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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 ($N \geq 2$) 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 non-quantized 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 $N \geq 3$ Landau levels. Remarkably, these unexpected features emerge at temperatures considerably lower than the onset temperature of QHSs, suggestive of a new ground state.

The ground state of a two-dimensional electron gas (2DEG) at half-integer filling factors $\nu = i/2, i = 1, 3, 5, ...$, 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 ($\nu = i/2, i = 9, 11, ...$), 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 ν (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 $\langle 110 \rangle$ 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 partial filling factor $\nu^\star = \nu - \lfloor \nu \rfloor$, where $\lfloor \nu \rfloor$ is an integral part of ν, falls in the range of $0.4 \lesssim \nu^\star \lesssim 0.6$. The resistance anisotropy ratio $\alpha_R \equiv R_{xx}/R_{yy}$ normally achieves a single maximal value $\alpha_R \gg 1$ at $\delta\nu \equiv \nu^\star - 0.5 \approx 0$ 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 QHS 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$_{0.24}$Ga$_{0.76}$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 $\hat{x} \equiv \langle 1\bar{1}0 \rangle$ ($\hat{y} \equiv \langle 110 \rangle$) 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 maxima (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, α_R becomes a *non-monotonic* function of $|\delta\nu| = |\nu^\star - 0.5|$; it is relatively small at $\delta\nu = 0$ and exhibits maxima at $\delta\nu \approx \pm 0.08$. The variation of α_R with $\nu^\star$ is quite significant, it drops from $\alpha_R > 600$ at $\nu = \nu_+ \approx 6.58$ 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 $2R_{\mathrm{K}}/13$, where $R_{\mathrm{K}} \equiv h/e^2$ is the von Klitz-

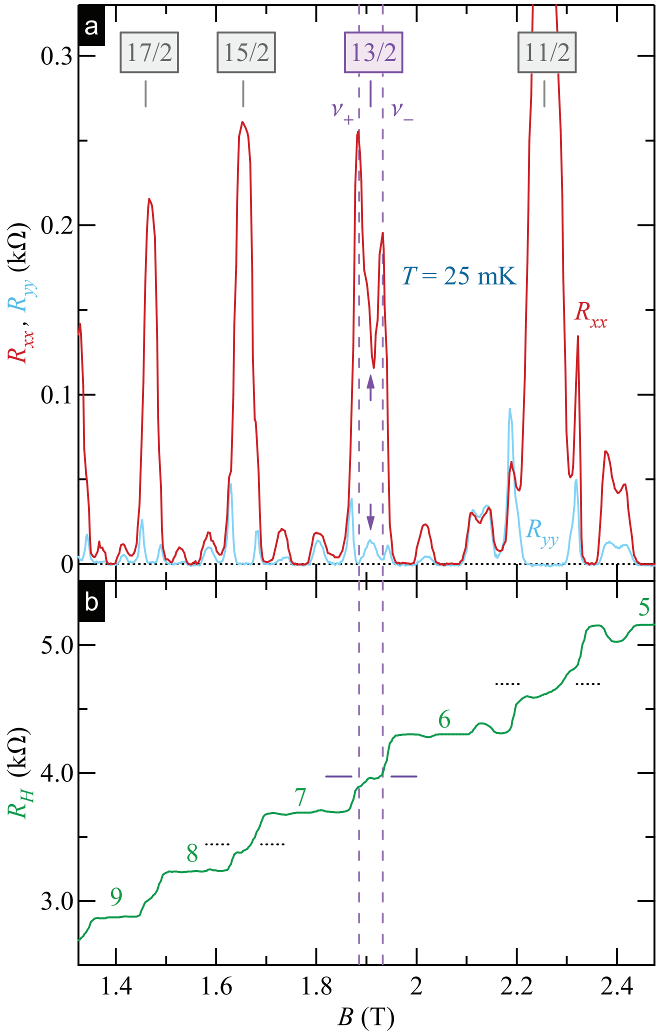

FIG. 1. (Color online) (a) R_{xx} and R_{yy} versus B measured in sample A at $T \approx 25$ mK. Half-integer ν are marked by $15/2, 13/2$, and $11/2$. The R_{xx} minimum and the R_{yy} maximum at $\nu \approx 13/2$ are marked by ↑ and ↓, respectively. Dashed vertical lines are drawn at $\nu_\pm = 6.5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

ing constant. While the plateau-like feature in R_H near $\nu = 13/2$ is very close to $2R_{\mathrm{K}}/13$, as one would expect for a developing even-denominator quantum Hall state, its appearance might be coincidental. Indeed, steps in R_H are also present near $\nu = 11/2$ and $\nu = 15/2$, albeit in these cases R_H is noticeably lower than half-integer-quantized values (cf. dashed horizontal line segments drawn at $2R_{\mathrm{K}}/11$ and $2R_{\mathrm{K}}/15$. We notice, however, that signatures of even-denominator quantum Hall states were recently observed in the $N = 3$ LL of graphene [16]. It was also established that in AlAs quantum wells, Hall quantization at $\nu = 3/2$ can occur in anisotropic setting

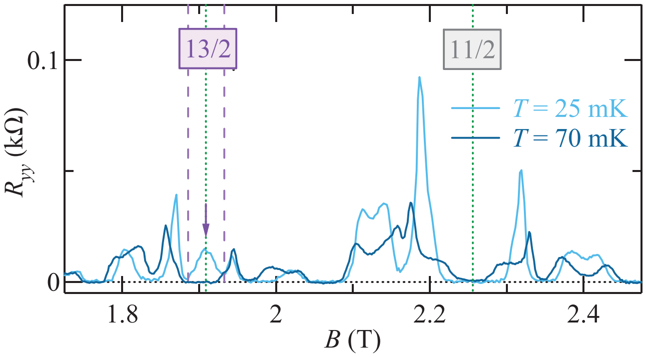

FIG. 2. (Color online) R_{yy} versus B measured in the sample A at $T \approx 25$ mK (light line) and at $T \approx 70$ mK (dark line). Half-integer ν are marked by 13/2, and 11/2.

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 ν [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 $2R_{\mathrm{K}}/i$, 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 $\nu^\star$ as in Fig. 1, i.e., at $\nu^\star = 1/2 \pm 0.08$, 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

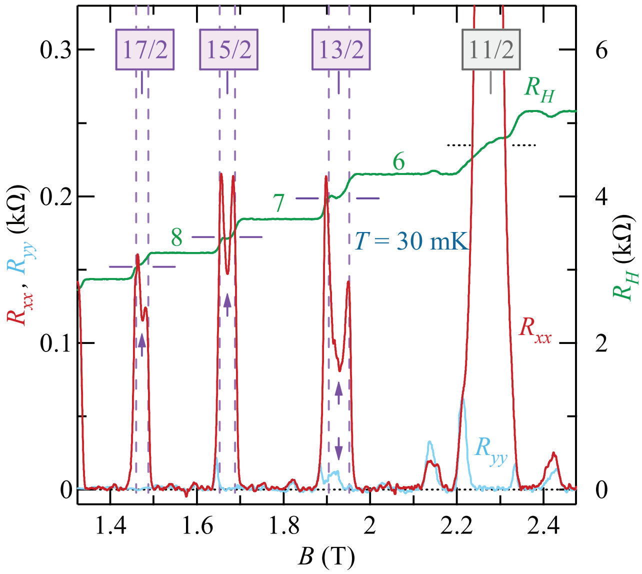

FIG. 3. (Color online) R_{xx}, R_{yy} (left axis), and R_H (right axis) versus B measured in sample B at $T \approx 30$ mK. Half-integer ν are marked by $17/2, 15/2, 13/2$, and $11/2$. The R_{xx} minima at $\nu = 13/2, 15/2, 17/2$ and the R_{yy} maximum near $\nu = 13/2$ are marked by ↑ and ↓, respectively.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

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 ↑ 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 $\nu = 11/2$ 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).

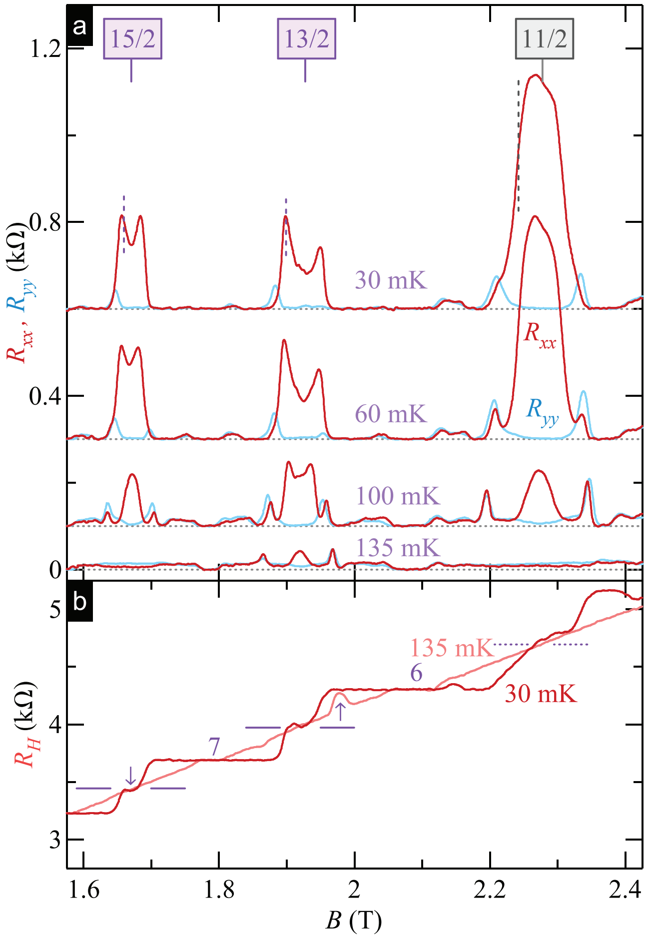

FIG. 4. (Color online) (a) R_{xx} (dark line), R_{yy} (light line) versus B measured in sample B at $T \approx 135$ mK (bottom), $T \approx 100$ mK (offset by 0.1 kΩ), $T \approx 60$ mK (offset by 0.3 kΩ), and $T \approx 30$ mK (offset by 0.6 kΩ). Vertical dashed lines mark $\nu^\star = 0.58$. (b) R_H 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 $2R_\mathrm{K}/13$ and $2R_\mathrm{K}/15$, while dashed horizontal lines are drawn at $2R_\mathrm{K}/11$.

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

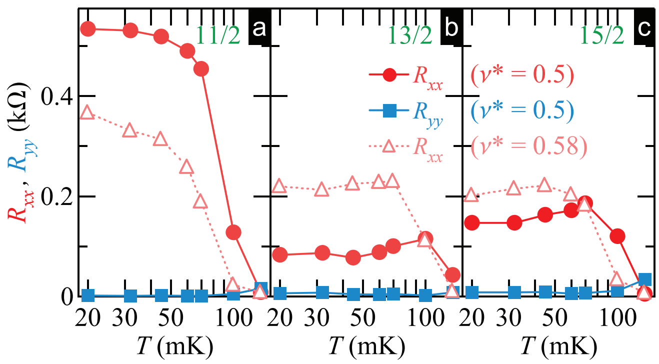

FIG. 5. (Color online) R_{xx} (circles), R_{yy} (squares) versus T at (a) $\nu = 11/2$, (b) $\nu = 13/2$, and (c) $\nu = 15/2$. For comparison, R_{xx} at $\nu^\star = 0.58$, cf. dotted vertical lines in Fig. 4(a), versus T is shown by triangles.

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, $T^\star_{13/2} \approx 100$ mK and $T^\star_{15/2} \approx 70$ 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 $T > T^\star_{13/2}$ ($T < T^\star_{15/2}$) and the opposite is true when $T < T^\star_{13/2}$ ($T > T^\star_{15/2}$). This observation further confirms that filling factors $\nu = i/2$ ($i = 13, 15$) are governed by the same physics which sets in at $T \approx T^\star_{i/2}$ 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 ν 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 3.6×10^{11} cm^{-2} [26], as neither have those using high density [$n_e = (4.1-4.3) \times 10^{11}$ cm^{-2}] heterostructures [27]. However, the carrier mobility in the above experiments was below 1.2×10^7 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 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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[21] We are aware of only two experiments which observed maximum resistance anisotropy at $\nu^\star > 0.5$ [25, 35].

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