# Electron-Hole Bilayers in Twisted Bilayer Graphene: Quantum Spin Hall and Fractional Quantum Hall States

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## Introduction

Twisted bilayer graphene (TwBLG) is the ultimate limit of a bilayer 2DEG, where two graphene layers are stacked with an interlayer distance of only 0.34nm. The interlayer tunnel coupling can be continuously tuned by twisting the two layers, leading to different physics in the small and large twist angle limits. For large twist angles and at moderate magnetic fields, it is possible to realize quantum spin Hall states in TwBLG by doping to form an electron-hole bilayer at moderate magnetic fields. In this regime, counter-propagating edge modes exist on different layers, and the occupation of edge modes on each layer can be independently controlled. At higher magnetic fields, electron-electron interactions fully break the graphene spin-valley symmetries, and fractional quantum Hall states are formed as well.

## Experimental

We studied electronic transport in our dual gated TwBLG devices in a helium-3 cryostat at Magnet Cell 9. The samples were cooled to 300 mK, and only perpendicular magnetic fields were applied. The occupation of edge modes on each layer was independently controlled using dual gates. The onset of fractional quantum hall states was observed at a magnetic field of ~15T. By doping one layer to an integer filling factor and simultaneously doping the other layer to a fractional filling factor, we measured the two terminal conductance resulting from the interactions between integer and fractional quantum Hall edge states. Figure 1a shows the two terminal conductance at 31T in the hole-hole bilayer regime, where each layer is independently doped from 0 to -1. Figure 1b shows a similar measurement in the hole-electron bilayer regime, with one layer at filling factor -2, and the other layer doped to filling factors from 0 to +2.

## Results and Discussion

Our measurements indicate that the total conductance is given by the sum of the upper layer and lower layer filling factors, even when the filling factors are of opposite sign. This indicates that edge states can backscatter into each other via interlayer tunneling, resulting in fractional reductions in the total conductance.

## Conclusions

We have measured the first fractional quantum Hall effect in twisted bilayer graphene, and the results are in line with the behavior of the integer plateaus. Our results show a promising path forward for realizing a fractional quantum spin Hall state with improved device geometries.

## Acknowledgements

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## References

[1] Sanchez-Yamagishi, J.D., *et al.*, Phys. Rev. Lett., **108**, 076601 (2012).

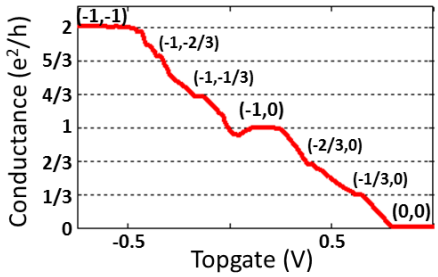


**Fig.1a Fractional quantum Hall effect in twisted bilayer graphene.** Two terminal conductance of TwBLG for hole-doping in both layers. Numbers indicate filling factors for the bottom and top layers, respectively.

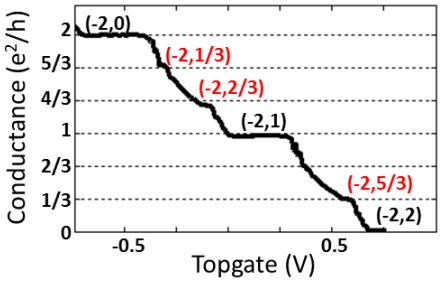


**Fig.1b Fractional plateaus due to electron-hole bilayers.** Two terminal conductance of TwBLG with one layer doped to filling factor -2, and the other layer doped to filling factors from 0 to 2. Fractional reductions in conductance were observed in the hole-electron bilayer regime.