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Fractional quantum anomalous Hall effect: a universal leap to topological quantum computation

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Quantum Hall effects have remained at the forefront of condensed matter physics research for decades, earning three Nobel Prizes in physics as a testament to their significance. In 1980, von Klitzing et al. discovered discrete Hall conductance $\sigma_{xy} = n\frac{e^2}{h}$ in a two-dimensional electron gas subjected to a magnetic field, where n represents the number of occupied Landau levels. This groundbreaking discovery is famously known as the integer quantum Hall effect and has been generalized in both fractional and anomalous ways (Fig. S1 online). On the one hand, electron–electron interaction can lift the degeneracy of the Landau levels and then fractionalize the Hall conductance to $\sigma_{xy} = \nu\frac{e^2}{h}$ ($\nu = \frac{p}{q}$ is the filling fraction with co-prime integers p and q), which is recognized as the fractional quantum Hall effect. On the other hand, Berry curvature emulates the magnetic field on bending the electron trajectory, albeit with an anomalous velocity, thereby quantizing the Hall conductance in the complete absence of magnetic fields to $\sigma_{xy} = C\frac{e^2}{h}$ (C is the Chern number of the occupied Bloch bands), which is identified as the quantum anomalous Hall effect.

The fractional quantum anomalous Hall effect, which is the fractional (anomalous) generalization of the quantum anomalous Hall effect (fractional quantum Hall effect), is the youngest member in the quantum Hall family. At certain filling fractions, the elementary excitations of the fractional quantum anomalous Hall effect and its superconducting analog may provide the non-Abelian statistics and the inherently robust fault tolerance needed by a topological qubit, rendering the fractional quantum anomalous Hall effect potentially pivotal for topological quantum computation. Specifically, as the fractional quantum anomalous Hall effect reproduces many filling fractions of the fractional quantum Hall effect (e.g., $\nu = \frac{2}{3}, \frac{3}{5}, \cdots$) [1–7], it is reasonable to expect anomalous generalization of the $\nu = N + \frac{k}{Mk+2}$ (N, M, and k are integers) Read-Rezayi fractional quantum Hall effects, among which the $\nu = \frac{13}{5}$ (i.e., $N = 2$, $M = 1$, and $k = 3$) one is characterized by the Read-Rezayi Z_3 parafermion state [8]. On the other hand, Vaezi [9] has proposed that a fractional topological superconductor formed by s-wave superconductivity proximitized $\nu = \frac{2}{3}$ fractional quantum anomalous Hall effect can also host a Z_3 parafermion state on the edge (Fig. S2a online). The Z_3 parafermion state supports non-Abelian Fibonacci anyons, whose braiding (Fig. S3 online) generates all the necessary quantum logic gates required by universal topological quantum computation.

A necessary first step towards universal topological quantum computation is to find the platforms supporting the fractional quantum anomalous Hall effect, which are known as the fractional Chern insulators. Recently, various experiments have identified $\sim 3.5^\circ$ twisted bilayer $MoTe_2$ ($tMoTe_2$) [1–4] and rhombohedral n-layer graphene/hexagonal boron nitride (RnG/hBN) moiré heterostructures with $n = 4, 5, 6$ [5–7] as fractional Chern insulators. So far, more filling fractions have been observed in the latter, presumably because RnG samples with high material quality and good contact fabrication are more easily accessible.

To implement universal topological quantum computation, the fractional Chern insulator candidates had better additionally support high filling fractions (i.e., $|\nu| > 1$, in particular, the $\nu = \frac{13}{5}$ filling fraction associated with the Read-Rezayi fractional quantum Hall effect [8]) or exhibit the fractional quantum anomalous Hall effect required by fractional topological superconductors that host parafermions [9]. In this regard, both $tMoTe_2$ and RnG/hBN moiré heterostructures can be promising platforms. It is found that $tMoTe_2$ can host multiple topological moiré bands with evidence of high filling fractions [10–12]. On the other hand, R4G and R5G exhibit quantum anomalous Hall effects with high Chern numbers $|C| = 3, 4, 5$ in the presence of spin–orbit coupling or magnetic fields [13–15], implying the possibility of fractional quantum anomalous Hall effects with high filling fractions. Both $tMoTe_2$ and RnG/hBN moiré heterostructures are promising to make fractional topological superconductors through the proximity effect (Fig. S2a online). Besides the proximity effect, superconductivity

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has been observed in Pd-metalized 3.7° tMoTe$_2$ [16] and predicted in R6G [17], rendering the two platforms promising candidates of fractional topological superconductors.

The experimental identification of the fractional quantum anomalous Hall effect in tMoTe$_2$ and RnG/hBN moiré heterostructures adopts dual-gated devices (Fig. S4 online). One major difference between the devices of the two fractional Chern insulator candidates lies in the real-space position of the moiré potential: between two rotationally misaligned MoTe$_2$ monolayers for the former [1–4], while between RnG and one of the hBN layers that is twisted by a small angle (0.22° for R4G/hBN, 0.77° for R5G/hBN, and 0.2° for R6G/hBN) for the latter [5–7].

Cai et al. [2] performed reflective magnetic circular dichroism on the 3.7° tMoTe$_2$ and rediscovered in the highest valence band ferromagnetism initially reported by Anderson et al. [18]. They subsequently identified on this band filling fractions $\nu=-\frac{2}{3}$ (without magnetic fields) and $\nu=-\frac{3}{5}$ (with a small magnetic field ~1T) using the trion photoluminescence technique [2]. Zeng et al. [3] provided thermodynamic evidence for the $\nu=-\frac{2}{3}$ fractional quantum anomalous Hall effect via optical compressibility measurements. The $\nu=-\frac{2}{3}$ filling fraction was further justified independently by Xu et al. [1] and Park et al. [4], where the quantized resistance plateaus (Fig. S5a–c online) served as the smoking-gun evidence of the fractional quantum anomalous Hall effect.

The transport measurements have recognized even more filling fractions in RnG/hBN moiré heterostructures, probably because of their higher material quality and better contact fabrication [5–7]. Lu et al. [5] observed in the R5G/hBN moiré heterostructure several filling fractions $\nu=\frac{2}{3},\frac{3}{5},\frac{4}{7},\frac{2}{5},\frac{3}{7},\frac{4}{9}$ (Fig. S5d–f online), which can be understood as the quantum anomalous Hall effect of the 2-flux anomalous composite fermions belonging to the $\nu=\frac{p}{2p\pm1}$ (p is integer) Jain sequence. On the other hand, Xie et al. [6] found in the R6G/hBN moiré heterostructure filling fractions $\nu=\frac{2}{3},\frac{3}{5},\frac{5}{7},\frac{7}{9}$ (Fig. S5g online), the latter two of which are associated with 4-flux anomalous composite fermions. In a subsequent work of Lu et al. [7], two more fractional quantum anomalous Hall states with $\nu=\frac{5}{9},\frac{5}{11}$ were observed in the R5G/hBN moiré heterostructure and $\nu=\frac{2}{3},\frac{3}{5}$ fractional quantum anomalous Hall effects were identified in a R4G/hBN moiré device. Remarkably, even-denominator filling fractions [5,6] have also been observed in RnG/hBN moiré heterostructures: the $\nu=\frac{1}{2}$ filling fraction in the R5G/hBN moiré heterostructure likely characterizes an anomalous composite Fermi liquid because of the linear R_{xy}-ν relationship (Fig. S5f online), while the $\nu=\frac{3}{4}$ filling fraction in the R6G/hBN moiré heterostructure still corresponds to the fractional quantum anomalous Hall effect due to the quantized Hall and locally minimized longitudinal signals (Fig. S5h online).

Density functional theory simulations, continuum models, and exact diagonalizations have been adopted to theoretically verify the fractional quantum anomalous Hall effect at various filling fractions of tMoTe$_2$ [19] and RnG/hBN moiré heterostructures [20].

Wang et al. [19] performed large-scale density functional theory simulations for the 3.89° tMoTe$_2$ and pointed out the critical role of lattice reconstruction in flattening and isolating the highest valence band (Fig. S6c online), which is topological and responsible for the experimentally observed fractional quantum anomalous Hall effect of filling fractions $\nu=-\frac{2}{3}$ [1–4] and $\nu=-\frac{3}{5}$ [2,4]. Projecting the gate-screened Coulomb interaction on this band, Wang et al. [19] further found that the spin gap of the $\nu=-\frac{2}{3}$ filling fraction dominated that of the $\nu=-\frac{1}{3}$ filling fraction (Fig. S6d online) and the many-body spectrum resulting from exact diagonalization unambiguously exhibited 3-fold ground state degeneracy (Fig. S6e online). Both features may demonstrate the presence (absence) of the $\nu=-\frac{2}{3}$ ($\nu=-\frac{1}{3}$) fractional quantum anomalous Hall effect in experiments [1–4].

Zhou et al. [20] employed a similar approach to demonstrate the fractional quantum anomalous Hall effect in the R5G/hBN moiré heterostructure and found similar spectral features (Fig. S6g, h versus Fig. S6c, e online). However, there are several key differences worthy to be noted. First, the Chern band in the R5G/hBN moiré heterostructure is induced by interaction (Fig. S6f, g online) rather than the moiré potential [20], which is responsible for the Chern band in the 3.89° tMoTe$_2$ [19]. Second, a large displacement field can stabilize the fractional quantum anomalous Hall effect in the R5G/hBN moiré heterostructure by flattening and isolating the Chern band (Fig. S6i online) [20], while the fractional quantum anomalous Hall effect in the 3.89° tMoTe$_2$ does not need such a displacement field [19], which may drive a topological phase transition to resistive/metallic states [1]. Lastly, Zhou et al. [20] argued that the moiré potential in the R5G/hBN moiré heterostructure, which is on the order of 0.01 meV and thus perturbative, was not necessary for the emergence of the fractional quantum anomalous Hall effect. Conversely, the moiré potential in the 3.89° tMoTe$_2$ is much larger (on the order of 10 meV) and is responsible for the presence of the flat Chern band with relatively uniform quantum geometry, a key ingredient for the fractional quantum anomalous Hall effect [19].

Universal topological quantum computation with parafermions may be implemented with highly filled fractional Chern insulators. To the best of our knowledge, no conclusive evidence of highly filled fractional quantum anomalous Hall effects has been reported in tMoTe$_2$ or RnG/hBN moiré heterostructures. Nevertheless, both platforms are known to host various highly filled topological states [10–15].

Highly filled integer and fractional quantum spin Hall effects have been identified in tMoTe$_2$ [10–12]. Kang et al. [10] experimentally studied the transport signatures of a 2.1° tMoTe$_2$ device with at most 4 valence moiré bands occupied in a valley (i.e., filling fraction up to $\nu=-8$) and revealed several quantum spin Hall states at $\nu=-2,-3,-4,-6$ by tracking the local minima of the four-terminal resistance and zeros of the Hall resistance (Fig. S7a–c online). Remarkably, the $\nu=-3$ filling fraction corresponds to a highly filled fractional quantum spin Hall effect, presumably comprising of a $\nu=-\frac{3}{2}$ fractional quantum anomalous Hall effect and its time-reversal partner [10], whose helical edge states have been confirmed by the nonlocal resistance measurement (Fig. S7d online). This $\nu=-\frac{3}{2}$ fractional quantum anomalous Hall effect might be extracted by increasing the twist angle, as Xu et al. [11] and Park et al. [12] have identified ferromagnetism in the second moiré band of tMoTe$_2$ with larger twist angles $\gtrsim 2.5°$. In the meanwhile, the topological nature of the second moiré band of tMoTe$_2$ [11,12] may shed new light in the pursuit of highly filled fractional quantum anomalous Hall effect.

Highly filled quantum anomalous Hall effects have been found in RnG/hBN moiré heterostructures [13–15]. Han et al. [13] experimentally identified in a dual-gated hBN-encapsulated R5G-WS$_2$ device (Fig. S7e online) quantum anomalous Hall effect of Chern number $C=-5$ (Fig. S7f–h online). Such a device differs from the R5G/hBN moiré heterostructure in two respects: (i) the presence of WS$_2$ that introduces spin–orbit coupling to R5G; and (ii) the absence of the moiré potential between R5G and hBN. Sha et al. [14] concurrently adopted a similar device comprising R4G and WSe$_2$ and revealed a $|C|=4$ quantum anomalous Hall effect. Han et al. [15] also reported quantum anomalous Hall effect of

$C = -3, -5$ in a dual-gated hBN-encapsulated R5G device subjected to a small magnetic field (Fig. S7i, j online). Highly filled fractional quantum anomalous Hall effect may emerge from the above high Chern number quantum anomalous Hall effects, if interaction can induce the needed fractionalization.

Universal topological quantum computation with parafermions may also be realized with fractional topological superconductors at the interface between the fractional quantum anomalous Hall effect and *s*-wave superconductivity [9]. Both tMoTe$_2$ and RnG/hBN moiré heterostructures can potentially be fabricated into such fractional topological superconductors via the proximity effect (Fig. S2a online). Besides the proximity effect, superconductivity may be induced or arise intrinsically in such platforms [16,17].

For the 3.7° tMoTe$_2$, a fractional Chern insulator verified by Cai et al. [2] and Park et al. [4], Jia et al. [16] found that superconductivity could be induced when the sample was Pd-metalized through the on-chip 2D growth mechanism. During this process, the Pd atoms of the pre-buried Pd nanostripes (Fig. S8a online) are triggered by annealing to react with MoTe$_2$, synthesizing a new compound Pd$_7$MoTe$_2$ [16]. Jia et al. [16] identified superconductivity in both Pd$_7$MoTe$_2$ and the Pd$_7$MoTe$_2$-tMoTe$_2$-Pd$_7$MoTe$_2$ moiré junction by measuring the critical temperature T_c and the critical field B_c (Fig. S8b–e online). In addition, Jia et al. [16] discovered that the critical current I_c displayed a "V-shaped" minimum at zero magnetic field (Fig. S8e online), in great contrast to the Fraunhofer pattern of a regular Josephson junction. All these features strongly imply anomalous superconductivity in the Pd-metalized 3.7° tMoTe$_2$. However, it is critically important to note that it is unclear whether superconductivity and fractional quantum anomalous Hall effect can simultaneously survive in the Pd-metalized 3.7° tMoTe$_2$ or the bare 3.7° tMoTe$_2$.

As for RnG/hBN moiré heterostructures, confirmed fractional Chern insulators for $n = 4, 5, 6$ [5–7], Boström et al. [17] applied extensive first-principles calculations for R6G to evaluate the phonon contribution to the superconducting pairing within the Eliashberg theory. Boström et al. [17] found two superconducting regions with their gap symmetry strongly depending on the parent normal state: a triplet f-wave gap arises from a spin and valley polarized parent state stabilized by electron correlation, while an extensive *s*-wave gap originates from a spin and valley unpolarized parent state where intervalley scattering dominates (Fig. S8f online). Intriguingly, Boström et al. [17] have also revealed at higher hole doping more superconducting regions, whose T_c's are comparable to those of the two lower-doping superconducting regions (Fig. S8g online). Tuning the top and back gate voltages allows access to the superconducting regions, studying the potential interplay between the fractional quantum anomalous Hall effect and superconductivity, and examining the possibility on the emergence of parafermions.

In the context of implementing universal topological quantum computation with parafermions potentially hosted by highly filled fractional Chern insulators and fractional topological superconductors, there are quite a few open questions urgently awaiting solutions (Table 1).

The first question is how to exactly realize parafermions. Despite the observed signatures of the highly filled fractional quantum spin Hall effect in 2.1° tMoTe$_2$ and the high Chern number quantum anomalous Hall effect in R4G and R5G with spin–orbit coupling or magnetic fields, there is still no theoretical or experimental evidence for the $\nu = \frac{13}{5}$ fractional quantum anomalous Hall effect, which is the lattice analog of the $\nu = \frac{13}{5}$ Read-Rezayi fractional quantum Hall effect and may potentially host Z_3 parafermion states. Moreover, though tMoTe$_2$ and RnG/hBN moiré heterostructures may in principle be fabricated into fractional topological superconductors, whether Z_3 parafermions can be supported in such venues is still unclear from both theoretical and experimental points of view. Furthermore, it would also be interesting to explore the possibility of realizing the more general $Z_{k\geq3}$ parafermions in both highly filled fractional Chern insulators and fractional topological superconductors.

Table 1
Potential interesting directions for studying the parafermions in the fractional quantum anomalous Hall effect and fractional topological superconductors.

Directions	Details
Search for Z_3 parafermions in highly filled fractional Chern insulators	Fractional Chern insulators exhibiting the $\nu = \frac{13}{5}$ fractional quantum anomalous Hall effect may host Z_3 parafermions. This hypothesis deserves careful theoretical and experimental examination.
Search for Z_3 parafermions in fractional topological superconductors	Whether *s*-wave superconductivity proximitized tMoTe$_2$ and RnG/hBN moiré heterostructures can possibility host Z_3 parafermions had better be checked from both theoretical and experimental points of view.
Search for $Z_{k\geq3}$ parafermions	Design fractional Chern insulators that inherently host $Z_{k\geq3}$ parafermions or support such parafermions in the presence of proximitized superconductivity.
Fabricate high-quality fractional Chern insulators	Improving the sample quality of fractional Chern insulators may pave the way to high filling fractions (e.g., the $\nu = \frac{13}{5}$ filling fraction in the Read-Rezayi fractional quantum Hall effect) associated with parafermions.
Fabricate high-quality fractional topological superconductors through the proximity effect	The air-sensitive tMoTe$_2$ and RnG need hBN protection and seem inherently difficult to be proximitized. It would be of great significance to insert an *s*-wave superconductor inside the hBN protection during the fabrication of fractional topological superconductors.
Examine the coexistence of superconductivity and the fractional quantum anomalous Hall effect in the 3.7° tMoTe$_2$	The 3.7° tMoTe$_2$ exhibits fractional quantum anomalous Hall effect and superconducts upon Pd metalization. It is useful to check whether the two features can coexist and lead to fractional topological superconductivity.
Examine the coexistence of superconductivity and the fractional quantum anomalous Hall effect in the R6G/hBN moiré heterostructure	Superconductivity has been predicted in R6G. It is useful to check whether the superconductivity persists in the presence of moiré potential arising from hBN encapsulation as well as interaction and displacement fields, under which circumstance fractional quantum anomalous Hall effect emerges.
Understand the superconductivity in the Pd-metalized 3.7° tMoTe$_2$	The "V-shaped" minimum of the critical current at zero magnetic field suggests in the Pd-metalized 3.7° tMoTe$_2$ anomalous superconductivity, whose nature may be verified by studying the associated boundary/vortex states.
Search for optimal twist angle for tMoTe$_2$	Study how the properties of tMoTe$_2$ rely on the twist angle and determine whether there exists an optimal twist angle for hosting parafermions.
Search for optimal layer number for RnG/hBN moiré heterostructures	Study how the properties of RnG/hBN moiré heterostructures rely on the number of layers n and determine whether there exists an optimal n for hosting parafermions.

The second issue is to fabricate high-quality fractional Chern insulators and fractional topological superconductors. On the one hand, to reach high filling fractions such as $\nu = \frac{13}{5}$ in fractional Chern insulators, the sample must be of good material quality. On the other hand, to obtain parafermion-hosting fractional topological superconductors through the proximity effect, the fabrication process must be delicately designed. This is because $t\mathrm{MoTe_2}$ and RnG are air-sensitive and should be protected by hBN encapsulation when pursuing the fractional quantum anomalous Hall effect, rendering the proximity challenging. To address this challenge, both the Pd-metalization-induced superconductivity in the 3.7° $t\mathrm{MoTe_2}$ and the intrinsic superconductivity in R6G may be possible solutions. However, as such superconductivity is hosted by devices slightly different from those harboring the fractional quantum anomalous Hall effect, the coexistence of superconductivity and the fractional quantum anomalous Hall effect had better be checked. In addition, the superconductivity in the Pd-metalized 3.7° $t\mathrm{MoTe_2}$ seems not s-wave and deserves a further examination (e.g., by checking the boundary/vortex states).

Last but not least, as $t\mathrm{MoTe_2}$ (RnG) is highly tunable with respect to the twist angle (number of layers), there may be an optimal value of twist angle (number of layers) for $t\mathrm{MoTe_2}$ (RnG/hBN moiré heterostructures) to host parafermions. If so, the value had better be settled by both theoretical and experimental approaches.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.04.063.

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