# Quenching of the quantum Hall effect in graphene with scrolled edges

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Compared to graphene deposited on substrate, suspended samples show exceptionally high charge mobility, which can even be orders of magnitude larger. Surprisingly enough, the integer quantum Hall effect is easily observable in deposited graphene even at room temperature, while its experimental demonstration for suspended samples has been difficult to achieve.

The typical mechanism that causes the deviation from the integer quantum Hall effect is the crosslinking of the chiral channels due to strong disorder, as impurities [1] or elastic strains [2]. However, suspended graphene has very low disorder and the absence of substrate preserves it from remote Coulomb impurities. Moreover, the continuous progress of the experimental techniques has allowed the fabrication of samples with size up to several microns, for which such sources of scattering can be generally ruled out. Another factor that might play a role is that of *hot spots* [1] for samples in the four-terminal configuration, where the unfortunate placement of the contacts affects the potential felt by the probes, thus reducing of the Hall voltage. Again, the large size of the current samples makes this issue irrelevant in most cases. The only other known mechanism of disrupting the quantum Hall effect is edge reconstruction, which can generate counter-propagating channels at the same edge. However, previously discussed edge reconstructions [3,4] are not unique to suspended graphene and originate from a generic tendency of a 2D metal to have an irregular density near the edge.

In this contribution, we propose an alternative explanation for the difficult observation of the quantum Hall effect in suspended graphene. Our analysis starts from the matter-of-fact that suspended graphene often has scrolled edges, as commonly observed experimentally [5]. In general, scrolling is most common in four-terminal devices as the graphene samples are suspended underneath the contacts and these regions are loose and can easily scroll.

In the region of the scrolls, the component of the magnetic field perpendicular to the graphene surface oscillates and changes its sign due the curvature. This translates into an effective almost vanishing magnetic field nearby the edge regions, and it turns the scrolls into conventional non-chiral conductors, where backscattering can be easily induced by a minimum amount of disorder. The current in these regions flows in parallel with the current in the flat part of the sample, thus leading to the quenching of the quantum Hall effect.

We support this scenario by simulating electronic structure and transport in large graphene nanoribbons with scrolled edges under magnetic fields up to 20 T [6], fig.1. From the calculation of the energy bands, fig.2, we clearly demonstrate the rise of non-chiral edge states, with the typical Dirac-like dispersion, which coexist with the usual Landau states in the bulk region. The simulations of electronic transport based on the Green function formalism, figs.3 and 4, show the detrimental impact that disorder has on the transmission of the non-chiral channels and, consequently, on the global conductance quantization. Note that strain is not supposed to play any role, because either it is absent (scrolls form to release strain) or it is so inhomogeneous that the effect of the generated pseudomagnetic fields vanishes.

Our results provide a consistent and meaningful interpretation of the possible suppression of quantum Hall regime in suspended graphene and rationalize its complicate observation.

## References

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## Figures

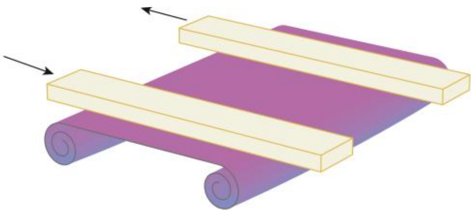
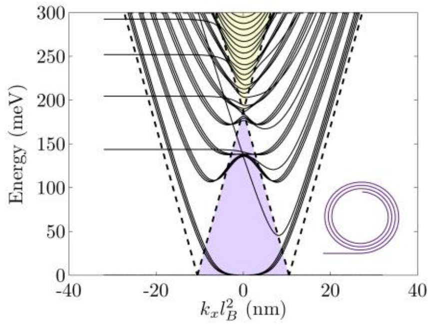


*Figure 1. Configuration of the system under study in which a suspended graphene ribbon has scrolled edges. The ribbon is attached to the source and drain contacts. The arrows indicate the external current.*

*Figure 2. Band structure of a scroll with the inner and outer radii $r_i$=9.91 and $r_o$=11.1 nm, respectively, at B=20T computed from the Dirac equation with the zigzag edge boundary condition. The dashed lines are defined by equations $E=\sim v(k_x \pm l_B^{-2} r_o)$, where v is the velocity of electrons at the charge neutrality point of 2D graphene, $l_B$ is the magnetic length and $k_x$ is the component of the wave vector along the scroll axis. The cross-section of the system is sketched in the bottom right corner of the figure. For clarity, the flat region (full width 100 nm) is truncated and the layer separation inside the scroll is enlarged.*





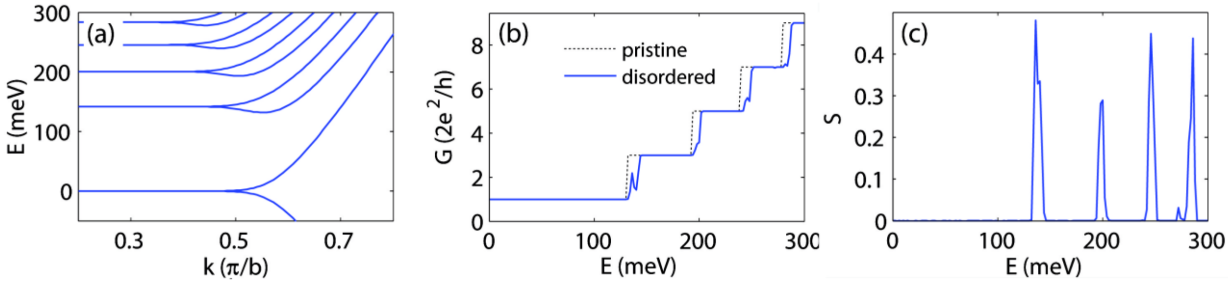




*Figure 3. (a) Band structure of a flat 100 nm wide armchair nanoribbon under a perpendicular magnetic field B=20T. (b) Conductance as a function of the electron energy for pristine and disordered ribbons. Disorder extends over a section of length 210 nm and includes a short-range component generated by randomly varying the on-site energies within the range [−25,25] meV, and a finite-range component given by 50 Gaussians impurities with range $\xi$ =1 nm and strengths in the range [−500,500] meV. Thanks to the chirality of the edge channels, the integer quantum Hall effect is robust against disorder and the conductance quantization is observed. (c) Corresponding shot-noise, which indicates the perfect transmission except around the van Hove singularities.*

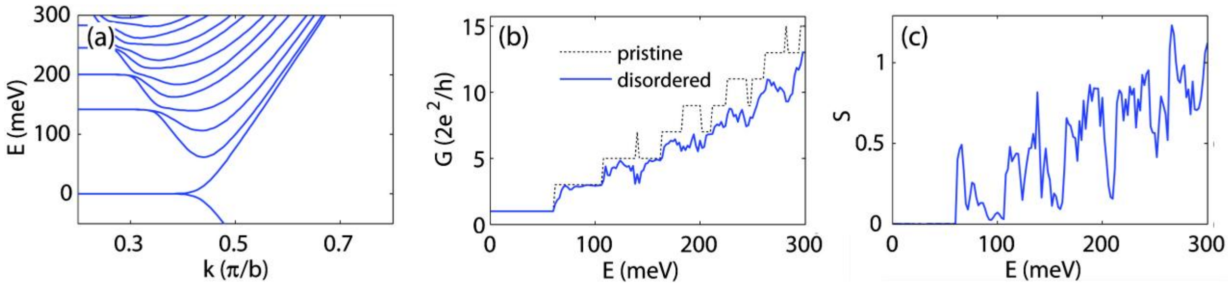




*Figure 4. (a) Band structure of a100 nm wide armchair nanoribbon under a perpendicular magnetic field B=20T in the presence of nanoscrolls of arc length 15 nm and two full turns. (b) Conductance as a function of the electron energy for pristine (black dashed lines) and disordered (blue solid lines).The quantization is clearly destroyed in the whole energy spectrum, with the exception of the region of the first plateau, where non-chiral channels are absent. (c) Corresponding shot-noise, which confirms the strong enhancement of backscattering.*