Fractional Quantum Hall State at $\nu = 1/2$ with Energy Gap Up to 6 K and Possible Transition from the One- to Two-Component State

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The fractional quantum Hall state (FQHS) observed in the lowest Landau level at filling factor $\nu = 1/2$ in wide quantum wells has been enigmatic for decades because the two-dimensional electron system (2DES) has a bilayer charge distribution but with significant interlayer tunneling. Of particular interest is whether the $1/2$ FQHS in this system has a one-component (1C) or two-component (2C) origin; these are typically identified as the Pfaffian (non-Abelian) or the Ψ_{331} (Abelian) FQHSs, respectively. We report here our experimental study of the evolution of the correlated states of an ultrahigh-quality 2DES confined to a 72.5-nm-wide GaAs quantum well. At the lowest densities, the 2DES displays only odd-denominator FQHSs, and the ground state at $\nu = 1/2$ is a composite fermion Fermi sea. As the density is increased, an FQHS emerges at $\nu = 1/2$, and becomes very strong. In a finite density range where the $1/2$ FQHS is strongest, we also observe its daughter FQHSs at $\nu = 8/17$ and $7/13$, consistent with the theoretically expected daughter states of a Pfaffian $1/2$ FQHS. At the highest densities, the 2DES becomes 2C, signaled by the emergence of a bilayer Wigner crystal state and the transitions of FQHSs flanking $\nu = 1/2$. The $1/2$ FQHS remains robust near this transition and, notably, its charge transport energy gap exhibits an *upward* cusp with a maximum value of about 6 K on the 1C side of the transition; this is the largest gap reported for any even-denominator FQHS. Our observation of the transition of the 2DES ground states near $\nu = 1/2$ to 2C states at high densities, and our measurements of the robustness of the $1/2$ FQHS against charge distribution asymmetry, suggest that the $1/2$ FQHS also makes a transition from 1C to 2C. Such a transition from a non-Abelian to Abelian state can open avenues for topological quantum information and quantum criticality.

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In low-disorder, interacting, two-dimensional electron systems (2DESs), the composite fermions (CFs) at a half-filled Landau level (LL) can undergo pairing to exhibit even-denominator fractional quantum Hall states (FQHSs). This was first observed at LL filling factor $\nu = 5/2$ in the $N = 1$ LL [1]. The $5/2$ FQHS is widely believed to host non-Abelian anyons [2–4] and is most likely characterized by one of the three wave functions: Pfaffian [5], anti-Pfaffian [6,7], or PH-Pfaffian [8]. The CF pairing is facilitated by the weaker electronic repulsion in the $N = 1$ LL because of the node wave function [2,9]. Non-Abelian anyons have potential use for highly fault-tolerant quantum technologies [2,10], leading to significant interest in even-denominator FQHSs.

In the $N = 0$ LL, even-denominator FQHSs were also observed at $\nu = 1/2$ in 2DESs confined to wide GaAs quantum wells (QWs) [11–13] and double QWs [14]. The 2DES in a wide QW has a bilayer charge distribution but with significant interlayer tunneling [15]. This has led to several experimental [11–13,16–22] and theoretical [23–30] works debating whether the $1/2$ FQHS in wide GaAs QWs is a one-component (1C), non-Abelian state stabilized by large tunneling, or a two-component (2C), Abelian (Ψ_{331}) state [31] that is stable in a bilayer system with negligible tunneling. Some of the earlier studies [13,25,27,28] argued for a 2C origin. However, direct measurements of the CF Fermi sea wave vector [19,20], and some theoretical calculations [23,24,26,29,30] favor a 1C, non-Abelian origin. Most recently, the observation of the daughter states of the $1/2$ FQHS at $\nu = 8/17$ and $7/13$ was reported in 2DESs with appropriate parameters, confined to ultrahigh-quality wide GaAs QWs [22]. Insofar as these are precisely the theoretically expected fillings for the daughter states of the Pfaffian $1/2$ FQHS [32–34], the observations strongly suggest a 1C, non-Abelian origin. This is also corroborated by very recent theoretical works [30,35]. In fact, Ref. [30] calculates a phase boundary between the CF Fermi sea and a $1/2$ FQHS using a variational wave function that is in the same universality class as the Pfaffian state, and this boundary is in good agreement with the experimental results.

We report here our latest findings on the evolution of the correlated states in a wide GaAs QW as a function of interlayer tunneling that we tune by changing the electron density (n) in the QW [12,13,15,18,22,36,37]. Figure 1(a) shows a simple schematic of our sample with front

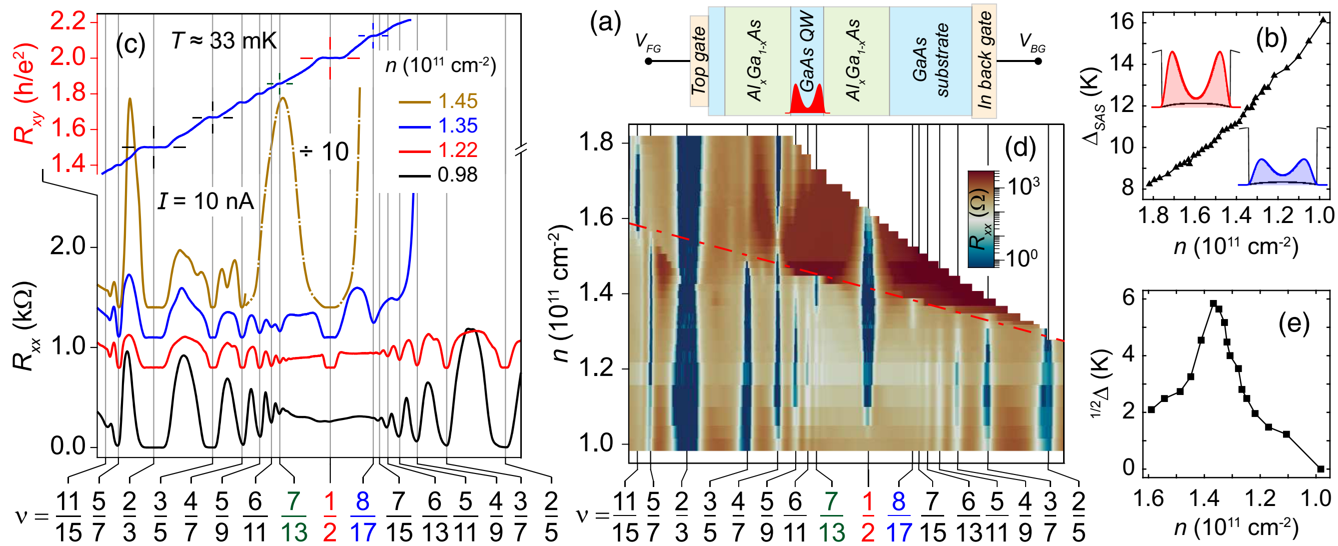

FIG. 1. (a) Sample schematic. (b) Δ_{SAS} extracted from the Shubnikov–de Haas oscillations at low B field. Self-consistent Hartree calculations of the charge distribution and potential at $n = 1.82$ and 1.00 in a 72.5-nm-wide GaAs QW are shown as top and bottom insets, respectively. (c) Characteristic longitudinal resistance R_{xx} traces which coarsely capture the most notable transitions such as the CF Fermi sea to FQHS at $\nu = 1/2$ (red trace), the emergence of the daughter states of the 1/2 FQHS at $\nu = 8/17$ and 7/13 (blue trace), and the bilayer Wigner crystal flanking $\nu = 1/2$ at the highest densities (brown trace). Also shown is the Hall resistance (R_{xy}) at $n = 1.35$, displaying well quantized plateaus for the $\nu = 1/2$, 8/17, and 7/13 FQHSs. (d) Color-scale phase diagram of the 2DES in the $N = 0$ LL, rich with correlated electronic solid and liquid phases. Transitions of the odd-denominator FQHSs and the emergence of a bilayer Wigner crystal signal the 1C to 2C transition of the 2DES as n increases (indicated by the red dashed-dotted line, a guide to the eye). (e) Energy gap of the 1/2 FQHS ($^{1/2}\Delta$) as a function of n, peaking to about 6 K.

and back gates to control both n and charge distribution symmetry. Shown in Fig. 1(b) are the interlayer tunneling values determined from the Fourier transforms of the low-field Shubnikov–de Haas oscillations [11–13,36,38]; see Supplemental Material (SM) Sec. I [39]. The parameter Δ_{SAS}, which is the energy difference between the QW's symmetric and antisymmetric electric subbands, directly measures the interlayer tunneling of a symmetric charge distribution. As n is raised, the electrons repel each other, forcing them toward the QW's walls and resulting in a bilayer charge distribution. This also raises the potential near the QW's center, thus reducing the interlayer tunneling [11–13,36,38]; see insets in Fig. 1(b) and SM Sec. IV [39].

Our sample is a modulation-doped, 72.5-nm-wide, GaAs QW with as-grown $n = 1.16$ (in units of 10^{11} cm^{-2} used throughout this Letter) and mobility $\mu \simeq 10 \times 10^6$ cm^2/Vs at $T = 0.3$ K, an order of magnitude larger than the samples in which the 1/2 FQHS was first observed [11]. This improvement is evident from the R_{xx} traces shown in Fig. 1(c). The traces are plotted as a function of $1/\nu$ with the x-axis tick marks displaying the expected positions of the various FQHSs. The lowest two traces at $n = 0.98$ and 1.22 show the transition of the CF Fermi sea to a robust FQHS at $\nu = 1/2$. The 1C nature of the 1/2 FQHS can be inferred from the numerous high-order, odd-denominator Jain states [40] flanking $\nu = 1/2$. At $n = 1.35$, the daughter states of the 1/2 FQHS emerge, competing against the Jain FQHSs at $\nu = 8/17$ and 7/13 [22,35,41]. The daughter FQHSs are observed as anomalously deep minima in R_{xx} accompanied by well-developed plateaus in R_{xy}; see the top trace in Fig. 1(c). The values of ν for these daughter states are consistent with those theoretically expected for the Pfaffian state [32–34]. Another major feature seen in Figs. 1(c) and 1(d) is an insulating phase that first emerges at small fillings ($\nu < 8/17$ at $n = 1.35$) and eventually surrounds the 1/2 FQHS at $n = 1.45$. Previous transport [12,36] and microwave resonance studies [42] identify this insulating phase as a pinned *bilayer* Wigner crystal.

The 2DES in wide GaAs QWs is rich with several high-order FQHSs at various ν as n is varied between $0.98 \lesssim n \lesssim 1.82$, summarized in Fig. 1(d); see SM Sec. II [39] for a complete set of R_{xx} traces [39]. Evidence for a 1C to 2C transition of the 2DES can be seen in Fig. 1(d) at states that are now accessible thanks to the much improved quality of our sample; these will be discussed at length later in the Letter.

Figure 1(e) manifests the robustness of the 1/2 FQHS in the form of its energy gap ($^{1/2}\Delta$) plotted as a function of n. The $^{1/2}\Delta$ is extracted by measuring R_{xx} at $\nu = 1/2$ for $0.03 \lesssim T \lesssim 0.4$ K and fitting it to the expression $R_{xx} \propto \exp(-^{1/2}\Delta/2k_BT)$; see SM Sec. III [39]. The most striking feature here is that the 1/2 FQHS at its maximum strength has an energy gap of about 6 K ($n = 1.37$). On either direction of the peak energy gap, $^{1/2}\Delta$ falls

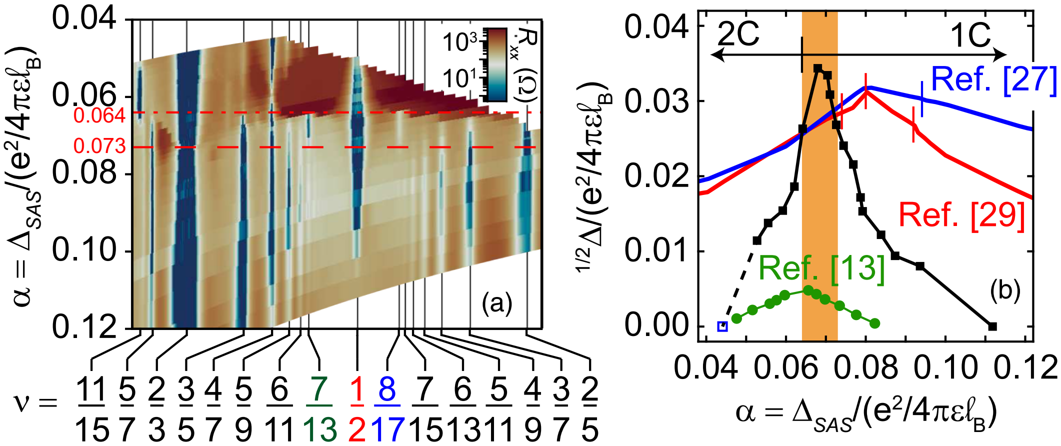

FIG. 2. Data of Figs. 1(d) and 1(e) are replotted in (a) and (b) respectively using the parameter $\alpha = \Delta_{\mathrm{SAS}}/(e^2/4\pi\epsilon\ell_B)$, the interlayer tunneling normalized to the Coulomb energy. (a) The daughter states of a 1C 1/2 FQHS emerge at $0.064 \lesssim \alpha \lesssim 0.073$ while the 1C to 2C transition of the 2DES near $\nu = 1/2$ occurs at $\alpha \lesssim 0.064$. (b) The measured $^{1/2}\Delta$ (black squares), normalized to the Coulomb energy [46], are about 8 times larger than those reported in a sample with much lower mobility (green circles) [13]. The orange band near $\alpha \simeq 0.07$ denotes the region of stability of the daughter 8/17 and 7/13 FQHSs, and straddles the peak $^{1/2}\Delta$ quite symmetrically. Also plotted are theoretical calculations for $^{1/2}\Delta$ in Refs. [27] (blue) and [29] (red). Note that both sets of calculations predict a boundary near the maximum $^{1/2}\Delta$ between the Pfaffian and Ψ_{331} phases as α is reduced. The vertical lines denote the experimental (black, at $\alpha \simeq 0.064$) 1C-2C transition of the 2DES, and theoretical (red and blue) predictions of the 1C-2C transition of the 1/2 FQHS; see SM Sec. VI [39] for details.

off sharply, by ≃50% to about 3 K at $n = 1.28$ and 1.45, which correspond to less than 7% change in n.

It is illuminating to examine the evolution of the correlated states in the lowest LL and their various transitions as a function of the parameter $\alpha = \Delta_{\mathrm{SAS}}/(e^2/4\pi\epsilon\ell_B)$ instead of n, as shown in Fig. 2; ϵ is the GaAs dielectric constant, and $\ell_B = \sqrt{\hbar/eB}$ is the magnetic length. The parameter α is the interlayer tunneling normalized to the Coulomb energy and is used to parametrize theoretical calculations and their comparison with experimental data [27,29]. Similarly, $^{1/2}\Delta$ is expressed in units of the Coulomb energy. Figure 2(a) makes it clear that the 2DES makes a 1C to 2C transition near $\nu = 1/2$ at $\alpha \simeq 0.064$. This is heralded by the emergence of the bilayer Wigner crystal insulating phases [12,36,42] on the flanks of $\nu = 1/2$ for $\alpha < 0.064$, and the disappearance of the *odd-numerator* FQHSs at 3/7, 5/11, 5/9, 3/5, and 5/7 when $\alpha < 0.064$ [43]. In contrast, the *even-numerator* FQHS at $\nu = 4/7$ is weakest at $\alpha \simeq 0.06$, also signaling a 1C to 2C transition [44,45].

It is evident in Fig. 2 that, while the 2DES is undergoing a 1C to 2C transition, the 1/2 FQHS remains strong and in fact has its maximum energy gap near this transition [Fig. 2(b)]. Also significant is that the FQHSs at $\nu = 8/17$ and 7/13, which are the predicted, simplest daughter states of a Pfaffian 1/2 FQHS [32–34], are seen in the range $0.064 < \alpha < 0.073$ where the 2DES exhibits 1C FQHSs while also displaying the largest energy gap [see orange shaded region in Fig. 2(b)]. These observations provide strong evidence that the 1/2 FQHS we observe in the range $\alpha > 0.064$ has a 1C origin. Moreover, Fig. 2(a) clearly shows that the 1/2 FQHS is observed even when $\alpha < 0.064$ and the 2DES has entered the 2C regime. The evolution of the interaction landscape of the 2DES raises the interesting question of a possible 1C to 2C transition of the 1/2 FQHS itself.

The susceptibility of the 1/2 FQHS to charge distribution asymmetry is another microscopic property that can shed light on the nature of the 1/2 FQHS. We probe this susceptibility by appropriately biasing the back and front gates to transfer charge from one side of the QW to the other side while keeping n in the QW constant; we quantify this charge transfer by $\Delta n/n$, where Δn is the difference of density between two sides of the QW determined from the measured variation of n with gate biases. In Fig. 3(a) we show examples of self-consistently calculated charge distributions for $n = 1.45$ and 1.28 for the symmetric (upper panels) and asymmetric (lower panels) cases, as indicated. Our measurements show that, regardless of n, the 1/2 FQHS monotonically becomes weaker and eventually turns into a compressible CF Fermi sea beyond a critical charge distribution asymmetry $(\Delta n/n)_C$ that depends on n. Data for $n = 1.17$ are shown in Fig. 3(b), revealing the destabilization of the 1/2 FQHS at $(\Delta n/n)_C \simeq 18\%$.

The measured $(\Delta n/n)_C$ at different densities are plotted in Fig. 3(c) (red circles, right y axis), and contrasted against $^{1/2}\Delta$ (black squares, left y axis). We find that the trend of $(\Delta n/n)_C$ is correlated to that of $^{1/2}\Delta$ as a function of n.

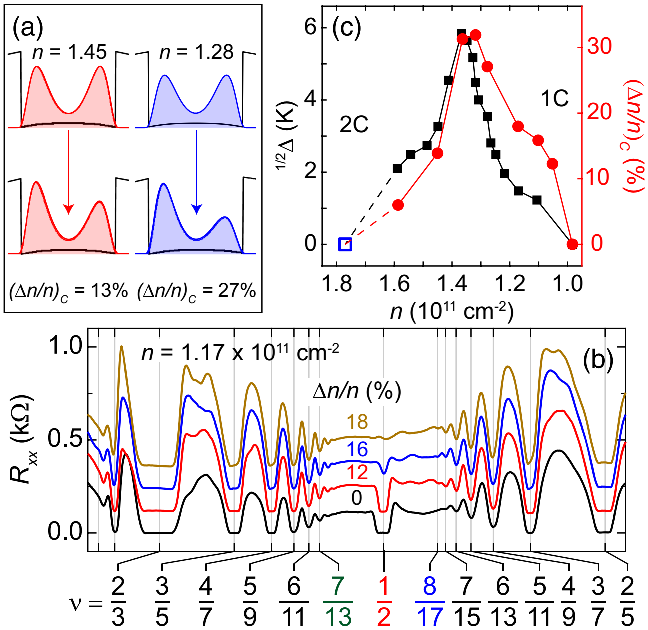

FIG. 3. (a) Calculated charge distributions at $n = 1.45$ (red) and $n = 1.28$ (blue) in a symmetric and asymmetric QW. (b) Characteristic R_{xx} traces at $n = 1.17$ showing the evolution of the $1/2$ FQHS as the charge distribution is made asymmetric. (c) The critical layer density imbalance $(\Delta n/n)_C$ required to destabilize the $1/2$ FQHS, plotted together with ${}^{1/2}\Delta$, as a function of n. The $1/2$ FQHSs on the high-density side of the ${}^{1/2}\Delta$ peak have smaller $(\Delta n/n)_C$.

However, smaller values of $(\Delta n/n)_C$ are required to destabilize the $1/2$ FQHS on the high-density side of the peak ${}^{1/2}\Delta$, as compared to the low-density side. For example, when the charge distribution is symmetric, the $1/2$ FQHS has the same strength (${}^{1/2}\Delta \simeq 3.3$ K) at $n = 1.45$ and 1.28. However, $(\Delta n/n)_C \simeq 13\%$ for $n = 1.45$ is significantly smaller than $(\Delta n/n)_C \simeq 27\%$ for $n = 1.28$. Considering the intuitive expectation that a 2C $1/2$ FQHS, e.g., the Ψ_{331} state, would be less robust against charge distribution asymmetry compared to a 1C state such as the Pfaffian [47] or a Pfaffian-like state [30], our observation suggests that the $1/2$ FQHS we see at high densities is a 2C state.

A comparison of our data to those reported in Ref. [13], which studied the evolution of the $1/2$ FQHS in a 77-nm-wide-GaAs QW, is instructive. In Fig. 2(b) we have included the ${}^{1/2}\Delta$ vs α data (open circles) reported in Ref. [13]. The data are qualitatively consistent with our new results in that ${}^{1/2}\Delta$ vs α exhibits a peak, and the peak position (in α) is in fact very close to what we observe. However, there are several important differences; we attribute these to the much higher quality of our sample, which has about 10 times larger mobility (SM Sec. VII [39]). First, the measured ${}^{1/2}\Delta$ are about 8 times larger in the new sample, reflecting the much less significant role of disorder. Second, the new sample exhibits many more FQHSs on the flanks of the $\nu = 1/2$, including daughter states of the $1/2$ FQHS at $\nu = 8/17$ and $7/13$ when the $1/2$ FQHS is strong. These collectively allow us to observe a clear 1C to 2C transition of the 2DES (below $\alpha \simeq 0.064$). Third, in Ref. [13], typical $(\Delta n/n)_C$ for the disappearance of the $1/2$ FQHS were only $\simeq 20\%$, and this lack of robustness to charge distribution asymmetry in fact led Suen *et al.* to conclude that the $1/2$ FQHS had a 2C origin [13]. In contrast, our data in Fig. 3(c) show that the $1/2$ FQHS is stable even for $(\Delta n/n)_C$ exceeding 30%, consistent with its having a 1C origin. We emphasize that our conclusion is based not only on the absolute value of $(\Delta n/n)_C$, but also on its trend as a function of n, namely that the $1/2$ FQHS is much more robust to charge distribution asymmetry when the 2DES exhibits 1C features.

Several theory groups have focused on the competition between the 1C (Pfaffian) and 2C (Ψ_{331}) FQHSs at $\nu = 1/2$ in wide QWs [26,27,29]. Their calculations, which ignore the CF Fermi sea as a competing state, generally indicate a transition between a 1C FQHS at large α to a 2C FQHS at small α. In Fig. 2(b) we show the results of Refs. [27,29]; also see Refs. [48,49]. Similar to the experimental data, the theoretical results exhibit a nonmonotonic dependence of ${}^{1/2}\Delta$ on α with a maximum energy at an intermediate α. At first sight, the similarity of the theoretical and experimental results is quite impressive in that α at which the gap reaches its maximum value, as well as the magnitude of the maximum gap, are in reasonably good agreement.

However, there are several noteworthy caveats. First, it is surprising that the measured gaps near their maximum exceed the calculated values. Measured gaps for FQHSs are generally smaller than the gaps calculated for ideal 2DESs because of finite (nonzero) electron layer thickness, LL mixing, and disorder in real samples [50–55]. The role of finite layer thickness is presumably included in Refs. [27,29] as these studies consider charge distributions that are appropriate for 2DESs in wide QWs. But, to make the calculations feasible, they use only "model" charge distributions, and it is possible that the calculated energy gaps are inaccurate as they can sensitively depend on the exact charge distributions (see SM Secs. IV and V [39] for a more detailed discussion).

Second, compared to the theoretical curves, the experimental data in Fig. 2(b) exhibit a much sharper peak and a much narrower range of α where the $1/2$ FQHS is stable. This might reflect the fact that the energy gap calculations in Refs. [27,29] do not consider the competition with the CF Fermi sea (for large values of α) or a bilayer Wigner crystal (for small α). This shortcoming of the calculations is clear considering that both the experimental data [Fig. 2(b)] and recent theoretical results [30] show that in our wide QW the $1/2$ FQHS gives way to a CF Fermi sea at $\alpha > 0.11$, while the calculations in Refs. [27,29] predict that the 1C FQHS continues to persist up to much larger α.

Another important feature of Fig. 2 data is the critical α (α_C) at which the transition between the 1C and 2C $1/2$

FQHS occurs. Our experimental data [Fig. 2(a)] indicate that the 2DES undergoes its 1C to 2C transition at $\alpha_C \simeq 0.064$, which is just to the left of the observed peak in ${}^{1/2}\Delta$ [Fig. 2(b)]. We note that $\alpha_C \simeq 0.064$ is obtained from the 1C to 2C transitions observed at other fillings near 1/2. References [27,29] predict that the 1C to 2C transition of the 1/2 FQHS occurs in the vicinity of the peak ${}^{1/2}\Delta$; see SM Sec. VI [39]. Regardless of the precise value of α_C, it is remarkable that both experimental data and calculations indicate that the 1/2 FQHS energy gap does not collapse when the 2DES makes a 1C to 2C transition, and in fact shows a *maximum* near the transition, with a persisting Hall plateau [56]. This is surprising, although it has been suggested that the 1C Pfaffian state can continuously evolve to the 2C Ψ_{331} state [57–61] by varying the interlayer tunneling. References [26,29] identify that the peak in ${}^{1/2}\Delta$ likely occurs because of a level crossing at $\nu = 1/2$ between the lowest excited state and higher energy levels with 1C and 2C character. This is also discussed by Wen [60] in his theory of continuous topological phase transitions, characteristics of which include finite charge gap but collapse of the neutral gap. In the special case of the Pfaffian and Ψ_{331} states, a continuous topological phase transition involves a neutral Majorana mode at the critical point, while the charged excitations remain gapped [60,62,63]. To summarize, our data provide clear evidence for a 1C to 2C transition of the 2DES on the flanks of $\nu = 1/2$, and suggest that the 1/2 FQHS also makes such a transition [64]. A topological phase transition between a 1C (non-Abelian) and 2C (Abelian) FQHSs, to the best of our knowledge, is unique to the 1/2 FQHS in wide GaAs QWs, opening avenues to experiments in quantum criticality such as those proposed in Ref. [65].

We close by remarking that even-denominator FQHSs at half-filled LLs have been reported in the excited $N = 1$ LL in several platforms such as 2DESs in GaAs [1,66,67], ZnO [68], AlAs [69], monolayer, bilayer and trilayer graphene [70–77], and WSe_2 [78]. They have also been reported in the $N = 0$ LL in 2D hole systems confined to wide GaAs QWs [79,80], and 2DESs in wide AlAs QWs [81]. Very recently, 2D hole systems in ultrahigh-quality GaAs QWs have also revealed a number of even-denominator FQHSs at unusual fillings, e.g., at $\nu = 3/4$, 3/8, 3/10, and 1/4 [82–84]. We would like to emphasize that the 6 K gap we measure for the 1/2 FQHS in our sample is the largest transport gap ever reported for any even-denominator FQHS. This is particularly impressive considering that our sample size ($\simeq$20 mm^2) is macroscopic, and is about 10^7 larger than the typical size of bilayer graphene samples where comparable energy gaps (up to $\simeq$5 K) have been reported [74]. The very large energy gap and sample size, together with the evidence that the 1/2 FQHS we observe is 1C, most likely a Pfaffian (non-Abelian) state, make this FQHS a prime candidate platform for topological quantum computing.

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Data availability—The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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[44] One would expect similar transitions for other even-numerator FQHSs near $\nu = 1/2$, but they are engulfed on the 2C side by the strong insulting phases that surround $\nu = 1/2$, especially for $\nu < 1/2$; see Ref. [36].

[45] The transitions at $\nu = 2/3$ and $4/7$ occur at slightly different values of α. The $2/3$ FQHS undergoes its 1C to 2C transition at $\alpha \simeq 0.073$ as signaled by the narrowing of the $2/3$ FQHS plateau.

[46] Note that the blue, open square in Fig. 2(b) represents the density ($n \simeq 1.78$) at which, based on the phase diagram for the stability of $1/2$ FQHS in wide GaAs QWs [18], we expect the $1/2$ FQHS to collapse and give way to an insulating phase. In our experiments we do not have access to the magnetic fields required to reach $\nu = 1/2$ at $n = 1.78$, but the weakening of the $1/2$ FQHS and the dominance of the insulating phase as this density is approached is evident in Fig. 1(d).

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