Anomalous Nematic States in High Half-Filled Landau Levels

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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 [8, 9], 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 [9–12].

The generic QHS features are a maximum (minimum) in a longitudinal resistance $R_{xx}$ ($R_{yy}$), which develop at temperatures $T \lesssim 0.1$ K, and a non-quantized Hall resistance $R_H$ [13, 14]. More precisely, QHSs form when $E \lesssim 0.4 \lesssim \nu^* \lesssim 0.6$. The resistance anisotropy ratio $\alpha_R \equiv R_{xx}/R_{yy}$ normally achieves a single maximal value $\alpha_R \approx 1$ at $\delta \nu \equiv \nu^* - 0.5 \approx 0$ and quickly drops to $\alpha_R \approx 1$ at $\delta \nu \approx \pm 0.1$. 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 $N \geq 3$ Landau levels. The global maxima (minima) in the $R_{xx}$ ($R_{yy}$) occur away from half-filling, at $\delta \nu \approx \pm 0.08$, 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$_0.25$Ga$_0.75$As barriers. After a brief low-temperature illumination, samples nominally had the electron density $n_e \approx 3.0 \times 10^{11}$ cm$^{-2}$ and the mobility $\mu \gtrsim 2 \times 10^7$ cm$^2$V$^{-1}$s$^{-1}$. Samples were 4 × 4 mm squares [15] with indium contacts fabricated at the corners and the mid-sides. $R_{xx}$ ($R_{yy}$) was measured using a four-terminal, low-frequency lock-in technique, with the current sent between mid-side contacts along $\hat{x} \equiv (110)$ ($\hat{y} \equiv (110)$) direction.

In Fig. 1(a) we present $R_{xx}$ and $R_{yy}$ versus magnetic field $B$ measured in sample A at $T \approx 25$ mK. Near $\nu = 11/2, 15/2$, and $\nu = 17/2$, $R_{xx}$ ($R_{yy}$) exhibits maximum (minima), with $R_{xx} \gg R_{yy}$, as expected of the usual QHS phases. Remarkably, the behavior in the vicinity of $\nu = 13/2$ is qualitatively different; even though $R_{xx} \gg R_{yy}$ (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 non-monotonic function of $\delta \nu \equiv |\nu^* - 0.5|$; it is relatively small at $\delta \nu = 0$ and exhibits maxima at $\delta \nu \approx \pm 0.08$. The variation of $\alpha_R$ with $\nu^*$ is quite significant, it drops from $\alpha_R > 600$ at $\nu = \nu_+ \approx 6.68$ to $\alpha_R < 10$ near half-filling.

In Fig. 1(b) we show the Hall resistance $R_H$ as a function of $B$. Concurrent with the unexpected extrema in $R_{xx}$ and $R_{yy}$ at $\nu = 13/2$, the Hall resistance shows a plateau-like feature, marked by solid horizontal lines drawn at $2R_K/13$, where $R_K \equiv h/e^2$ is the von Klitz-
quantization at was also established that in AlAs quantum wells, Hall recently observed in the signatures of even-denominator quantum Hall states were in these cases its appearance might be coincidental. Indeed, steps in for a developing even-denominator quantum Hall state, quantized values (cf. dashed horizontal line segments = 13 ν

FIG. 1. (Color online) (a) $R_{xx}$ and $R_{yy}$ versus $B$ measured in sample A at $T \approx 25$ mK. Half-integer $\nu$ are marked by $15/2, 13/2$, and $11/2$. The $R_{xx}$ minimum and the $R_{yy}$ maximum at $\nu \approx 13/2$ are marked by $\dagger$ and $\downarrow$, respectively. Dashed vertical lines are drawn at $\nu \backsim 6.5 \pm 0.08$. (b) Hall resistance $R_H$ versus $B$. Solid horizontal lines, drawn at $2R_K/13$, mark a plateau-like feature near $\nu = 13/2$, while dashed horizontal lines are drawn at $2R_K/11$ ($\nu = 11/2$) and $2R_K/15$ ($\nu = 15/2$), where $R_K \equiv h/e^2 = 25812.80745$ $\Omega$ is the von Klitzing constant.

and be accompanied by a maximum in easy resistance [17]. Finally, fractional quantum Hall nematic states have been reported at $\nu = 7/3$ [18] and $\nu = 5/2$ [19] in tilted magnetic fields.

The anomalous nematic state near $\nu = 13/2$ depicted in Fig. 1 is best observed at low temperatures. As a glimpse at the temperature dependence, we present in Fig. 2 the easy resistance $R_{yy}$ as a function of $B$ measured in sample A at two different temperatures. Remarkably, as the temperature is raised from $T \approx 25$ mK to $T \approx 70$ mK, the two $R_{yy}$ minima near $\nu = 13/2 \pm 0.08$ and the maximum near $\nu = 13/2$ are replaced by single minimum, centered at $\nu = 13/2$ with $R_{yy} \approx 0$. Such a broad minimum is a characteristic feature of the well-developed QHS phase. In contrast, the broad minimum near $\nu = 11/2$ observed at $T \approx 25$ mK becomes narrower at $T \approx 70$ mK, consistent with previous studies of QHSs. These data demonstrate that unexpected extrema near $\nu = 13/2$ emerge at temperatures lower than the onset temperature of QHSs.

Remarkably, some of our samples revealed the unexpected $R_{xx}$ minima not only near $\nu = 13/2$, as in Fig. 1, but also near other half-integer $\nu$ [20]. In Fig. 3 we show the data obtained from sample B which exhibit pronounced $R_{xx}$ minima at $\nu = 13/2$, 15/2, and 17/2. All of these minima are accompanied by plateau-like features in $R_H$, see right axis, which assumes the values close to $2R_K/i$, with $i = 13, 15, 17$, as indicated by horizontal line segments in Fig. 3. Moreover, the $R_{xx}$ maxima occur nearly precisely at the same $\nu^*$ as in Fig. 1, i.e., at $\nu^* = 1/2 \pm 0.08$, as illustrated by vertical dashed lines. Whether or not the value of $|\delta \nu| = 0.08$ 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 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. Near $\nu \approx 13/2$, however, the

FIG. 2. (Color online) $R_{yy}$ versus $B$ measured in the sample A at $T \approx 25$ mK (light line) and at $T \approx 70$ mK (dark line). Half-integer $\nu$ are marked by 13/2, and 11/2.
anisotropy is already developed ($\alpha_R \approx 6$) and $R_H$ shows a clear signature of a re-entrant 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 [21]. 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. 13).

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 three 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 $\nu \approx 11/2$ remains qualitatively unchanged, although the anisotropy ratio becomes even higher ($\alpha_R \approx 400$). Near $\nu \approx 13/2$, 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 the QHS anisotropy sets in, the data at both filling factors exhibit normal behavior, i.e., a broad single maximum (minimum) in the $R_{xx}$ ($R_{yy}$). Upon cooling down further, both filling factors demonstrate the gradual development of the “splitting” in the $R_{xx}$, around half-filling, marked by a reduction of the anisotropy ratio and by the emergence of plateau-like features in the

![FIG. 3.](image-url) (Color online) $R_{xx}$, $R_{yy}$ (left axis), and $R_H$ (right axis) versus $B$ measured in sample B at $T \approx 30$ mK. Half-integer $\nu$ are marked by $17/2$, $15/2$, $13/2$, and $11/2$. The $R_{xx}$ minima at $\nu = 13/2$, $15/2$, $17/2$ and the $R_{yy}$ maximum near $\nu = 13/2$ are marked by $\uparrow$ and $\downarrow$, respectively. Dashed vertical lines are drawn at $\nu_{\pm} = i/2 \pm 0.08$, $i = 13, 15, 17$. Near $\nu = 1/2$ ($i = 13, 15, 17$), $R_H$ shows plateau-like features with $R_H \approx 2R_K/i$, marked by solid horizontal lines.

![FIG. 4.](image-url) (Color online) (a) $R_{xx}$ (dark line), $R_{yy}$ (light line) versus $B$ measured in sample B at $T \approx 135$ mK (bottom), $T \approx 100$ mK (offset by 0.1 kΩ), $T \approx 60$ mK (offset by 0.3 kΩ), and $T \approx 30$ mK (offset by 0.6 kΩ). Vertical dashed lines mark $\nu^* = 0.58$. (b) $R_H$ versus $B$ at $T \approx 30$ mK (dark line) and at $T \approx 135$ mK (light line). Solid horizontal lines next to the $R_H$ mark concurrent plateau-like features at $2R_K/13$ and $2R_K/15$, while dashed horizontal lines are drawn at $2R_K/11$. 
R_H. We can thus conclude that, while definitely more robust in the lower spin branch of the N = 3 LL, the anomalous nematic state is also supported by the upper spin branch.

The contrasting behavior between temperature dependencies of the \( R_{xx} \) (circles) and of the \( R_{yy} \) (squares) near \( \nu = 13/2 \), 15/2 and those near \( \nu = 11/2 \) is summarized in Fig. 5. While \( R_{xx} \) (\( R_{yy} \)) at \( \nu \approx 11/2 \) monotonically increases (decreases) as the temperature is lowered, \( R_{xx} \) (\( R_{yy} \)) at both \( \nu = 13/2 \) and \( \nu = 15/2 \) shows a clear maximum (minimum) at some intermediate “turnover” temperatures, \( T_{13/2} \approx 100 \text{ mK} \) and \( T_{15/2} \approx 70 \text{ mK} \), respectively [22]. For comparison, we also include in Fig. 5 the \( R_{xx} \) data at \( \nu = i/2 + 0.08 \) (\( i = 11, 13, 15 \)), represented by triangles. As can be seen in Fig. 5(a), the \( R_{xx} \) at \( \nu = 5.58 \) is always smaller than that at \( \nu = 11/2 \) at all temperatures studied. In contrast, at \( \nu = 6.58 \) (\( \nu = 7.58 \)) \( R_{xx} \) is larger than at \( \nu = 13/2 \) (\( \nu = 15/2 \)) only at \( T > T_{13/2} \) (\( T < T_{15/2} \)) and the opposite is true when \( T < T_{13/2} \) (\( T > T_{15/2} \)). This observation further confirms that filling factors \( \nu = i/2 \) (\( i = 13, 15 \)) are governed by the same physics which sets in at \( T \approx T_{i/2} \) and is considerably more effective at reducing the transport anisotropy at \( \nu = i/2 \) than away from half-filling. Indeed, the temperature dependencies of the \( R_{xx} \) at \( \nu = 6.58, 7.58 \) are rather similar to that at \( \nu = 5.58 \).

According to the transport theory of QHS state, which treats it as a pinned smectic [23], the decrease (increase) of the \( R_{xx} \) (\( R_{yy} \)) upon cooling can be attributed to the increased electron scattering between stripe edges. This model, however, predicts weaker anisotropy away from half-filling than at \( \nu = i/2 \), in contrast to our observations. In addition, Ref. 23 predicts considerably stronger \( T \)-dependence of \( R_{xx} \) and \( R_{yy} \) at \( \nu = i/2 \) [24] 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 [25]. Instead, the observed low-temperature emergence of unexpected extrema in \( R_{xx} \) and \( R_{yy} \) along with the plateau-like features in the \( R_H \) 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 \( \times 10^{11} \text{ cm}^{-2} \) [26], as neither have those using high density \( [n_{e} = (4.1-4.3) \times 10^{11} \text{ cm}^{-2}] \) heterostructures [27]. However, the carrier mobility in the above experiments was below \( 1.2 \times 10^{7} \text{ cm}^{2} \text{V}^{-1} \text{s}^{-1} \) 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 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 in-plane magnetic field remains poorly understood even for conventional QHSs [26, 28, 29] which might complicate the interpretation of the data.

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