Peer Review File

Manuscript Title: Fractional Quantum Anomalous Hall Effect in Multilayer Graphene

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

The paper presents the discovery of fractional quantum anomalous Hall effect (FQAHE) in graphene-based superlattices at zero magnetic fields. Very recently, FQAHE has been observed in transition-metal dichalcogenides (TMDs) but since graphene offers a platform of potentially superior quality it is an important achievement to show that FQAHE states can be stabilized in it. Furthermore, more extensive FQAHE i.e., many more fractions, have been reported here compared to what has been seen in the TMDs. Nevertheless, fundamentally, I do not think the work reported in this manuscript is sufficiently novel, original, or significant to warrant publication in Nature. This work is important and should be published. A journal such as Nat. Comm. or perhaps Nat. Phys. is more appropriate for it.

Like in the TMDs, all the fractions that have been observed are likely integer quantum Hall (IQH) states of composite fermions (CFs) so although many more states have been seen in this work they all fall in the same family of Jain sequence (this is more a testament to the quality of the sample as opposed to uncovering any fundamentally novel physics as compared to TMDs). Moreover, this was theoretically suggested and is somewhat expected since the QH physics of flat bands is analogous to the fractional quantum Hall (FQH) physics that occurs in the lowest Landau level (LLL) where it is well-known that CF states are stabilized.
An observation of non-Abelian states, that is talked about in the abstract as well as other places in the manuscript, and has not yet been seen in the TMDs, will raise the level of the work to that which can be published in Nature. At the moment it is unclear how that would materialize since non-Abelian states in LLs are usually stabilized only in higher LLs (such as at filling 5/2) or in wide quantum wells (which requires a strong modification of the interaction from its bare Coulomb form) in the LLL.

Another potentially interesting avenue that can result in something different from usual LL FQH physics is if interaction in a single Chern 2 or higher band stabilizes an FQAH state. Can this scenario be engineered in van Der Waals structures based on graphene?

Minor comment: define the acronym CFL at the first instance of its use.

Referee #2 (Remarks to the Author):

Lu et al reported on the observation of fractional Chern insulator states in a rhombohedrally stacked 5L graphene aligned with BN. The authors studied R_xx and R_xy in a multi-terminal device and examined their temperature, B, and D-field dependences. The main results of the work are: 1. The observation of a quantized quantum anomalous Hall effect with C=1. 2. The observation of a series of fractional Chern insulator states following the Jain sequence surrounding filling factor 1/2, up to 4/9. For the most part, I find the results to be technically sound and the manuscript is clearly written. The fractional Chern insulator states look credible to me and are of higher quality that previously observed in twisted MoTe2 devices. As the authors mentioned, graphene systems are potentially cleaner and easier to contact electrically. So this work opens the door to many future studies of the fractional Chern insulator, which has potential technological impact on topological quantum computing. As far as I know, only the authors worked on the 5L/h-BN structure. Based on the materials novelty, timeliness of the observation and its potential impact, I think this work meets the publication criteria of Nature. I have the following questions and comments for the authors to consider before publication.

1. Although Rxy takes the value of 2h/e^2 at filling factor ½, I don't see any evidence of quantization in the data. To claim quantization requires Rxy to develop a plateau over a range of filling factors. No such plateau is present in the data. In existing theories of the FQHE, filling factor ½ is NOT a fractional quantum Hall state.
2. In Figs. 2b, c and Fig. 3a-c, the data shown are acquired at a small magnetic field of 0.1 T. While the underlying physics of the fractional Chern insulator remains the same as zero field, it is more convincing to show the data at B=0. I understand that a small field may improve the appearance of the fractional states. I think the readers would appreciate seeing the equivalent of Fig. 3c at B=0 regardless of how pretty it looks.
3. The authors commented on the width of the C=integer resistance plateaus by saying "The width of the IQAHE plateau corresponds to a ~10 times smaller charge density than that in t-MoTe210,12. This could be due to a combination of the smaller gap size of the IQAHE (possibly due to the 5-times smaller electron density in the topological flat band, and as implied by the lower temperature threshold of quantized Rxy) and a smaller charge/moiré-period inhomogeneity in our graphene-based moiré superlattice than in the t-MoTe2 moiré superlattice." I am not sure that I follow what the authors meant. First of all, the width of the plateau at C=1 seems to be very different than that of the C=2,3… Secondly, the width of a QH resistance plateau strongly depends on sample disorder. Even if two samples have the same Landau level gaps, they may show plateaus of different width. Authors please clarify.
4. In Fig. 3d-j, some R_xx peaks appear to not line up with the abrupt changes in R_xy. For example, in Fig. 3f, R_xy changes abruptly at -100 mT but there is no corresponding peak in R_xx. This is puzzling. Authors please check the traces carefully.
5. In my view, Fig. 3c shows the strongest evidence of the fractional Chern insulator states, where R_xy exhibits developing plateaus and shoulders at the expected filling factors, accompanied by R_xx minima at the same filling factors in a density sweep. However none of them looks to be quantized to me, by the standards of the quantum Hall community. In addition, Figs. 3d-j do not constitute evidence of quantization, despite the fact that R_xy exhibits the correct values and these values remain a constant in a window of B. If the authors were to conduct the same measurement at filling factor 0.55, which is not expected to be a fractional state at all, I believe the authors would find a

hysteresis loop similar to those shown in Figs. 3d-j. Surely one cannot conclude that filling factor 0.55 exhibits quantization based on this result? I think the authors also used the same criteria to conclude that filling factor ½ is "quantized" in Fig. 4. Well, if the authors conducted similar measurements at filling factor 0.52, would they also obtain similar looking plots? As I mentioned in the first bullet point, for the quantum hall community, "quantization" means having a Chern number and exhibit the corresponding experimental signatures (quantized R_xy plateau, R_xx minimum, quantized two-terminal conductance, etc) over a range of filling factors. It doesn't just mean a constant value. I suggest that the authors go through the manuscript carefully to evaluate every situation where the word quantized is used. Statement such as "The quantization and magnetic hysteresis of Rxy are consistent with a FQAH state at v = ½" is incorrect. However the data in Fig. 4c does suggest to me that filling factor ½ undergoes phase transitions.

6. In Figs. 3g and k, it is difficult for me to see any features along the dashed lines the authors drew, apart from the blue blob at 2/3. Even so, it is far from clear that the blue blob has a slope indicated by the dashed line. Can the authors work to improve these plots? I think line cuts are much more useful in this case to indicate a shift. In fact, the most prominent features in Figs. 3g and k are the two orange-colored "wings". What are those?

7. I suggest removing the fractions marking the value of R_xy throughout the manuscript. I find the notation of (nu, R_xy (in unit of h/e^2)) such as (2/5, 5/2), instead of simply noting the filling factor 2/5 to be confusing because 5/2, 3/2, 7/3 etc can be the filling factors of actual fractional quantum Hall states so this double notation is confusing to some readers.

8. References cited in the manuscript heavily lean towards more recent literature studying Moire or Moire-adjacent systems. For example, when the authors discuss rhombohedral graphene, only results from 2019 on are cited (41-47). Was rhombohedral graphene not studied and its key electronic properties underlying the later work unknown prior to 2019? I'd encourage the authors to dig a little deeper beyond the "latest hot stuff" in their referencing practices.

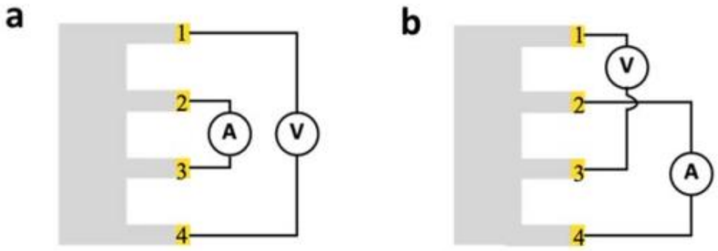
9. Please check the measurement configuration of R_xx shown in extended Fig. 1a. That looks unusual to me. Are current and voltage probes mislabeled?

Referee #3 (Remarks to the Author):

The current manuscript unveils, for the first time, the observation of the fractional quantum anomalous effect (FQAHE) in pentalayer graphene utilizing an hBN superlattice. While the FQ AHE has been successfully demonstrated in the t-MoTe2 system, its existence within a graphene-based system had not been established prior to this work. This manuscript asserts the identification of quantized Hall resistance values at specific filling factors: R_{xy} = $\frac{h}{e^2}, \frac{3h}{2e^2}, \frac{5h}{3e^2}, \frac{7h}{4e^2}, \frac{9h}{4e^2}, \frac{7h}{3e^2}, \frac{5h}{2e^2}$ for v = 1, 2/3, 3/5, 4/7, 4/9, 3/7 and 2/5 respectively, accompanied by dips in the longitudinal resistance Rxx. Additionally, it highlights a transition from a composite Fermi liquid to various other correlated states.

The discovery of the FQAHE in a graphene-based system is particularly intriguing, given that graphene serves as an ideal platform for potential exploration of non-abelian braiding in the future. I find the experimental findings within this work to be both fascinating and significant for the scientific community. However, I do harbor reservations regarding the current presentation of the manuscript.

My primary concern regarding this research pertains to the measurement methodology employed in this study. The measurement scheme described in extended data figure 1 appears quite confusing. In the method section, it says voltage bias scheme being used as following; "*longitudinal and Hall resistance Rxx and Rxy with an AC voltage bias 80 uV at a frequency at 17.77 Hz*." However, in order to accurately measure Rxx and Rxy, a 4-probe measurement is typically required. This involves the implementation of a constant current within the circuit and the subsequent measurement of longitudinal and transverse voltages. It's worth noting that a similar scheme has been utilized by this same research group in their prior works



Extended Data Figure 1. Illustration of the measurement scheme. a&b. *correspond to the circuit configuration of R_{xx} and R_{xy} measurements, respectively.*

https://doi.org/10.1038/s41586-023-06572-w].

Let's assume they have used the current biased scheme but not described properly in the manuscript. The scheme is shown in page 17 as shown above;

I believe a constant current is passed through the contacts 2 and 3 for the Rxx, and between 2 and 4 for the Rxy measurements, respectively. Unfortunately, the optical image of the two devices are not available in the paper. As can be seen from the above schematic figures that all the contacts are at one side of the device in contrast to the conventional Hall bar geometry being used to measure Rxx and Rxy in the literatures as well as by the same group [*Nat. Nanotechnol.* (2023). https://doi.org/10.1038/s41565-023-01520-1, *Nature* (2023). https://doi.org/10.1038/s41586-023-06572-w]. One of the main concern of above measurement scheme is that there is large entanglement between the Rxx and Rxy, and deconvolution using symmetrising Rxx, and anti-symmetrising Rxy are not ideal.

The raw data used to symmetrize Rxx, and anti-symmetrize Rxy are also not available in the manuscript. Further, how symmetrisation and anti-symmetrisation are performed not described properly in the manuscript. In the method section, it only says following; "*In Fig. 1c 384 and 2c we plotted (*Rxy *(0.1 T) -* Rxy *(-0.1 T))/2, while in 2e&f, 3b&c and 4a&c we plotted (*Rxy *(-0.1 T) –* Rxy *(0.1 T))/2 for the convenience of presentation*". However, it is not clear how the data are obtained for magnetic sweep measurements in Fig. 1a. 1b, Fig. 2d-j etc.

Now let's discuss the result obtained after the deconvolution from a non-ideal geometry used in the present manuscript. For the IQAHE, the Rxy plateau is robust with a finite Rxx ~ 50 ohm. However, my main concern is related to FQAHE, where the plateau like features are observed with large Rxx ~ 7-9 kOhm (Fig. 3c, Extended data Fig. 3a-f). Though, the dips are seen in Fig. 3c, but it does not represent the minimum resistance as can be seen that even at non plateau region, the resistance are with similar value or slightly smaller value.

The manuscript attempts to emphasize the benefits of employing multilayer (pentalayer) graphene over t-MoTe2, citing improved contacts, among other advantages. However, in Nature 622, 74–79 (2023), the observation of IQAHE demonstrates Rxx measurements less than ONE ohm, and FQAHE exhibits finite Rxx measurements less than 1 kOhm using the conventional Hall bar geometry. Additionally, it is evident from the Nature 622, 74–79 (2023) that both IQAHE and FQAHE exhibit significantly more robust characteristics compared to the current study. For instance, the IQAHE in t-MoTe2 remains resilient even up to 10K, highlighting its superior robustness.

Minor comments in line 146; "Solid (dashed) lines correspond to scanning B from positive (negative) values to positive (negative) values." I guess there are some mistakes.

Author Rebuttals to Initial Comments:

Responses to the referees

We sincerely thank the referees for taking the time to assess our manuscript and raising suggestions to improve it. We believe that this letter and the revised manuscript fully addressed their questions and comments. In the following, we respond in detail to the questions and comments that were raised one by one. Throughout this letter we used blue color for the questions by the referees and black color for our responses. Changes made in the revised manuscript are highlighted in yellow.

Referee #1 (Remarks to the Author):

The paper presents the discovery of fractional quantum anomalous Hall effect (FQAHE) in graphene-based superlattices at zero magnetic fields. Very recently, FQAHE has been observed in transition-metal dichalcogenides (TMDs) but since graphene offers a platform of potentially superior quality it is an important achievement to show that FQAHE states can be stabilized in it. Furthermore, more extensive FQAHE i.e., many more fractions, have been reported here compared to what has been seen in the TMDs.

Response 1

We thank the referee for carefully reading and summarizing the manuscript. In the following, we address the comments and questions in detail.

Nevertheless, fundamentally, I do not think the work reported in this manuscript is sufficiently novel, original, or significant to warrant publication in Nature. This work is important and should be published. A journal such as Nat. Comm. or perhaps Nat. Phys. is more appropriate for it.

Response 2

We do not agree with the referee's comment on the novelty, originality and significance of our work. The novelty and significance have been explicitly pointed out and appreciated by referees #2 and #3. Our work reports for the first time the experimental discovery of fractional quantum anomalous Hall in a graphene system. As we argue below, our discovery is novel, original and significant. Novelty: no prior theory predicted FQAHE in pentalayer graphene/hBN. This is very different from the case of t-MoTe2, in which the existence of FQAHE was theoretically proposed before the recent experimental observations by three groups. Originality: our group is the only one who has published results on rhombohedral pentalayer graphene. Significance: our work has already simulated enormous interest in the community. Within 1.5 months since it was posted to the arXiv, several leading theory groups, including Ashvin Vishwanath at Harvard and our colleague Senthil Todadri at MIT, have posted theoretical studies of FQAHE in our system, see (arXiv: 2311.03445, arXiv: 2311.04217, arXiv: 2311.05568).

Like in the TMDs, all the fractions that have been observed are likely integer quantum Hall (IQH) states of composite fermions (CFs) so although many more states have been seen in this work they all fall in the same family of Jain sequence (this is more a testament to the quality of the sample as opposed to uncovering any fundamentally novel physics as compared to TMDs). Moreover, this was theoretically suggested and is somewhat expected since the QH physics of flat bands is analogous to the fractional quantum Hall (FQH) physics that occurs in the lowest Landau level (LLL) where it is well-known that CF states are stabilized.

Response 3

We are not sure why the referee said 'this was theoretically suggested', but this statement is not true for our system. FQAHE in our material system, pentalayer graphene/hBN, was not suggested by any prior theoretical work as far as we can tell. Furthermore, all previous theoretical studies on related systems, 2-, 3-layer graphene/hBN, predicted Chern bands with high Chern numbers C=2 and 3 respectively, whereas our experiment revealed a quantum anomalous Hall state with Chern number 1. Indeed, a recent theory paper arXiv: 2311.05568 wrote '*the origin and the character of the Chern band in rhombohedral pentalayer graphene [42] has so far been a mystery*.'

Therefore, we believe our discovery of FQAHE, the first one in a graphene system, is not just a testament of the quality of materials, but also points out new directions to explore topology and fractionalization in 2D materials. For example, motivated by our experiment, recent theoretical studies have proposed a novel scenario of FQAHE coexisting with charge density wave order. Such a FQAH-crystal has no analog in the lowest Landau level. In addition, our experiment shows various phase transitions from CFL and FQAHE to other phases. The phase transition from FQAH state to a valley-polarized Fermi liquid is a new one that is absent from the t-$MoTe_2$ system and could not be described by any existing theory.

An observation of non-Abelian states, that is talked about in the abstract as well as other places in the manuscript, and has not yet been seen in the TMDs, will raise the level of the work to that which can be published in Nature. At the moment it is unclear how that would materialize since non-Abelian states in LLs are usually stabilized only in higher LLs (such as at filling 5/2) or in wide quantum wells (which requires a strong modification of the interaction from its bare Coulomb form) in the LLL.

Response 4

The observation of non-Abelian states will of course be very exciting. Indeed, we hope our work, together with recent works on t-$MoTe_2$, will provide a solid foundation for FQAHE and trigger wide interest from both the fractional quantum Hall and 2D materials communities to search for non-Abelian states at zero magnetic field.

Another potentially interesting avenue that can result in something different from usual LL FQH physics is if interaction in a single Chern 2 or higher band stabilizes an FQAH state. Can this scenario be engineered in van Der Waals structures based on graphene?

Response 5

We thank the referee for pointing out the possibility of searching for unusual FQAH states in Chern bands with a higher Chern number. In fact, there are two systems to be explored immediately for higher-Chern-number bands and more exotic FQAH states, following our current manuscript: 1. A C=2 Chern insulator has been observed in the rhombohedral trilayer graphene/hBN moiré superlattice (Chen et al., *Nature* **579**, 56–61 (2020)); 2. An integer quantum anomalous Hall state with C=5 has been observed in WS_2-proximitized rhombohedral pentalayer graphene (arXiv: 2310.17483). The former one, although has not shown quantized Hall resistance at zero magnetic field, should be re-checked with higher device quality and lower temperatures, given our results in this current manuscript. The latter one, which is observed by our group, hosts potential to show FQAHE if we introduce a moiré superlattice by aligning hBN on the opposite side of WS_2.

It would be exciting to study the possibility of realizing non-Abelian FQAH states in these systems, but such a prospect is beyond the scope of our current work. Given that this is the first observation of FQAHE in graphene-based systems, we believe it is a significant and firm step towards more exotic phases and worth reporting. Again, this significance has been pointed out by referees #2 and #3.

Minor comment: define the acronym CFL at the first instance of its use.

Response 6

We appreciate this suggestion and we have added a definition for CFL in the revised manuscript as suggested by this referee.

Referee #2 (Remarks to the Author):

Lu et al reported on the observation of fractional Chern insulator states in a rhombohedrally stacked 5L graphene aligned with BN. The authors studied R_xx and R_xy in a multi-terminal device and examined their temperature, B, and D-field dependences. The main results of the work are: 1. The observation of a quantized quantum anomalous Hall effect with C=1. 2. The observation of a series of fractional Chern insulator states following the Jain sequence surrounding filling factor 1/2, up to 4/9. For the most part, I find the results to be technically sound and the manuscript is clearly written. The fractional Chern insulator states look credible to me and are of higher quality that previously observed in twisted MoTe2 devices. As the authors mentioned, graphene systems are potentially cleaner and easier to contact electrically. So this work opens the door to many future studies of the fractional Chern insulator, which has potential technological impact on topological quantum computing. As far as I know, only the authors worked on the 5L/h-BN structure. Based on the materials novelty, timeliness of the observation and its potential impact, I think this work meets the publication criteria of Nature. I have the following questions and comments for the authors to consider before publication.

Response 7

We thank the referee for appreciating the quality and merits of our manuscript. We also appreciate the detailed comments/questions from this referee that have helped to improve our manuscript. We address the comments in detail below.

1. Although Rxy takes the value of 2h/e^2 at filling factor ½, I don't see any evidence of quantization in the data. To claim quantization requires Rxy to develop a plateau over a range of filling factors. No such plateau is present in the data. In existing theories of the FQHE, filling factor ½ is NOT a fractional quantum Hall state.

Response 8

We thank the referee for raising this concern and we apologize for the mistake. As the referee pointed out, there is no R_{xy} plateau at filling factor ½, nor R_{xx} local minimum. The state at filling factor ½ is a composite Fermi liquid state (CFL) instead of the fractional quantum anomalous Hall state. We have corrected it in the updated manuscript.

2. In Figs. 2b, c and Fig. 3a-c, the data shown are acquired at a small magnetic field of 0.1 T. While the underlying physics of the fractional Chern insulator remains the same as zero field, it is more convincing to show the data at B=0. I understand that a small field may improve the appearance of the fractional states. I think the readers would appreciate seeing the equivalent of Fig. 3c at B=0 regardless of how pretty it looks.

Response 9

We thank the referee's question which gives us a chance to clarify the following technical considerations.

1. The small magnetic field applied is used to suppress the fluctuation of the magnetization. At $B = 0$, the system may choose randomly one of the two magnetization directions, which is typical for micron-size devices. A tiny magnetic field beyond the coercive field is used to stabilize the system to one of the magnetization directions.

   We still followed the referee's request by performing the measurement of Fig. 3c at $B = 0$ and repeated the scans by 6 times. As shown in Fig. R1a, spikes appear randomly in all curves at $B = 0$ as we scan the moiré filling factor v. These fluctuations correspond to the random switching of the orbital magnetization in our micron-sized devices. At $B = \pm$ 100mT, these fluctuations are completely suppressed. We have also performed scans at even smaller magnetic fields. As shown in Fig. R1b, all the curves at B = 10mT, 50mT and 100mT overlap well. Therefore, the magnetic field of ±0.1T we used in our previous manuscript is just to avoid fluctuations, while the phenomena we observed are robust at $B = 0$.

   We have included Fig. R1 as Extended Data Fig. 6 in the revised manuscript, as suggested by the referee.

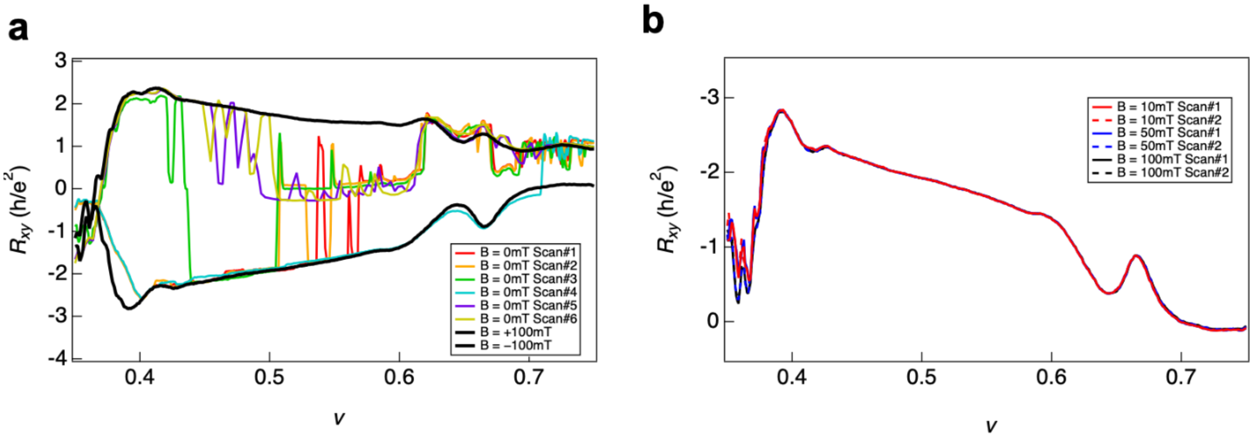


Fig. R1. R_{xy} line scans at small magnetic fields. a. *R_{xy} line scan versus moiré filling factor v at D/ε_0 = 0.93V/nm. Curves with rainbow colors represent multiple scans at B=0. Black curves show scans at B = ± 100mT.* ***B.*** *R_{xy} line scans versus v at B= 10mT, 50mT, 100mT.*

2. We need to measure at two opposite magnetic fields to remove the mixing of R_{xx} and R_{xy} due to imperfect device geometry. The longitudinal resistance R_{xx} is symmetric with B, while the Hall resistance R_{xy} is antisymmetric. Measurements performed at opposite fields (larger than the coercive field) can thus be used to extract R_{xx} and R_{xy} at $B = 0$, following:

$$R_{xx}(0) = (R(B) + R(-B))/2$$

$$R_{xy}(0) = (R(B) - R(-B))/2$$

   Such field symmetrization and anti-symmetrization cannot be performed at $B = 0$.

   This methodology has been applied widely by studies of the FQAHE and IQAHE in 2D materials. Examples include FQAHE in twisted $MoTe_2$ (Park et al., *Nature* **622**, 74–79 (2023), Xu et al., *Phys. Rev. X.* **13**, 031037 (2023)), IQAHE in twisted bilayer graphene (Serlin et al., *Science* **367**, 900–903 (2020)), IQAHE in $MoTe_2/WSe_2$ heterostructure (Li et al., *Nature* **600**, 641–646 (2021)) and so on. The application of $B = \pm 0.1$T is typical in these studies.

We note that the previous studies on FQHE in high magnetic fields did not suffer from the problems while these are essential when measuring the anomalous Hall effect. We have added the discussions above to the Methods part in our revised manuscript.

3. The authors commented on the width of the C=integer resistance plateaus by saying "The width of the IQAHE plateau corresponds to a ~10 times smaller charge density than that in t-MoTe210,12. This could be due to a combination of the smaller gap size of the IQAHE (possibly due to the 5-times smaller electron density in the topological flat band, and as implied by the lower temperature threshold of quantized Rxy) and a smaller charge/moiré-period inhomogeneity in our graphene-based moiré superlattice than in the t-MoTe2 moiré superlattice." I am not sure that I follow what the authors meant. First of all, the width of the plateau at C=1 seems to be very different than that of the C=2,3… Secondly, the width of a QH resistance plateau strongly depends on sample disorder. Even if two samples have the same Landau level gaps, they may show plateaus of different width. Authors please clarify.

Response 10

We understand that the original statement could cause confusions. We agree that the width of the plateaus depends on many factors including the size of energy gap and density of sample disorder. As the referee pointed out, the widths of the *C*=1 state and the *C*=2,3 are very different. This could be attributed to the more robust Chern gap compared to the Landau level gaps at small magnetic fields. This is also observed in the $MoTe_2/WSe_2$ system (Li et al., *Nature* **600**, 641–646 (2021) where both IQAHE and QHE from Landau levels co-exist.

Our comparison with the width in t-$MoTe_2$ was probably not proper, as suggested by the referee. Although it is reasonable to assume a smaller charge inhomogeneity and moiré-period variations in our system (due to higher material quality and the nature of hetero-bilayer moiré), the width of the quantized state also depends on the gap size. It is known that FQAHE can persist to higher temperatures in t-$MoTe_2$ than in our system. As a result, the width itself cannot be used as an experimental gauge of inhomogeneity. We have modified the manuscript by removing the statement 'This could be due to a combination of the smaller gap size of the IQAHE (possibly due to the 5-times smaller electron density in the topological flat band, and as implied by the lower temperature threshold of quantized Rxy) and a smaller charge/moiré-period inhomogeneity in our graphene-based moiré superlattice than in the t-MoTe2 moiré superlattice.'.

4. In Fig. 3d-j, some R_xx peaks appear to not line up with the abrupt changes in R_xy. For example, in Fig. 3f, R_xy changes abruptly at -100 mT but there is no corresponding peak in R_xx. This is puzzling. Authors please check the traces carefully.

Response 11

Indeed, there was disagreement between the positions of R_{xy} jumps and the R_{xx} peaks in Fig. 3d-j. Such disagreement is likely due to the formation of domains in different areas across the sample. Therefore, it highly depends on the measurement pin configuration. To test this hypothesis, we have performed four-probe measurements with all possible pin combinations and shown the results at $\nu=3/5$ in Fig. R2 as an example. The position of R_{xx} peak may not agree with position of R_{xy} change, if we compare Fig. R2b&c or a&d. But the R_{xx} peak and the R_{xy} change in Fig. R2b&d happen at the similar position. We have checked measurement configuration carefully and replaced the traces in Fig. 3d-j with more properly measured ones. We have also performed such measurements at other fractional filling factors, and could find combinations that show R_{xx} peak and the R_{xy} change happen at the same position.

To address the referee's concern, we have included the discussion above as a section in Methods and Fig. R9 (which includes Fig. R2) as Extended Data Figure 5 in the revised manuscript. We have also replaced Fig. 3d-j by combining plots such as Fig. R2b&d to show changes at the same position.

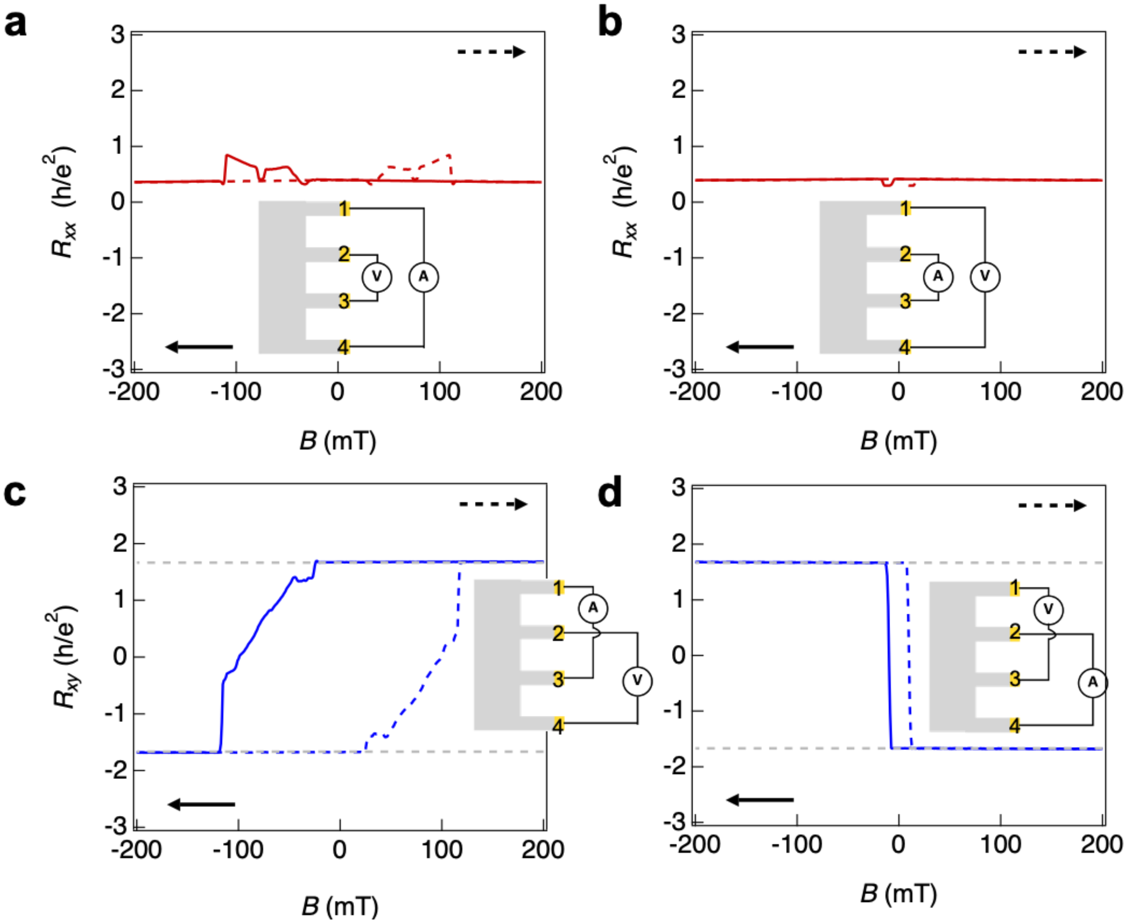


Fig. R2. R_{xx} and R_{xy} hysteresis with different pin combinations. a&b. R_{xx} as a function of B using the pin configurations shown. **c&d.** R_{xy} as a function of B using the pin configurations shown.

5. In my view, Fig. 3c shows the strongest evidence of the fractional Chern insulator states, where R_xy exhibits developing plateaus and shoulders at the expected filling factors, accompanied by R_xx minima at the same filling factors in a density sweep. However none of them looks to be quantized to me, by the standards of the quantum Hall community.

Response 12

We agree the R_{xy} data in the previous version of Fig. 3c does not show clear enough plateaus at the FQAH states. We later optimized the measurement scheme by retaking Fig. 3c using a 'constant current' scheme instead of the 'constant voltage' scheme previously used. Fig. R3 shows the results of the optimized measurement, where obvious plateaus at the fractional filling and corresponding quantized values are clearly seen in R_{xy}, while the dips in R_{xx} are still obvious if not more obvious than in the previous Fig. 3c. We understand that the referee might also have question on why the R_{xx} is not zero at fractional fillings. Please see our **Response 28** in the latter section of this letter, where we respond to the same question raised by referee #3.

We have updated Fig. 3c in the revised manuscript by using Fig. R3.

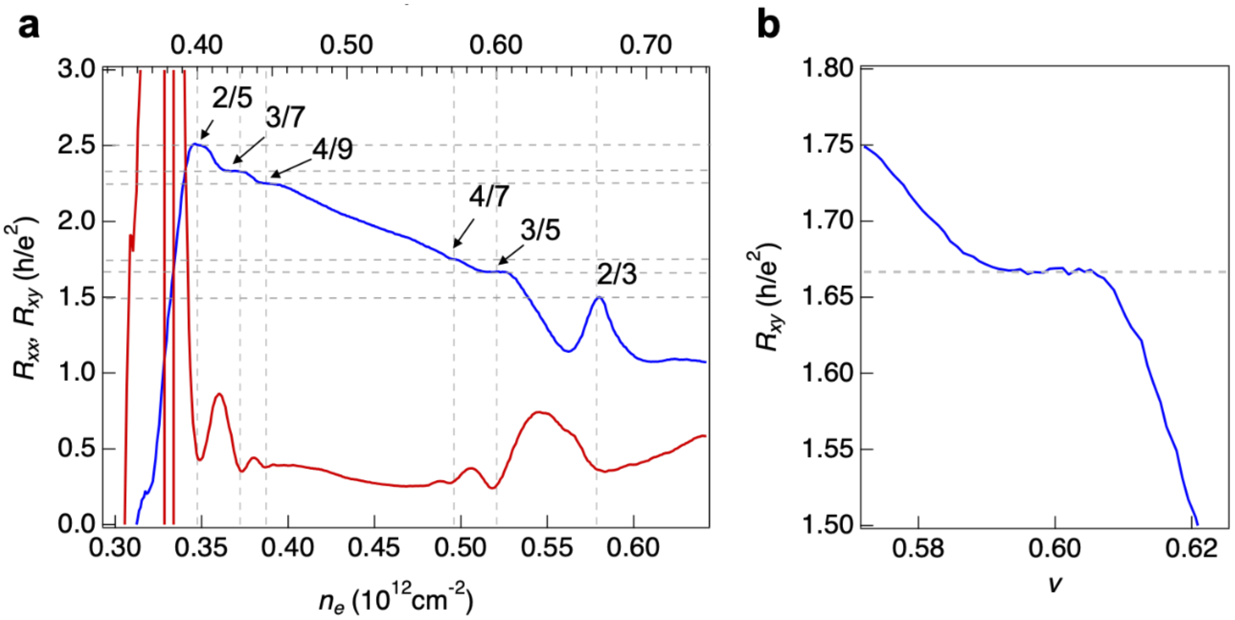


Fig. R3. R_{xx} and R_{xy} measured with the constant current configuration. a. *Clear R_{xy} plateaus are observed at fractional fillings together with corresponding dips in R_{xx}.* ***b.*** *Zoomed in R_{xy} plot near $\nu=3/5$ showing a plateau at $5/3 * h/e^2$ ±0.5%.*

In addition, Figs. 3d-j do not constitute evidence of quantization, despite the fact that R_xy exhibits the correct values and these values remain a constant in a window of B. If the authors were to conduct the same measurement at filling factor 0.55, which is not expected to be a fractional state at all, I believe the authors would find a hysteresis loop similar to those shown in Figs. 3d-j. Surely one cannot conclude that filling factor 0.55 exhibits quantization based on this result?

Response 13

We agree that the anomalous Hall effect and magnetic field hysteresis itself are not direct evidence for the FQAH states. As the referee pointed out, the plateaus in R_{xy} and the corresponding R_{xx} minima indicate the emergence of the FQAH states.

I think the authors also used the same criteria to conclude that filling factor ½ is "quantized" in Fig. 4.

Response 14

We agree with the referee that $\nu=1/2$ is not an FQAHE state and we believe it is a composite Fermi liquid state with anomalous Hall effect. The hysteresis plot in Fig. 4 was to show the magnetic switching as expected for anomalous Hall states. We have corrected the figure caption of Fig. 4 and the main text in the revised manuscript to eliminate 'quantized' and 'quantization' when describing the $\nu=1/2$ state.

Well, if the authors conducted similar measurements at filling factor 0.52, would they also obtain similar looking plots? As I mentioned in the first bullet point, for the quantum hall community, "quantization" means having a Chern number and exhibit the corresponding experimental signatures (quantized R_xy plateau, R_xx minimum, quantized two-terminal conductance, etc) over a range of filling factors. It doesn't just mean a constant value. I suggest that the authors go through the manuscript carefully to evaluate every situation where the word quantized is used.

Response 15

We agree with the referee on the meaning of quantization and we understand the confusion our previous manuscript has rendered. We have constrained the usage of ‘quantization’ in the revised manuscript to integer and fractional states that clear dips in R_{xx} were observed, including $v = 1, 2/3, 3/5, 4/7, 4/9, 3/7$, and $2/5$ but not $v = 1/2$.

Statement such as “The quantization and magnetic hysteresis of Rxy are consistent with a FQAH state at v = ½” is incorrect.

Response 16

We agree with the referee and have modified the revised manuscript by eliminating this statement.

However the data in Fig. 4c does suggest to me that filling factor ½ undergoes phase transitions.

Response 17

We thank the referee for agreeing with our observation. We believe this is indeed a new observation which shows different behavior from the twisted $MoTe_2$ system.

6. In Figs. 3g and k, it is difficult for me to see any features along the dashed lines the authors drew, apart from the blue blob at 2/3. Even so, it is far from clear that the blue blob has a slope indicated by the dashed line. Can the authors work to improve these plots? I think line cuts are much more useful in this case to indicate a shift.

Response 18

This is a good suggestion. We stacked a few linecuts taken at $B = 0$ to 1.5 T, as shown in Fig. R4, to reveal the shift as the referee suggested. We have included Fig. R4 as Extended Data Figure 7 in the revised manuscript. We also modified Fig. 3g&k by removing the dashed lines on one side of the magnetic field for clarity.

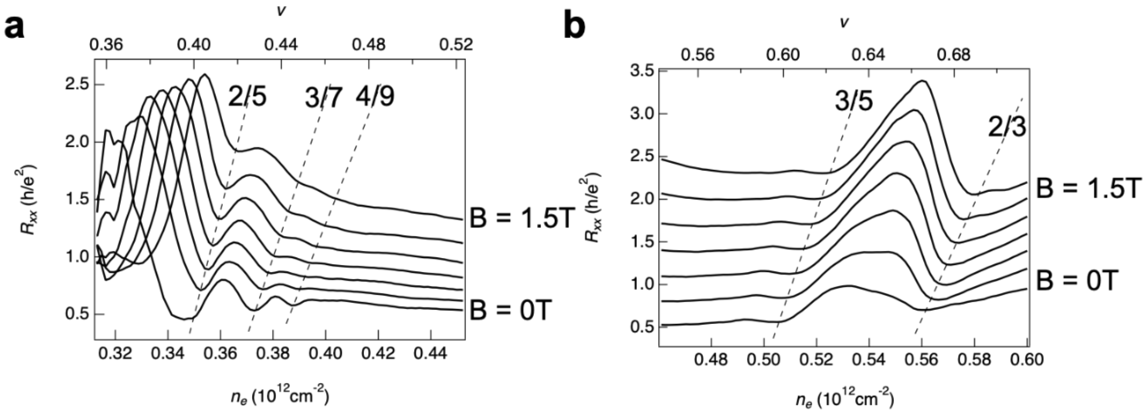


Fig. R4. R_{xx} line scans at varying magnetic field. a&b. *R_{xx} line scans with moiré filling factor $v < 1/2$ and $v > 1/2$, respectively. Dips at fractional filling factors shift with magnetic field as indicated by the dashed lines. Curves are equally shifted vertically for clarity.*

In fact, the most prominent features in Figs. 3g and k are the two orange-colored “wings”. What are those?

Response 19

The 'wing' on the lower-density side is the phase boundary between the v=2/5 FQAH state and another state with a much smaller anomalous Hall signal. This could be due to a phase transition from anomalous Hall state to a state with zero valley polarization. This boundary seems to shift to higher filling factors in magnetic field. The higher-density one is between the 3/5 and 2/3 state and we are not certain about the nature of this state. The two features are also obvious in the *n-D* colormap at low magnetic field in Fig. 3a.

7. I suggest removing the fractions marking the value of R_xy throughout the manuscript. I find the notation of (nu, R_xy (in unit of h/e^2)) such as (2/5, 5/2), instead of simply noting the filling factor 2/5 to be confusing because 5/2, 3/2, 7/3 etc can be the filling factors of actual fractional quantum Hall states so this double notation is confusing to some readers.

Response 20

We have followed the referee's suggestion and removed them in the revised manuscript.

8. References cited in the manuscript heavily lean towards more recent literature studying Moire or Moire-adjacent systems. For example, when the authors discuss rhombohedral graphene, only results from 2019 on are cited (41-47). Was rhombohedral graphene not studied and its key electronic properties underlying the later work unknown prior to 2019? I'd encourage the authors to dig a little deeper beyond the "latest hot stuff" in their referencing practices.

Response 21

We have followed the referee's suggestion and added references that we are aware of (rhombohedral trilayer and tetralayer graphene) in the revised manuscript. Please feel free to suggest other references to add.

Here are the new references we added:

1. Bao, W. *et al.* Stacking-dependent band gap and quantum transport in trilayer graphene. *Nat. Phys.* **7**, 948–952 (2011).
2. Zhang, L., Zhang, Y., Camacho, J., Khodas, M. & Zaliznyak, I. The experimental observation of quantum Hall effect of l=3 chiral quasiparticles in trilayer graphene. *Nature Physics 2011 7:12* **7**, 953–957 (2011).
3. Zou, K., Zhang, F., Clapp, C., MacDonald, A. H. & Zhu, J. Transport studies of dual-gated ABC and ABA trilayer graphene: Band gap opening and band structure tuning in very large perpendicular electric fields. *Nano Lett* **13**, 369–373 (2013).
4. Lee, Y. *et al.* Competition between spontaneous symmetry breaking and single-particle gaps in trilayer graphene. *Nat. Commun.* **5**, (2014).
5. Myhro, K. *et al.* Large tunable intrinsic gap in rhombohedral-stacked tetralayer graphene at half filling. *2d Mater* **5**, 045013 (2018).

9. Please check the measurement configuration of R_xx shown in extended Fig. 1a. That looks unusual to me. Are current and voltage probes mislabeled?

Response 22

We appreciate the referee's sharp observation and the chance for us to clarify the measurement configurations. For a device with four contacts on the same side, there are two ways to measure R_{xx}, which are related by the Onsager reciprocal relation. In **Response 11** we show the result of both configurations. The coercive fields we got from the two configurations are different and we attribute this to the possible domain structure in the device (see also in Serlin et al., *Science* **367**, 900–903 (2020)). We emphasize that they behave similarly when the magnetic field is above the coercive field. Therefore, we chose to use the configuration with a smaller coercive field to perform measurements at lowest magnetic field to prevent random switching of the magnetization.

Such a choice of the R_{xx} measurement scheme was also adopted in previous studies of rhombohedral trilayer graphene (Zhou et al., *Nature* **598**, 434–438 (2021)). They chose the same configuration (configuration 1 in Fig. R5) as we did due to the larger contact resistance on one of the outer contact leads. The results from the two configurations are similar and they chose configuration 1 due to the smaller heating effect and lower noise.

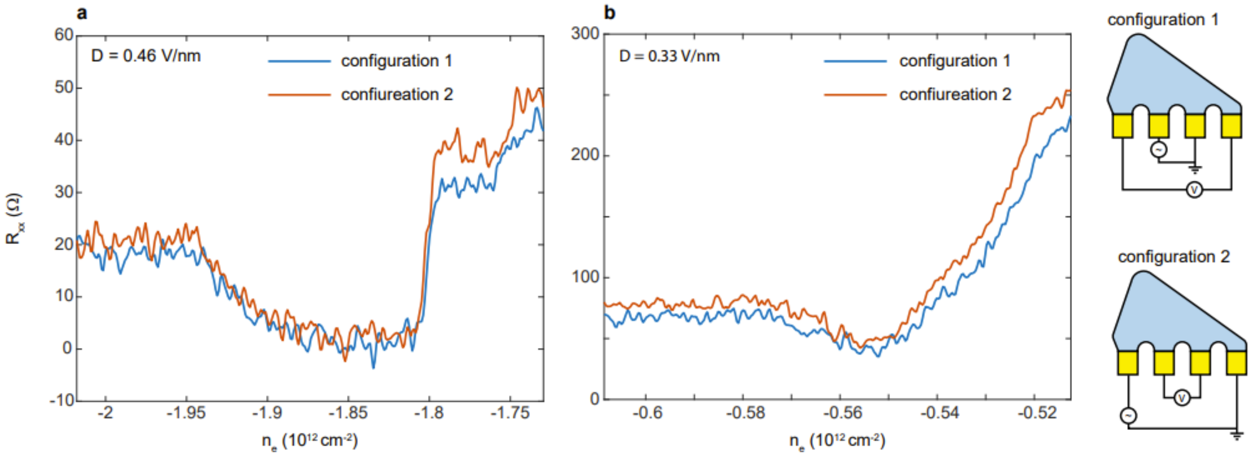


Fig. R5. R_{xx} vs n_e measured with different contact configurations. a, *D =0.46V/nm, near SC1.* ***b***, *D = 0.33V/nm, near SC2. Figure is adapted from Zhou et al., Nature* ***598****, 434–438 (2021).*

Referee #3 (Remarks to the Author):

The current manuscript unveils, for the first time, the observation of the fractional quantum anomalous effect (FQAHE) in pentalayer graphene utilizing an hBN superlattice. While the FQAHE has been successfully demonstrated in the t-MoTe2 system, its existence within a graphene-based system had not been established prior to this work. This manuscript asserts the identification of quantized Hall resistance values at specific filling factors: Rxy = *h* *e* 2 , 3*h* 2*e* 2 , 5*h* 3*e* 2 , 7*h* 4*e* 2 , 9*h* 4*e* 2 , 7*h* 3*e* 2 , 5*h* 2*e* 2 for v = 1, 2/3, 3/5, 4/7, 4/9, 3/7 and 2/5 respectively, accompanied by dips in the longitudinal resistance Rxx. Additionally, it highlights a transition from a composite Fermi liquid to various other correlated states.

The discovery of the FQAHE in a graphene-based system is particularly intriguing, given that graphene serves as an ideal platform for potential exploration of non-abelian braiding in the future. I find the experimental findings within this work to be both fascinating and significant for the scientific community.

Response 23

We thank the referee for appreciating the quality and merits of our manuscript. We also appreciate the detailed comments/questions from this referee that have helped to improve our manuscript. We address the comments in detail below.

However, I do harbor reservations regarding the current presentation of the manuscript. My primary concern regarding this research pertains to the measurement methodology employed in this study. The measurement scheme described in extended data figure 1 appears quite confusing. In the method section, it says voltage bias scheme being used as following; “longitudinal and Hall resistance Rxx and Rxy with an AC voltage bias 80 uV at a frequency at 17.77 Hz.” However, in order to accurately measure Rxx and Rxy, a 4-probe measurement is typically required. This involves the implementation of a constant current within the circuit and the subsequent measurement of longitudinal and transverse voltages.

Response 24

We thank the referee for the question about the measurement methodology and for giving us a chance to clarify. We would like to point out that we actually are doing 4-probe measurements. We understand the Extended Data Figure 1 and Methods might have confused the referee, and here we show the circuit diagram to clarify on it.

We applied 60uV output from a lock-in amplifier across the source and drain of the device, as shown in Fig. R6a. The reason we chose to apply a constant voltage excitation instead of a constant current one is the existence of very insulating states at v = 0 to 1/2. To take the maps in Fig. 1b&c and Fig. 3a&b, a constant voltage excitation can capture multiple features with very different resistance at the same time, while a constant current excitation might build a huge voltage across source-drain when the channel resistance is very big. Fig. 3c was extracted from Fig. 3a&b so it was based on constant voltage measurement. Basically, we were doing four-probe measurements, although we were not using the constant current scheme.

Still, we did additional measurement using a constant current of 2nA (circuit diagram shown in Fig. R6b), as requested by this referee. We restricted the filling factor range to avoid the insulating state at $v \leq 1/2$, so a constant current measurement does not cause a big source-drain voltage. It shows consistent results as we have included in our previous version of the manuscript, and even better quantized plateaus of R_{xy} at the fractional states as shown in Fig. R6c. We have replaced the original Fig. 3c with the data taken with the constant current measurement in our revised manuscript.

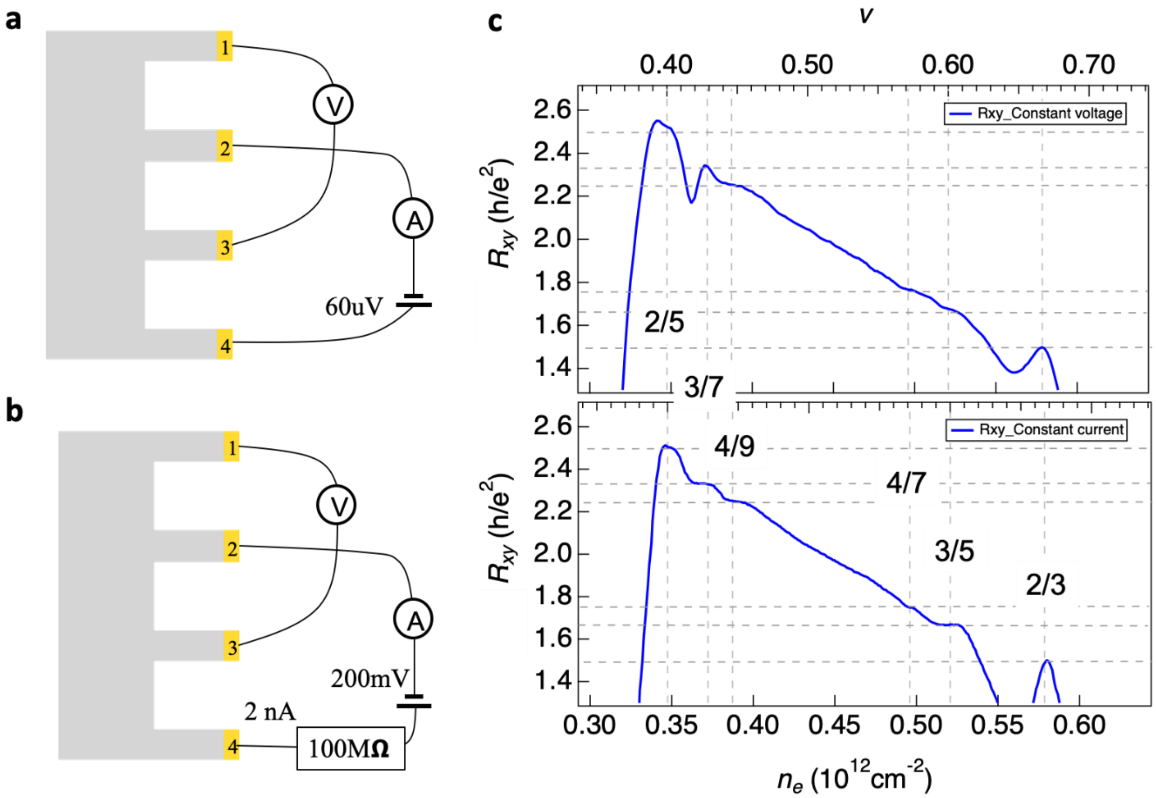


***Fig. R6. Constant voltage versus constant current. a**, Scheme of the constant voltage measurement. 60uV is applied from the lock-in amplifier internal voltage source to contact #4. The current going through contacts #2 and #4 is measured by the current channel of the same lock-in amplifier. The voltage drops between contacts #1 and #3 are captured by the "A-B" channel of another lock-in amplifier. **b.** Scheme of the constant current measurement. 200mV is applied from lock-in amplifier internal voltage source to a 100MΩ resistor connected in series with the sample to create a 2nA constant current across the source and drain. The voltage difference between contact #1 and #3 is measured with another lock-in amplifier. **c.** R_{xy} line scans performed in the constant voltage (upper panel) and the constant current (lower panel) scheme.*

It's worth noting that a similar scheme has been utilized by this same research group in their prior works [Nat. Nanotechnol. (2023). https://doi.org/10.1038/s41565-023-01520-1, Nature (2023). https://doi.org/10.1038/s41586-023-06572-w]. Let's assume they have used the current biased scheme but not described properly in the manuscript. The scheme is shown in page 17 as shown above; I believe a constant current is passed through the contacts 2 and 3 for the Rxx, and between 2 and 4 for the Rxy measurements, respectively. Unfortunately, the optical image of the two devices are not available in the paper. As can be seen from the above schematic figures that all the contacts are at one side of the device in contrast to the conventional Hall bar geometry being used to measure Rxx and Rxy in the literatures as well as by the same group [Nat. Nanotechnol. (2023). https://doi.org/10.1038/s41565-023-01520-1, Nature (2023). https://doi.org/10.1038/s41586-023-06572-w].

Response 25

As we explained above, our measurement shown in the previous manuscript was done in a 4-probe configuration. We have also demonstrated similar results using both constant voltage and constant current schemes in **Response 24**. Now we discuss the measurement scheme by using electrodes on one side of the device. We show the optical image of the two devices in Fig. R7c&d, as wanted by the referee. We aimed to fabricate the device into a Hall bar geometry, as done in our previous transport works on rhombohedral graphene. But the contact resistance on one side of device turned out to be very big at mK temperatures due to the formation of an n-p-n junction. This makes the conventional Hall bar geometry measurement inaccurate.

Specifically, as shown in Fig. 7Rb, we have an n-p-n junction at the left side of the device when the channel is in FQAH states. As shown in our previous work (Han, T. et al. Nat. Nanotechnol. (2023).), the $n = 0 = D$ state of rhombohedral pentalayer graphene is a correlated insulator at low temperature. Therefore, we need to dope the graphene area that is only controlled by the silicon gate to make a good contact to the channel. Given the voltages on the local graphite gates to be positive on the top and negative at the bottom, a large positive (negative) voltage on the silicon gate will result in an n-p-n junction on the left (right) side. In an ideal device geometry as shown in Fig. R7a, such that top and bottom graphite gates are perfectly aligned, this issue will not show up. But the misalignment between the top and bottom gates can hardly be avoided during the stacking process. In previous works on rhombohedral graphene, the required graphite gate voltages were low enough that the n-p-n junction never caused a big contact resistance. But FQAHE in this work requires a much bigger D and subsequently much larger V_t and V_b---amplifying the contact issue due to the n-p-n junction. This issue could potentially be avoided by engineering a larger local graphite top (bottom) gate than the local graphite bottom (top) gate, but would take much longer time to realize due to the challenges in fabricating rhombohedral graphene devices, especially with a moiré superlattice with hBN.

We stress that measuring R_{xx} and R_{xy} using devices that have contacts on one side is a standard measurement scheme that has been used by other works in the field (Serlin et al., *Science* **367**, 900–903 (2020), Zhou et al., *Nature* **598**, 429–433 (2021)). We have included the optical image of the devices in the Methods section of the revised manuscript.

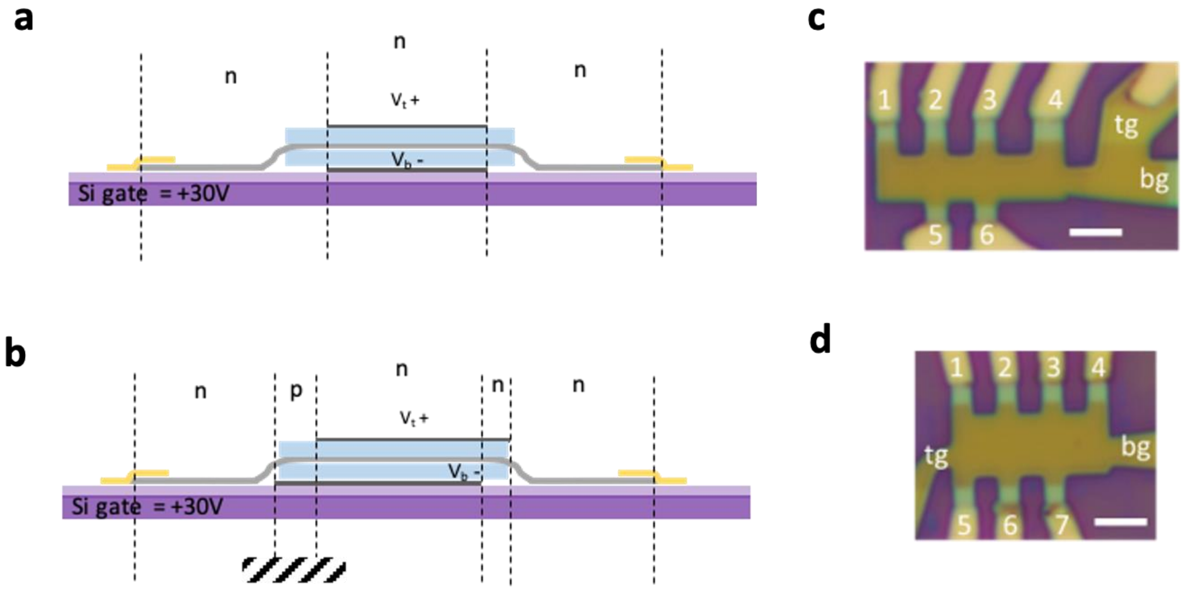


Fig. R7. Schematics of gates and contacts geometry and optical micrograph of our devices. a. *Gates and contacts layout in perfect geometry.* ***b****. Top and bottom graphite gate shifted relative to each other creating a n-p-n junction on one side of the contacts.* ***c.*** *Device 1 from which the data in the main text is taken. Scale bar: 3µm* ***d.*** *Device 2, the data of which is included in Extended Data Fig. 8&9. Scale bar: 3µm*

One of the main concern of above measurement scheme is that there is large entanglement between the Rxx and Rxy, and deconvolution using symmetrising Rxx, and anti-symmetrising Rxy are not ideal. The raw data used to symmetrize Rxx, and anti-symmetrize Rxy are also not available in the manuscript. Further, how symmetrisation and anti-symmetrisation are performed not described properly in the manuscript. In the method section, it only says following; "In Fig. 1c 384 and 2c we plotted (Rxy (0.1 T) - Rxy (-0.1 T))/2, while in 2e&f, 3b&c and 4a&c we plotted (Rxy (-0.1 T) – Rxy (0.1 T))/2 for the convenience of presentation".

Response 26

We first explain in details the symmetrization/anti-symmetrization method that we used.

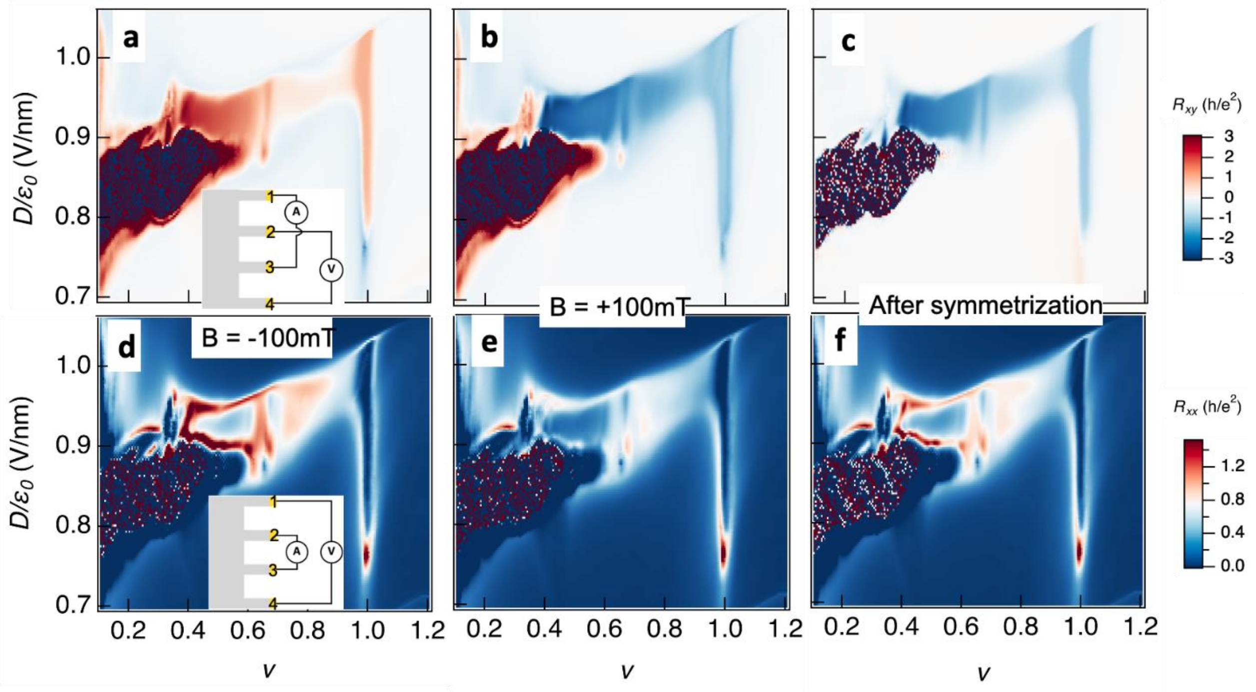


Fig. R8. Symmetrization/anti-symmetrization method to obtain Fig. 1b&c. a,b&d,e. *Raw data of* $R_{13,24}$ *and* $R_{23,14}$ *measured as functions of displacement field and moiré filling factor* ν *at* $B=\pm 100$ *mT. The insets show the measurement pin configurations.* ***c&f.*** R_{xy} *and* R_{xx} *obtained after the symmetrization/anti-symmetrization process.*

The device geometry is such that no pair of contacts allows a perfect measurement of pure R_{xy} or R_{xx}. To disentangle R_{xx} and R_{xy} in the resistance tensor, we used magnetic field symmetrization/anti-symmetrization method, which is a well-established method for R_{xx} and R_{xy} (Sample et al., *J. Appl. Phys.* **61**, 1079–1084 (1987), Serlin et al., *Science* **367**, 900–903 (2020)). This method has been used by many other published works on 2D materials, including ones published at Nature (Zhou et al., *Nature* **598**, 429–433 (2021)). **Even for Hall bar devices, there is always a finite entanglement between** $\boldsymbol{R_{xy}}$ **and** $\boldsymbol{R_{xx}}$ **due to imperfect device geometry. The same symmetrization/anti-symmetrization method has been applied widely by studies of the FQAHE and IQAHE in 2D materials.** Examples include FQAHE in twisted $MoTe_2$ (Park et al., *Nature* **622**, 74–79 (2023), Xu et al., *Phys. Rev. X.* **13**, 031037 (2023)), IQAHE in twisted bilayer graphene (Serlin et al., *Science* **367**, 900–903 (2020)), IQAHE in $MoTe_2/WSe_2$ heterostructure (Li et al., *Nature* **600**, 641–646 (2021)) and so on. The application of $B = 0.1$T is typical in these studies.

Specifically, the longitudinal resistance and Hall resistance can be separated by using magnetic field symmetrization is based on the fact that R_{xx} is symmetric with B, while R_{xy} is antisymmetric. Measurements performed at opposite magnetic fields (larger than the coercive field) can thus be used to extract R_{xx} and R_{xy} at $B = 0$ for the QAH states, following:

$$R_{xx}(0) = (R(B) + R(-B))/2 \qquad\qquad R_{xy}(0) = (R(B) - R(-B))/2$$

In Fig. R8. we demonstrate the field symmetrization/anti-symmetrization method step by step from the raw data to the plot we used in Fig. 1b&c as an example. For simplicity, $R_{12,34}$ corresponds to a resistance measured by applying current from contact #1 to #2 and measuring the voltage between #3 and #4. $R_{13,24}$ is measured at $B = \pm 100\text{mT}$ as shown in Fig. R8a&b. The R_{xy} can be obtained by extracting the field antisymmetric part of $R_{13,24}$ or $R_{24,13}$, following:

$$R_{xy}(0) = (R_{13,24}(100\text{mT}) - R_{13,24}(-100\text{mT}))/2$$

Since the longitudinal component is symmetric with respect to magnetic field, they will be cancelled by this subtraction process at the same magnitude of magnetic field but with opposite sign. Therefore, the disentangled R_{xy} could be obtained which is plotted in Fig. R8c and used in Fig. 1c. Following the same argument, resistance measurement of $R_{23,14}$ is performed at $B = \pm 100\text{mT}$ as shown in Fig. R8d&e. The longitudinal resistance can be separate by following:

$$R_{xx}(0) = (R_{23,14}(100\text{mT}) + R_{23,14}(-100\text{mT}))/2$$

Since the Hall resistance is anti-symmetric respect to magnetic field, they will be perfectly removed by this summation process at opposite magnetic field. So that longitudinal resistance can be separated and plot in Fig. R8f and also shown in Fig. 1b.

To clarify the methodology of our measurements, we have included the discussion above as a section in Methods and Fig. R8 as Extended Data Figure 4.

However, it is not clear how the data are obtained for magnetic sweep measurements in Fig. 1a. 1b, Fig. 2d-j etc.

Response 27

To answer this question on magnetic sweep data, we performed four-probe magnetic hysteresis measurements with all possible pin combinations and have shown the results of raw data and data after processing at $\nu=3/5$ in Fig. R9 as an example. First, we follow the same symmetrization/anti-symmetrization method that was described in **Response 26** to disentangle R_{xx} and R_{xy}. Magnetic field sweep of $R_{13,24}$ is shown as solid (dashed) line in Fig. R9a. In this case, Hall resistance can be extracted by following the field anti-symmetrization method:

$$R_{xy\_solid} = (R_{13,24\_\text{solid}}(+B) - R_{13,24\_\text{dash}}(-B))/2. \qquad\qquad R_{xy\_dash} = (R_{13,24\_\text{dash}}(+B) - R_{13,24\_\text{solid}}(-B))/2$$

The obtained R_{xy} is plotted in Fig. R9g with anomalous Hall value equals to the quantized value at v=3/5. Based on the raw data shown in Fig. R9b, magnetic field sweep of $R_{24,13}$ can be treated in a similar way:

$$R_{xy\_solid} = (R_{24,13\_\text{solid}}(+B) - R_{24,13\_\text{dash}}(-B))/2. \qquad\qquad R_{xy\_dash} = (R_{24,13\_\text{dash}}(+B) - R_{24,13\_\text{solid}}(-B))/2$$

The hysteresis loop after anti-symmetrization is shown in Fig. R9h.

The magnetic sweep of longitudinal resistance can be extracted based on the raw data from $R_{14,23}$ and $R_{23,14}$ measurements by following the magnetic field symmetrization method:

$R_{xx\_solid}=(R_{14,23\_\mathrm{solid}}(+B) + R_{14,23\_\mathrm{dash}}(-B))/2.$ $R_{xx\_dash}=(R_{14,23\_\mathrm{dash}}(-B) + R_{14,23\_\mathrm{solid}}(+B))/2$

$R_{xx\_solid}=(R_{23,14\_\mathrm{solid}}(+B) + R_{23,14\_\mathrm{dash}}(-B))/2.$ $R_{xx\_dash}=(R_{23,14\_\mathrm{dash}}(-B) + R_{23,14\_\mathrm{solid}}(+B))/2$

The symmetrized R_{xx} is plotted in Fig. R9i&l.

Other than relying on the symmetrization/anti-symmetrization with respect to magnetic field. We also performed symmetrization/anti-symmetrization by using Onsager reciprocal relation (Sample et al., *J. Appl. Phys.* **61**, 1079–1084 (1987), Serlin et al., *Science* **367**, 900–903 (2020)) to better capture the behaviors of the magnetic domain. $R_{14,23}$ and its Onsager reciprocal $R_{23,14}$ are mainly contributed by R_{xx}. The symmetrization can then be performed by following:

$R_{xx\_solid}=(R_{14,23\_\mathrm{solid}}+R_{23,14\_\mathrm{solid}})/2.$ $R_{xx\_dash}=(R_{14,23\_\mathrm{dash}}+R_{23,14\_\mathrm{dash}})/2$

The hysteresis loop of the disentangled longitudinal resistance obtained by Onsager reciprocal relation is plotted in Fig. R9n. While $R_{24,13}$ and its Onsager reciprocal $R_{13,24}$ are dominated by R_{xy}. The longitudinal part can be eliminated by performing the following anti-symmetrization relation:

$R_{xy\_solid}=(R_{13,24\_\mathrm{solid}}-R_{24,13\_\mathrm{solid}})/2.$ $R_{xy\_dash}=(R_{24,13\_\mathrm{dash}}-R_{13,24\_\mathrm{dash}})/2$

As we can see from Fig. R9c,f&m, no matter what symmetrization method we use, the Hall resistance values always stay quantized at $B = 0$. Since the physics we would like to address in the manuscript is not about magnetic domain, symmetrization/anti-symmetrization with respect to magnetic field is used for the hysteresis loop in Fig. 2a&b, Fig. 3d-j and Fig. 4b&d.

To clarify the symmetrization/anti-symmetrization process, we have included the discussion above as a section in Methods and Fig. R9 as Extended Data Figure 5 in the revised manuscript.

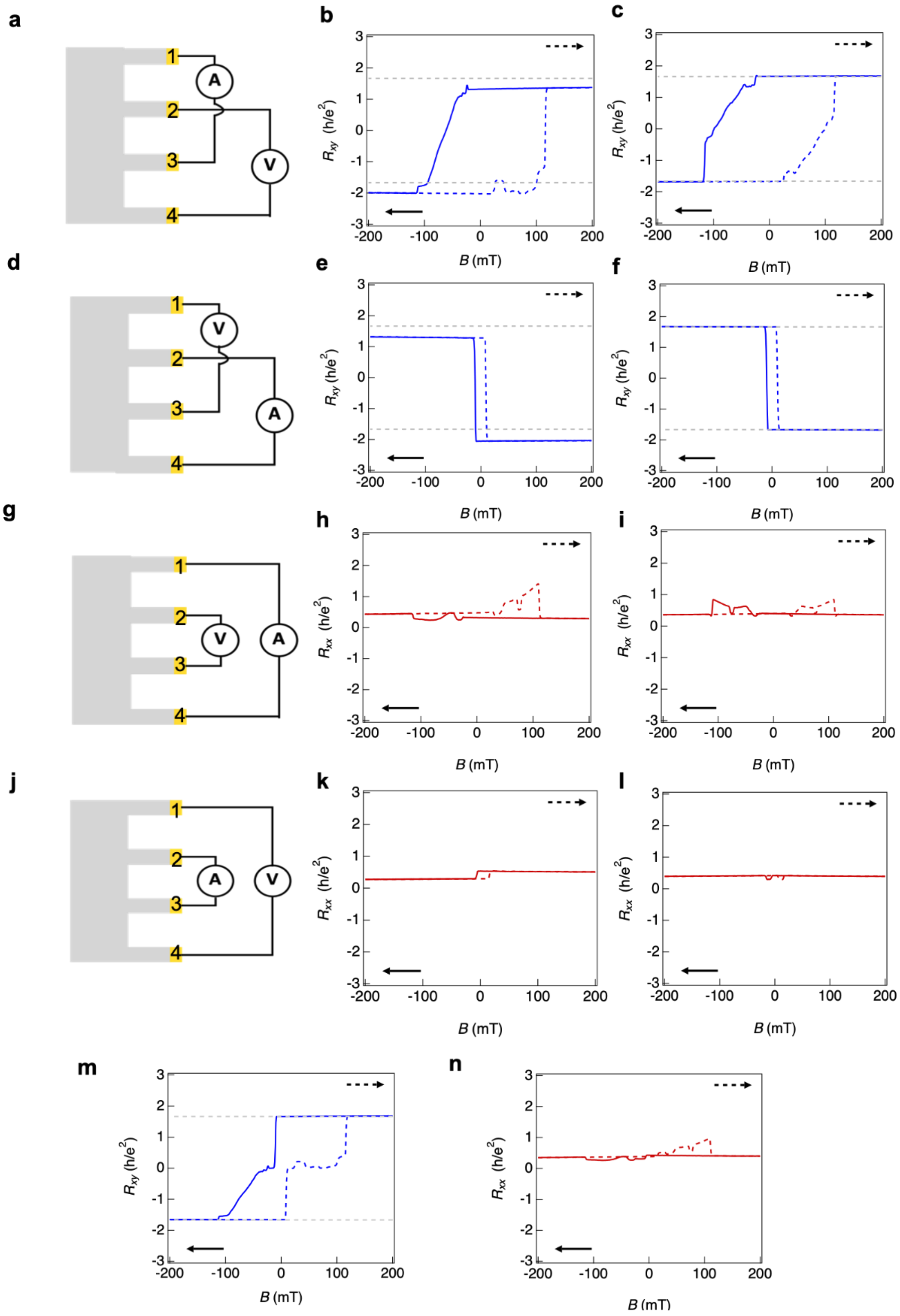


Fig. R9. Magnetic field and Onsager symmetrization/anti-symmetrization method to obtain magnetic hysteresis data at ν=3/5. a, b, d&e. *Raw data of $R_{13,24}$, $R_{24,13}$, $R_{14,23}$ and $R_{23,14}$ measured as functions of magnetic field. The insets show the measurement pin configurations.* ***g, h, i&j.*** *R_{xy} and R_{xx} obtained after the magnetic field symmetrization/anti-symmetrization process.* ***c&f.*** *R_{xy} and R_{xx} obtained after the symmetrization/anti-symmetrization process using the Onsager reciprocal relation.*

Now let's discuss the result obtained after the deconvolution from a non-ideal geometry used in the present manuscript. For the IQAHE, the Rxy plateau is robust with a finite Rxx ~ 50 ohm. However, my main concern is related to FQAHE, where the plateau like features are observed with large Rxx ~ 7-9 kOhm (Fig. 3c, Extended data Fig. 3a-f). Though, the dips are seen in Fig. 3c, but it does not represent the minimum resistance as can be seen that even at non plateau region, the resistance are with similar value or slightly smaller value. The manuscript attempts to emphasize the benefits of employing multilayer (pentalayer) graphene over t-MoTe2, citing improved contacts, among other advantages. However, in Nature 622, 74–79 (2023), the observation of IQAHE demonstrates Rxx measurements less than ONE ohm, and FQAHE exhibits finite Rxx measurements less than 1 kOhm using the conventional Hall bar geometry.

Response 28

Regarding the comment 'However, in Nature 622, 74–79 (2023), the observation of IQAHE demonstrates Rxx measurements less than ONE ohm', we could not find any evidence to support this comment. Fig. R10 is adapted from the Nature paper on t-MoTe$_2$. From the zoomed-in plot in Fig. R10b one can tell the noise level is ~2 kOhm which is much bigger than the 'ONE ohm' quoted by this referee. In addition, if we take roughly an average of R_{xx} as indicated by the green line, it is clearly below the dashed line that corresponds to zero---meaning the average is actually negative. A negative R_{xx} is clearly unphysical for QAHE. We believe that the referee might harbor some misunderstanding of the data in the MoTe$_2$ paper.

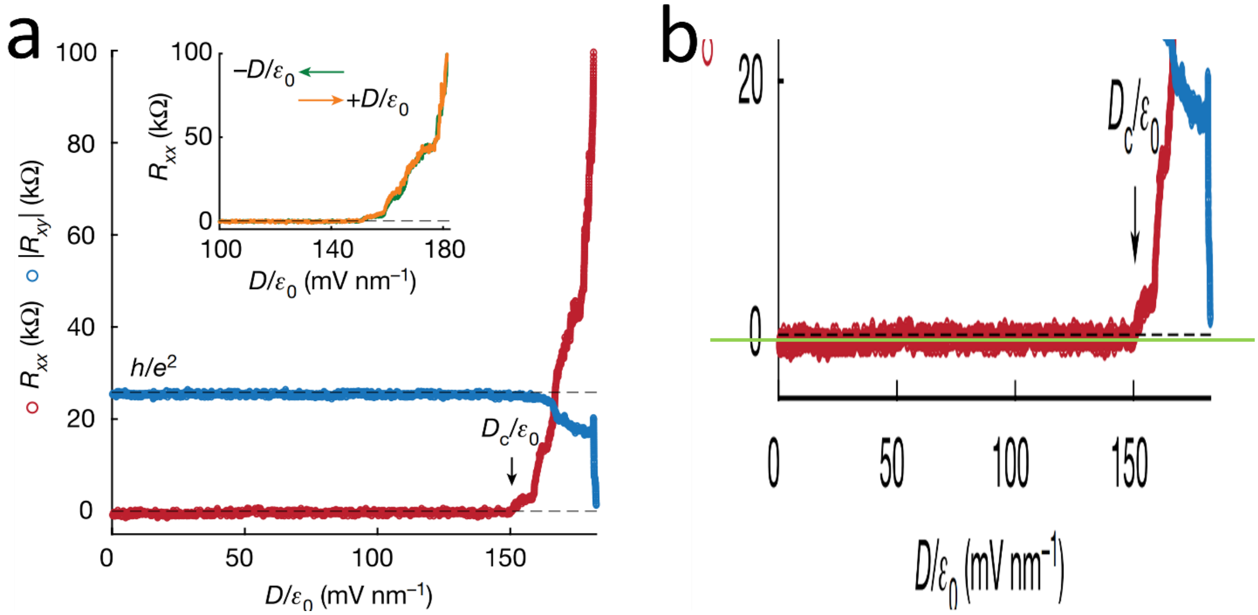


Fig. R10. R_{xx} and R_{xy} line scan in t-MoTe$_2$ in the IQAHE state. a. *Replication of Fig. 2b in Nature 622, 74–79 (2023).* ***b.*** *Zoomed-in of* ***a*** *to show the detail of R_{xx}. We add a green line to roughly indicate the average value of R_{xx}, which is clearly negative.*

Still, we tried to do our best about R_{xx} in IQAHE. With a careful measurement of this state using a longer average time, we are able to determine the value of R_{xx} to be < 5 Ohm, as shown in Fig. R11. This value is limited by the noise level, which is orders of magnitude smaller than the noise in Nature 622, 74–79 (2023) and implies a much better electrical contact to the sample. In our previous manuscript, we quoted 50 Ohm, which we thought was a small enough value to demonstrate the physics. We have replaced Fig. 2e by Fig. R11 and revised the caption and main text correspondingly.

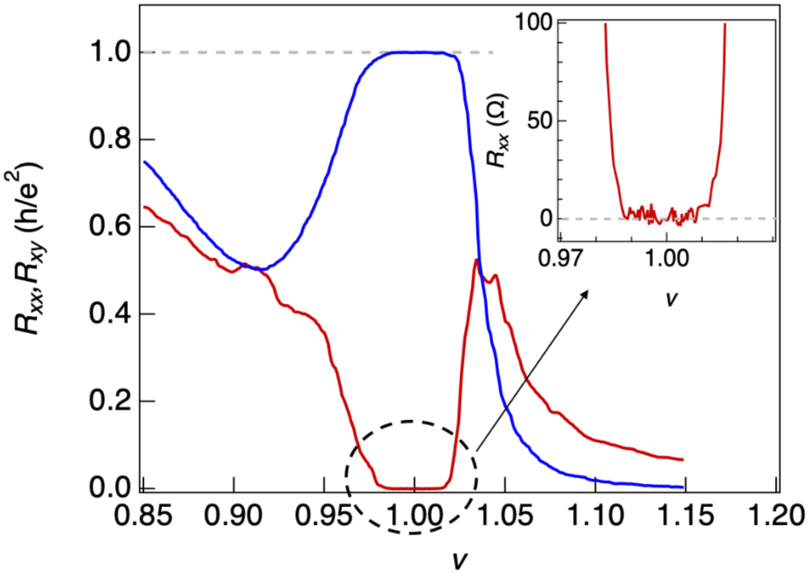


Fig. R11. R_{xx} and R_{xy} line scan with longer acquisition time. *Symmetrized R_{xx} (red) and anti-symmetrized R_{xy} (blue) as functions of ν at T = 10 mK and D/ε_0 = 0.97 V/nm, featuring plateau of quantized R_{xy} and R_{xx} < 5 Ω. Inset: zoomed-in plot to reveal the nearly zero longitudinal resistance.*

As for R_{xx} in the FQAH states, we are aware of the difference between our study and the t-MoTe$_2$ case. In the t-MoTe$_2$ work (Park et al., *Nature* **622**, 74–79 (2023)), the Hall bar geometry was defined by the contact gate instead of the lithographic patterning and physical etching process. Compared with the etched physical edges, the gate-defined edges suffer less from the edge disorder and result in better measurements of the edge state properties. The better performance of gate-defined edges has been demonstrated in the FQH experiment of monolayer graphene at high magnetic fields (Ribeiro-Palau et al., *Nano Lett.* 2019, 19, 4, 2583–2587). In Fig. R12, the integer QHE in both gate-defined-edge scheme and physical-edge scheme is well developed. However, the measurement of fractional QHE in the gate-defined-edge scheme is much better. We think the difference in R_{xx} is due to the quality of the edge, instead of the difference between Hall bar geometry and all-contacts-on-the-same-side geometry.

We note, however, that the successful implementation of the gate-defined-edge scheme relies on the insulating state in the single-gated area, which is the case for t-MoTe$_2$ and graphene at high magnetic fields. However, at zero magnetic field, it is hard to keep the single-gated area insulating in graphene systems. We agree that it would be ideal eventually to show a smaller value of R_{xx} at the FQAHE states. However, due to challenges in fabricating rhombohedral graphene devices and the lack of an insulating state in single-gated graphene, it would take significant extra efforts to get there. Nevertheless, I hope our new data (Fig. R6c) shows convincing enough evidence of quantization of R_{xy} to establish FQAHE.

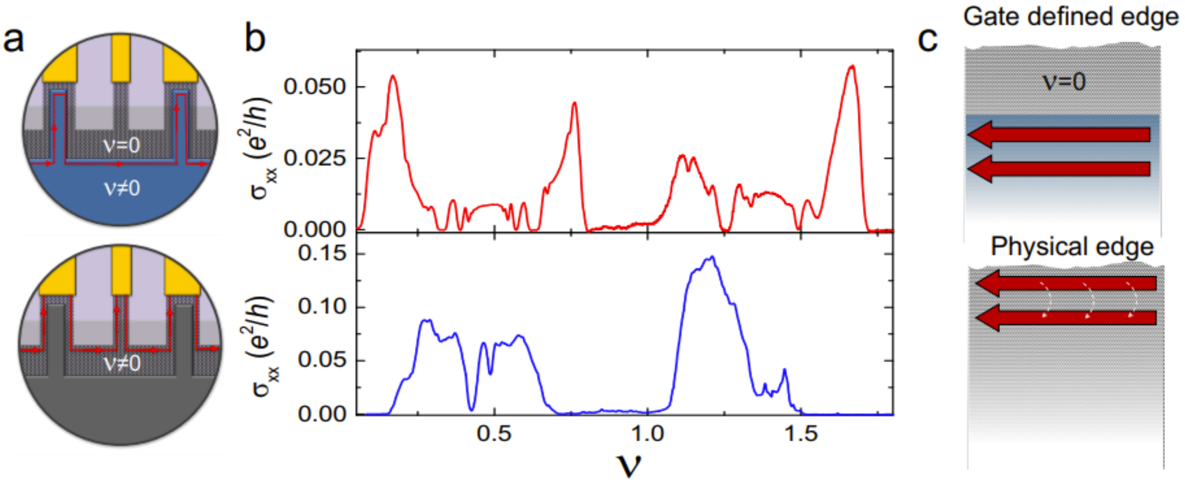


Fig. R12. Impact of gate-defined edge and physical edge on the measurement of fractional Hall effect in monolayer graphene. *Adapted from Ribeiro-Palau et al., Nano Lett. 2019, 19, 4, 2583–2587.*

Additionally, it is evident from the Nature 622, 74–79 (2023) that both IQAHE and FQAHE exhibit significantly more robust characteristics compared to the current study. For instance, the IQAHE in t-MoTe2 remains resilient even up to 10K, highlighting its superior robustness.

Response 29

We are aware of the difference of energy scales, and we have pointed out this fact in our previous version of manuscript. In addition, we gave a possible explanation for the lower critical temperature in our system, which is the 5-times difference in the charge density involved in the topological flat band.

Although the states in t-MoTe$_2$ can persist to higher temperatures, our system shows many more fractional states. This is due to the higher material quality and easier electrical contact to make. This referee pointed out ‘The discovery of the FQAHE in a graphene-based system is particularly intriguing, given that graphene serves as an ideal platform for potential exploration of non-abelian braiding in the future.’, which we believe is partially based on similar considerations. The temperature to observe FQAHE in our system is still well within the reach of commercial dilution refrigerators or even He-3 refrigerators. Overall, we think t-MoTe$_2$ and our system both have pros and cons. If one is conceiving experiments that could not be done at hundreds of mK, t-MoTe$_2$ might have an advantage. But just talking about the phenomenon of FQAHE, our system clearly shows many more states and better quantization of R_{xy}.

In addition, we think it could be interesting to study the dependence of FQAHE on twist-angle and charge density in the graphene/hBN moiré. However, due to no theory prediction on this and the significant challenges in fabricating rhombohedral pentalayer/hBN devices, the twist-angle dependence is clearly beyond the scope of this work.

Minor comments in line 146; “Solid (dashed) lines correspond to scanning B from positive (negative) values to positive (negative) values.” I guess there are some mistakes.

Response 30

We thank the referee for pointing out this error. We have replaced this statement by “Solid (dashed) lines correspond to scanning *B* from positive (negative) values to negative (positive) values.”

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

I still maintain what I said in the first review. Akin to the advance that was recently made in producing high-quality GaAs heterostructures [which by the way was published in Nat. Materials (https://www.nature.com/articles/s41563-021-00942-3)], although a lot of fractions are seen in the experiments reported in the current work, they are fundamentally the same (integer quantum Hall of composite fermions) as the ones seen in other TMDs such as MoTe2. It may not have been theoretically predicted per se in graphene but this is similar to seeing even-denominator FQHE in ZnO [again that has come out in Nat. Phys. (https://www.nature.com/articles/nphys3259) and as far as I know people had not suggested that even-denominator FQHE would arise in that system] when it is well-known that GaAs heterostructures produce 5/2. Once the problem is shown to be similar to the lowest Landau level one just expects composite fermion physics to prevail. Although the transitions out of the CFL have not been seen in t-MoTe2, as far as I understand, it is a materials quality thing (similar to how 4/9 has not yet been seen in the t-MoTe2 system). If the authors are saying that such transitions cannot be observed in the t-MoTe2 system then this point should be made in the paper with adequate reasoning.

In summary, I find this paper to be more of a materials science advance for which a journal like Nat. Materials would be more appropriate. I am not trying to undermine the work of the authors: it is an important piece of work that should definitely be published but in my view, it is not to the very high standards of novelty, and originality that the Nature Journal attests to.

Referee #2 (Remarks to the Author):

The authors have addressed the questions of the reviewers satisfactorily and the revised manuscript is much improved. I support publication as is.

Referee #3 (Remarks to the Author):

The authors have satisfactorily answered all my queries. They have conducted experiments based on my suggestions and added to the revised manuscript. Particularly the data taken at constant current bias improves the quality of the plateau as well as the Rxx min within 5 ohm is quite remarkable. They have clarified all the measurement protocols used and stated in the revised manuscript and methods, which

will help the broader audience.
I recommend publication in Nature