Anomalous Nematic States in High Half-Filled Landau Levels

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It is well established that the ground states of a two-dimensional electron gas with half-filled high (N ≥ 2) Landau levels are compressible charge-ordered states, known as quantum Hall stripe (QHS) phases. The generic features of QHSs are a maximum (minimum) in a longitudinal resistance $R_{xx}$ ($R_{yy}$) and a nonquantized Hall resistance $R_H$. Here, we report on emergent minima (maxima) in $R_{xx}$ ($R_{yy}$) and plateau-like features in $R_H$ in half-filled $N ≥ 3$ Landau levels. Remarkably, these unexpected features develop at temperatures considerably lower than the onset temperature of QHSs, suggestive of a new ground state.

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The ground state of a two-dimensional electron gas (2DEG) at half-integer filling factors $\nu = i/2, i = 1, 3, 5, \ldots$, can depend sensitively on the Landau level (LL) index $N$. At $N = 0$ ($\nu = 1/2, 3/2$) it is a compressible composite fermion metal [1], whereas at $N = 1$ ($\nu = 5/2, 7/2$) it is an incompressible fractional quantum Hall insulator formed by paired composite fermions [2,3]. At $N = 2$ and several higher LLs ($\nu = i/2, i = 9, 11, \ldots$), the competition between long-range repulsive and short-range attractive components of Coulomb interaction leads to compressible charge-ordered phases [4–6]. These phases can be viewed as unidirectional charge-density waves consisting of stripes with alternating integer $\nu$ (e.g., $\nu = 4$ and $\nu = 5$) and are commonly known as quantum Hall stripes (QHSs) [7].

With few exceptions [9,10], QHSs in a 2DEG confined to GaAs quantum wells align along (110) crystal axis of GaAs. This symmetry breaking field remains enigmatic, despite many efforts to identify its origin [10–13].

The generic QHS features are a maximum (minimum) in a longitudinal resistance $R_{xx}$ ($R_{yy}$), which develop at temperatures $T ≤ 0.1$ K, and a nonquantized Hall resistance $R_H$ [14,15]. More precisely, QHSs form when partial filling factor $\nu^* = \nu - [\nu]$, where $[\nu]$ is an integral part of $\nu$, falls in the range of $0.4 \leq \nu^* \leq 0.6$. The resistance anisotropy ratio $\alpha_R ≡ R_{xx}/R_{yy}$ normally achieves a single maximum value $\alpha_R ≃ 1$ at $\delta\nu ≃ 0.5 \pm 0.0$ and quickly drops to $\alpha_R ≃ 1$ at $\delta\nu ≃ 0.1$. This drop occurs due to a monotonic decrease (increase) of the $R_{xx}$ ($R_{yy}$) with $|\delta\nu|$.

In this Letter, we report on anomalous nematic states which are distinguished from QHSs by minima (maxima) in $R_{xx}$ ($R_{yy}$) and plateau-like features in $R_H$ in half-filled $N ≥ 3$ Landau levels. The global maxima (minima) in the $R_{xx}$ ($R_{yy}$) occur away from half filling, at $\delta\nu ≃ \pm 0.08$, where the resistance anisotropy ratio attains its maximal value. Remarkably, all these features emerge at temperatures considerably lower than the onset temperature of QHSs, which indicates possible transition to a new phase.

The 2DEG in sample A (B) resides in a GaAs quantum well of width 29 nm (30 nm) surrounded by Al$_{0.23}$Ga$_{0.76}$As barriers. After a brief low-temperature illumination, samples nominally had the electron density $n_e ≃ 3.0 \times 10^{11}$ cm$^{-2}$ and the mobility $\mu ≃ 2 \times 10^4$ cm$^2$ V$^{-1}$ s$^{-1}$. Samples were $4 \times 4$ mm squares [16] with indium contacts fabricated at the corners and the midides. $R_{xx}$ ($R_{yy}$) was measured using a four-terminal, low-frequency lock-in technique, with the current sent between midside contacts along $\hat{x} ≡ (110)$ ($\hat{y} ≡ (110)$) direction. $R_H$ was measured concurrently with $R_{xx}$.

In Fig. 1(a) we present $R_{xx}$ and $R_{yy}$ versus magnetic field $B$ measured in sample A at $T ≃ 25$ mK. Near $\nu = 11/2, 15/2$, and $\nu = 17/2, R_{xx}$ ($R_{yy}$) exhibits maxima (minima), with $R_{xx} ≫ R_{yy}$, as expected of the usual QHS phases. Remarkably, the behavior in the vicinity of $\nu = 13/2$ is qualitatively different; even though $R_{xx} ≫ R_{yy}$ (like at other $\nu = i/2$), $R_{xx}$ exhibits a pronounced minimum, whereas $R_{yy}$ shows a maximum near half filling. The global maxima (minima) in $R_{xx}$ ($R_{yy}$) occur away from half filling, namely at $\nu = 13/2 \pm 0.08$, as illustrated by vertical dashed lines. As a result, $\alpha_R$ becomes a nonmonotonic...
coincidental. Indeed, steps in RH plateau-like feature in RK of ν with function of B and exhibits maxima at T ≈ 70 mK, the two Ryy minima near ν = 13/2 ± 0.08 and the maximum near ν = 13/2 are replaced by single minimum, centered at ν = 13/2 with Ryy ≈ 0. Such a broad minimum is a characteristic feature of the well-developed QHS phase. In contrast, the broad minimum near ν = 11/2 observed at T ≈ 25 mK becomes narrower at T ≈ 70 mK, consistent with previous studies of QHSs. These data demonstrate that unexpected extrema near ν = 13/2 emerge at temperatures lower than the onset temperature of QHSs.

Some of our samples revealed the unexpected Rxx minima not only near ν = 13/2, as in Fig. 1, but also near other half-integer ν [21]. In Fig. 3 we show the data obtained from sample B which exhibit pronounced Rxx minima at ν = 13/2, 15/2, and 17/2. All of these minima are accompanied by plateau-like features in Ryy, see right axis, which assumes the values close to 2RK/i, with i = 13, 15, 17, as indicated by horizontal line segments in Fig. 3. Moreover, Rxx maxima occur nearly precisely at the same ν* as in Fig. 1, i.e., at ν* = 1/2 ± 0.08, as illustrated by vertical dashed lines. Whether or not the value of |δν| = 0.08 is universal remains an open question.
We now turn to the temperature dependence in sample $B$ which is illustrated in Fig. 4(a) showing $R_{xx}$ (dark line) and $R_{yy}$ (light line) as a function of $B$ measured at different $T$, as marked. The Hall resistances $R_H$ measured at $T \approx 135$ mK (light line) and $T \approx 30$ mK (dark line) are shown in Fig. 4(b). At $T \approx 135$ mK, $R_{xx}$ and $R_{yy}$ near $\nu = 11/2$ and $\nu = 15/2$ are featureless and $R_H$ is classical. At $\nu \approx 13/2$, however, the anisotropy is already developed ($\alpha_R \approx 6$) and $R_H$ shows a clear signature of a reentrant integer quantum Hall state near $\nu \approx 6.72$ (as marked by $\uparrow$ in the figure), indicative of a bubble phase. As anticipated, $R_{xx}$ ($R_{yy}$) exhibits a single maximum (minimum) at $\nu \approx 13/2$, i.e., the strongest anisotropy occurs close to half filling, consistent with nearly all previous experiments [26]. The fact that transport anisotropies in the lower-spin branches of a LL develop at higher temperatures (e.g., $\nu \approx 9/2, 13/2$) than in the upper-spin branches ($\nu \approx 11/2, 15/2$) is well documented (see, e.g., Ref. [14]).

Upon cooling to $T \approx 100$ mK, transport anisotropy with a maximum in $R_{xx}$ and a minimum in $R_{yy}$ also emerges at both $\nu \approx 11/2$ ($\alpha_R \approx 20$) and at $\nu \approx 15/2$ ($\alpha_R \approx 30$). Near $\nu \approx 13/2$, however, even though the anisotropy becomes an order of magnitude stronger ($\alpha_R \approx 60$), $R_{xx}$ now exhibits a pronounced minimum near half filling indicating an onset of the anomalous nematic state. When the sample is cooled to $T \approx 60$ mK, the resistance anisotropy at $\nu \approx 11/2$ increases dramatically ($\alpha_R > 300$), in agreement with previous studies. Concurrently, we observe that the $R_{xx}$ minimum at $\nu \approx 13/2$ deepens and that the resistance anisotropy is reduced by about a factor of 3 compared to its value at $T \approx 100$ mK. Remarkably, the $R_{xx}$ near $\nu \approx 15/2$ also develops a minimum at this temperature. At $T \approx 30$ mK, the magnetotransport near $\nu = 11/2$ remains qualitatively unchanged, although the anisotropy ratio becomes even higher ($\alpha_R \approx 400$). Near $\nu = 13/2$, however, further development of the $R_{xx}$ minimum and the appearance of the $R_{yy}$ maximum reduce the anisotropy to $\alpha_R \approx 10$. While we do not observe a maximum in the $R_{yy}$ near $\nu = 15/2$, the $R_{xx}$ minimum becomes more pronounced and the anisotropy reduces to $\alpha_R < 20$. As previously noted, the $R_{xx}$ minima near $\nu = 13/2$ and $\nu = 15/2$ are accompanied by plateau-like features in the $R_H$, see Fig. 4(b).

It is evident that the temperature dependencies near $\nu = 13/2$ and $\nu = 15/2$ are qualitatively similar. At temperatures immediately below the onset temperature at which
dependence of $R_{xx}$ and $R_{yy}$ at $\nu = i/2$ than away from half filling and our data do not reflect that. Therefore, the observed dependencies on $\nu$ and $T$ are inconsistent with QHS or a nematic-to-smectic phase transition [27]. Instead, the observed low-temperature emergence of unexpected extrema in $R_{xx}$ and $R_{yy}$ along with the plateaulike features in the $R_{xy}$ likely reflects the formation of another competing ground state.

In addition to the temperature dependence, it is interesting to investigate the effects of the carrier density and of the in-plane magnetic field. Our measurements on a state-of-the-art tunable-density van der Pauw device with in situ back gate have not revealed these anomalous states at any density from 2.2 to $3.6 \times 10^{11}$ cm$^{-2}$ [33], as neither have those using high density $[n_e = (4.1-4.3) \times 10^{11}$ cm$^{-2}$] heterostructures [34]. However, the carrier mobilities of samples used in the above experiments were below $1.2 \times 10^{7}$ cm$^{2}$ V$^{-1}$ s$^{-1}$, and, since the anomalous nematic states form at considerably lower temperatures than QHSs, it is reasonable to expect that they are more easily destroyed by disorder. The absence of anomalous nematic states in these more-disordered samples yields further support to the importance of electron-electron correlations. Measurements in tilted magnetic fields are currently under way and will be a subject of future publication. We note, however, that the effect of the in-plane magnetic field remains poorly understood even for conventional QHSs [33,35,36] which might complicate the interpretation of the data.

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[7] With further consideration of thermal and quantum fluctuations, several electron liquid crystal-like phases have also been proposed [8].


[16] Signatures of anomalous nematic states have also been observed in Hall bar geometry.


[21] Anomalous nematic states are very fragile and the $R_{xx}$ maxima near $\nu = i/2$ are more elusive than the $R_{xx}$ minima. As for other fragile states in quantum Hall systems forming below 0.1 K, the uniformity of the carrier density is obviously an important factor. Another requirement is a good sample “state” which, we believe, is determined by the disorder landscape. The latter, in turn, sensitively depends on the details of both cooldown and illumination procedures, which are known to produce charge redistribution between the quantum well, the doping layers, and the sample surface [22–24], thereby leading to different degrees of screening of the disorder potential [25]. Nevertheless, after multiple cooldowns of different samples we are confident that the phenomenon is generic.


[26] We are aware of only two experiments which observed maximum resistance anisotropy at $a > 0.5$ [27,28].


[29] A turnover in the temperature dependence has been observed previously [27,30], but no local resistance extrema near $\nu = 0.5$ have been reported to date.


[32] At $a = 1/2$, Ref. [31] predicts $\rho_{xx} \propto T^{-a}$ and $\rho_{yy} \propto T^{a}$ with $a \approx 0.5$. 

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