by thermal smearing of the spin-orbit interaction.

In conclusion, we have demonstrated a pronounced breakdown of the universal character of mesoscopic conduction in graphene, in experiments performed in a polarizer-analyzer geometry. This setup was used to exert an external SO coupling on carriers in the graphene, which was then detected non-locally, in the differential conductance, via the transformation of the weak-localization signature into one characteristic of anti-localization. Also present were giant fluctuations in the zero-bias conductance, as a function of the carrier concentration, with an amplitude that reached values much larger than the zero-bias conductance, as a function of the carrier concentration, with an amplitude that reached values much larger than $e^2/h$. This clear violation of the normal universal character of mesoscopic conduction was attributed to the strong mixing of local and non-local signatures in phase-coherent transport.

The experimental work was performed at Buffalo and was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering, under Award DE-FG02-04ER46180. The theoretical work was supported by the National Science Foundation (NSF), through Grant No. NSF-ECCS 1740136, as well as by the nCORE, a wholly owned subsidiary of the Semiconductor Research Corporation (SRC), through the Center on Antiferromagnetic Magneto-electric Memory and Logic task ID 2760.001 and 2760.002. JF collaborated on the interpretation of the experimental results and acknowledges support from the Swedish Research Council (Vetenskapsrådet).

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