Evidence for a fractional quantum Hall state with anisotropic longitudinal transport

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At high magnetic fields, where the Fermi level lies in the $N = 0$ lowest Landau level (LL), a clean two-dimensional electron system (2DES) exhibits numerous incompressible liquid phases which display the fractional quantized Hall effect (FQHE) [1]. These liquid phases do not break rotational symmetry, exhibiting resistivities which are isotropic in the plane. In contrast, at lower fields, when the Fermi level lies in the $N \geq 2$ third and several higher LLs, the 2DES displays a distinctly different class of collective states. In particular, near half filling of these high LLs the 2DES exhibits a strongly anisotropic longitudinal resistance at low temperatures [2, 3]. These "stripe" phases, which do not exhibit the quantized Hall effect, resemble nematic liquid crystals, possessing broken rotational symmetry and orientational order [4–8]. Here we report a surprising new observation: An electronic configuration in the $N = 1$ second LL whose resistivity tensor ***simultaneously*** **displays a robust fractionally quantized Hall plateau and a strongly anisotropic longitudinal resistance resembling that of the stripe phases.**

The sample we employ is a standard GaAs/AlGaAs heterostructure grown by molecular beam epitaxy. A 40 nm GaAs quantum well is embedded in thick $Al_{0.24}Ga_{0.76}As$ cladding layers. Si doping sheets in each cladding layer create a 2DES in the lowest subband of the GaAs quantum well. After illumination the density and mobility of this 2DES are $n = 1.6 \times 10^{11}$ cm^{-2} and $\mu = 16 \times 10^6$ cm^2/Vs, respectively. The sample is a 5 mm square chip whose edges are parallel to the $\langle 110\rangle$ and $\langle 1\bar{1}0\rangle$ crystal directions, henceforth referred to as the $\hat{x}$ and $\hat{y}$ directions, respectively. InSn ohmic contacts are positioned at the corners and side midpoints of the sample. Longitudinal resistance (R_{xx} and R_{yy}) measurements are performed by driving ac current (typically 2 nA at 13 Hz) between midpoint contacts on opposite sides the sample and detecting the resulting voltage difference between corner contacts on one side of the mean current axis. For the Hall resistances (R_{xy} and R_{yx}), the voltage difference between the two midpoint contacts on opposite sides of the current axis is recorded. Substantial in-plane magnetic fields $B_{||}$ may be added to the field $B_\perp$ perpendicular to the 2DES plane by tilting the sample at low temperatures. For the present studies, $B_{||}$ lies along the $\hat{x}$, or $\langle 110\rangle$, direction.

Figure 1 shows the longitudinal and Hall resistances at $T \approx 15$ mK with the magnetic field perpendicular to the 2DES plane (tilt angle $\theta = 0$). For the field range shown, the Fermi level lies in the lower spin branch of the $N = 1$ LL where the filling fraction $\nu \equiv nh/eB_\perp$ runs from $\nu = 2$ to $\nu = 3$. Deep minima in the longitudinal resistances and associated plateaus in R_{xy} and R_{yx} clearly signal the presence of FQHE states at $\nu = 7/3$, 5/2, and 8/3. While the $\nu = 7/3 = 2 + 1/3$ and $8/3 = 2 + 2/3$ states may be kin to the well-known $\nu = 1/3$ and 2/3 FQHE states in the $N = 0$ lowest LL [1, 9], the $\nu = 5/2$ state [10] is thought to be an example of the non-abelian Moore-Read paired composite fermion state [11]. In addition to these and a few weaker FQHE states, the four known re-entrant integer quantized Hall states [12], in varying stages of development, are also evident in Fig. 1. These insulating phases are poorly understood but may be related to the "bubble" phases found in the flanks of the $N \geq 2$ LLs and which also exhibit re-entrant integer Hall quantization [2–6]. As the data in Fig. 1 make clear, the longitudinal and Hall resistances are very similar [13] for current flow along $\langle 110\rangle$ and $\langle 1\bar{1}0\rangle$. Unlike the situation in the $N \geq 2$ LLs, no anisotropic phases have been found in 2D electron systems [14] in the $N = 1$ LL, at least in the absence of an external symmetry breaking field such as an in-plane magnetic field $B_{||}$.

Tilting the 2DES relative to the magnetic field direction has a profound influence on the various collective phases found in the $N = 1$ LL. In agreement with prior studies [12, 17–19], we find that the $\nu = 5/2$ FQHE state and the re-entrant integer quantized Hall states are suppressed by an in-plane magnetic field component, $B_{||}$. In addition to the destruction of these quantized Hall states, the general trend of the longitudinal resistance throughout the $N = 1$ LL is to become increasingly anisotropic as $B_{||}$ is initially applied, with R_{xx} (for which the mean current direction lies along $B_{||}$) growing significantly larger than R_{yy} [21, 22].

Figure 2 displays the temperature dependence of the longitudinal resistances R_{xx} and R_{yy} at $\nu = 7/3$ for various tilt angles θ. As expected, at $\theta = 0$ (Fig. 2a) we find R_{xx} and R_{yy} are very nearly equal at all temperatures. Below about $T = 100$ mK the $\nu = 7/3$ FQHE begins to develop, with R_{xx} and R_{yy} dropping rapidly toward zero in unison as the temperature falls. This temperature dependence is well-approximated by simple thermal activation, $R \sim \exp(-\Delta/2T)$, with $\Delta \approx 225$ mK (see the supplementary information).

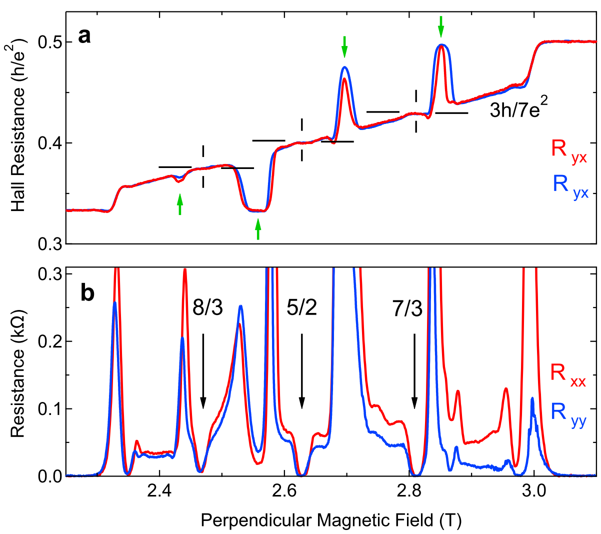

FIG. 1: Hall and longitudinal resistances at $T \approx 15$ mK vs. magnetic field in $N = 1$ Landau level, with $\nu = 7/3$, 5/2, and 8/3 FQHE states indicated by cross-hairs in a) and arrows in b). R_{xy} and R_{xx} are the Hall and longitudinal resistances, respectively, for mean current flow along the $\langle 110 \rangle$ direction; for R_{yx} and R_{yy} mean current flow is along $\langle 1\bar{1}0 \rangle$. Sample is perpendicular to the magnetic field ($\theta = 0°$). Green arrows in a) indicate locations of re-entrant integer quantized Hall states.

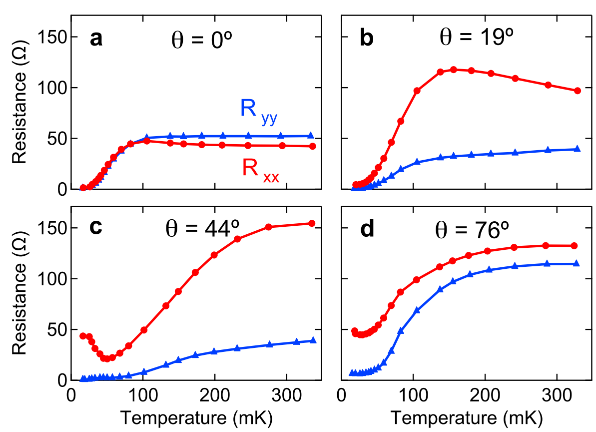

FIG. 2: R_{xx} (red dots) and R_{yy} (blue triangles) vs. temperature at $\nu = 7/3$ for $\theta = 0°$, 19°, 44°, and 76°.

Tilting the sample to just $\theta = 19°$ (Fig. 2b), where $B_{||} = 0.97$ T, creates a substantial anisotropy in the longitudinal resistance, with R_{xx} exceeding R_{yy}. The anisotropy is present at relatively high temperatures ($T \sim 300$ mK), well above where both resistances begin to fall sharply as the FQHE develops. Increasing the tilt angle to $\theta = 44°$ (Fig. 2c), where $B_{||} = 2.72$ T, enhances both the anisotropy and the temperature below which the resistances begin their FQHE-induced fall. This latter effect reflects the tilt-induced increase of the $\nu = 7/3$ FQHE energy gap noted previously in similar samples [23, 24]. At the large tilt angle of $\theta = 76°$ (Fig. 2d), the anisotropy in the longitudinal resistance has subsided significantly at high temperatures, in spite of the large in-plane magnetic field ($B_{||} = 11.3$ T) which breaks rotational symmetry. This surprising return toward isotropic transport has been noted previously and related to mixing of the Landau levels emanating from the two lowest subbands of the confinement potential [24].

The $\theta = 44°$ data in Fig. 2c reveal a curious effect: After falling steadily from $T \approx 250$ mK down to about 50 mK, R_{xx}, the resistance in the $\langle 110 \rangle$ direction, suddenly begins to *rise* as the temperature is lowered further. No such anomaly is observed in R_{yy}, the resistance in the $\langle 1\bar{1}0 \rangle$ direction, which drops to very small values in the low temperature limit. While Fig. 2d demonstrates that this peculiar behavior has almost vanished by $\theta = 76°$, Fig. 3a shows it to be quite pronounced at $\theta = 66°$, where $B_{||} = 6.33$ T at $\nu = 7/3$.

The $\theta = 66°$ data in Fig. 3 reveal three distinct regimes of resistive anisotropy. In the high temperature regime ($T > 250$ mK) the resistances R_{xx} and R_{yy} are essentially temperature independent, with R_{xx} exceeding R_{yy} by about a factor of 3. As Fig. 3e shows, the Hall resistances R_{xy} and R_{yx} do not exhibit a quantized Hall plateau in this regime. In the intermediate temperature range $50 < T < 250$ mK, the FQHE is beginning to dominate the transport. Both R_{xx} and R_{yy} fall with decreasing temperature and, as Fig. 3d illustrates, a Hall plateau at $R_{xy} = R_{yx} = 3h/7e^2$ appears below about 150 mK. The resistive anisotropy remains, with the ratio R_{xx}/R_{yy} growing as the temperature falls. (This behavior is inconsistent with simple activation, as explained in the supplementary information.) Finally, there is the low temperature regime, demarcated by a sudden change in the sign of dR_{xx}/dT at $T \approx 50$ mK. Below this temperature R_{xx} rises steadily, ultimately reaching $R_{xx} \approx 150$ Ω at $T \approx 15$ mK, our lowest measurement temperature. Throughout this low temperature range the Hall resistances R_{xy} and R_{yx} display well-quantized Hall plateaus, as Figs. 3b and 3c prove. Intriguingly, R_{yy} continues to fall toward zero in this low temperature regime, passing smoothly through $T \approx 50$ mK with no sign of the abrupt behavior exhibited by R_{xx}. (The expected local minima in R_{xx} and R_{yy} *vs.* magnetic field are shown in the supplementary information.)

The resistive anisotropy for $T \gtrsim 250$ mK shown in Fig. 3 recalls that observed in the stripe phases of the $N \geq 2$ LLs under similar tilted field conditions. Previous experiments on the $\nu = 9/2$ state have demonstrated that a weakly temperature dependent resistive anisotropy extends to high temperatures ($T \sim 500$ mK) when a strong in-plane magnetic field is present [20]. Furthermore, in common with the $\nu = 7/3$ anisotropy reported here, the

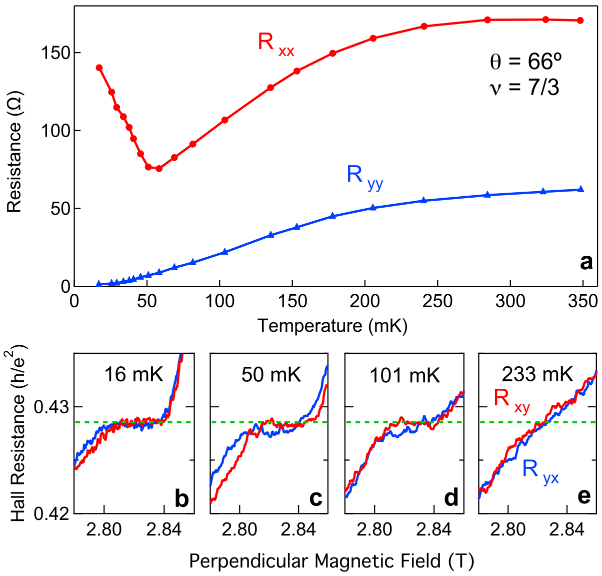

FIG. 3: Hall and longitudinal resistances at $\nu = 7/3$ for $\theta = 66°$. a) R_{xx} and R_{yy} vs. temperature; b)-e) Hall resistances R_{xy} and R_{yx} vs. magnetic field at various temperatures. Green dashed line indicates expected location of $\nu = 7/3$ Hall plateau.

orientation of this anisotropy is dictated by the direction of the in-plane magnetic field, with the high resistance direction parallel to $B_{||}$ [21–25]. We therefore speculate that in the present highly tilted $\nu = 7/3$ case, some form of stripe-like density modulation is present at relatively high temperatures and is responsible for the observed anisotropy in the longitudinal resistance. As the temperature is reduced, the FQHE begins to develop and compete with this stripe-like order. Since the resistive anisotropy persists to considerably higher temperatures than the FQHE, the energy scale for the stripe-like state exceeds that of the FQHE state. As a result, the quantum Hall fluid, which at these relatively high temperatures remains compressible, will accomodate itself to the density modulation. Unless the modulation is too strong, we believe that it will simply be translated into a spatial modulation of the density of fractionally-charged quasiparticles above the FQHE gap. The longitudinal resistance in such a weakly density-modulated FQHE state will certainly be anisotropic at finite temperatures and a quantized Hall plateau can be expected [28].

While the above scenario may explain the data in Fig. 3 in the high and intermediate temperature ranges, it does not readily account for the upturn in R_{xx} at $T \approx 50$ mK and the persistence of the Hall plateau down to $T \approx 15$ mK. Indeed, the abruptness of the upturn suggests the emergence of a new electronic configuration in the low temperature regime. The $\nu = 7/3$ longitudinal resistance data shown in Fig. 3a are, for $T \lesssim 50$ mK, again reminiscent of that seen in the stripe phases at half filling of the $N \geq 2$ LLs (e.g. at $\nu = 9/2$, $11/2$, etc.) only now as they appear in the *absence* of an in-plane magnetic field. Under these conditions a strong resistive anisotropy develops only at low temperatures ($T \lesssim 100$ mK). The resistance becomes large in one crystallographic direction and very small in the orthogonal direction. Here, at $\nu = 7/3$, R_{xx} rises rapidly below $T = 50$ mK, reaching approximately 150 Ω at $T \approx 15$ mK, while R_{yy} concurrently falls to ~ 1 Ω. However, in sharp contrast to the anisotropic phases at $\nu = 9/2$, $11/2$, etc., the anisotropic $\nu = 7/3$ state exhibits a robustly quantized Hall plateau down to the lowest temperatures studied.

The simultaneous presence, at $\nu = 7/3$ in the present instance, of an accurately quantized Hall plateau and strong, highly temperature dependent anisotropy in the longitudinal resistance, has not been encountered experimentally before. There have however, been theoretical suggestions of fractional quantized Hall phases with broken rotational symmetry. Using a variational approach, Musaelian and Joynt (MJ) [29] suggested that in wide quantum wells (which soften the short-range part of the Coulomb interaction) the 2DES at $\nu = 1/3$ in the $N = 0$ Landau level might be most stable in a phase analogous to a classical nematic liquid crystal. While exhibiting gapless neutral collective modes of the director order parameter, MJ nonetheless argue that charged excitations are gapped and thus the system would still exhibit the FQHE. How the transport coefficients would behave as functions of temperature, and what might pin the order parameter, was not addressed. More recently, Mulligan, Nayak, and Kachru (MNK) [30], using an effective field theory approach, have predicted a transition from an isotropic to an anisotropic FQHE state with nematic order. The transition is driven by subtle changes in the electron-electron interaction which, in the light of the present experimental results, MNK speculated arise from couplings between an in-plane magnetic field and the finite thickness of the 2DES. While MNK predict that both R_{xx} and R_{yy} will ultimately vanish at $T = 0$, they also find a regime, as in our experiments, where one of the two resistances increases as the temperature falls while the other falls. Future experiments at lower temperatures may find that the steady increase of R_{xx} below $T = 50$ mK shown in Fig. 3 eventually ceases and the resistance begins to fall toward zero.

In addition to the homogeneous nematic FQHE phases mentioned above, it is also possible that our results reflect a phase separated 2DES. In analogy with the situation at $\nu = 9/2$, a simple stripe phase picture at $\nu = 7/3$ (consisting, for example, of alternating stripes of $\nu = 2$ and $\nu = 3$ [31]) would yield anisotropic longitudinal transport but not quantization of the Hall resistance. Alternatively, one can imagine that at $\nu = 7/3$ the electrons in the 1/3-filled $N = 1$ Landau level exist in an anisotropic version of the quantized Hall insulator (QHI) first encountered experimentally at $\nu \lesssim 1/3$ in the $N = 0$ LL in relatively disordered samples [32, 33]. In Shimshoni and Auerbach's (SA) theory [32], the QHI is modeled as a collection of incompressible FQHE puddles immersed in an insulating background fluid and connected to one another by tunnel junctions. SA find that the longitudinal resistance diverges as $T \to 0$ and, remarkably, the Hall resistance is quantized at the value appropriate to the FQHE puddles. Adjusting this scenario to $\nu \lesssim 7/3{=}2{+}1/3$ suggests a Hall resistance quantized at $R_{xy} = 3h/7e^2$ and a longitudinal resistance R_{xx} which, though vanishing at $T = 0$, exhibits quasi-insulating behavior ($dR_{xx}/dT < 0$) in some intermediate temperature range. By construction, the SA model is isotropic. Thus, while our R_{xx}, R_{xy}, and R_{yx} data are broadly consistent with the SA model, it does not encompass the behavior we observe in R_{yy}. Nevertheless, it seems at least plausible that by assuming the FQHE puddles to be oblate and consistently oriented relative to the in-plane magnetic field, that anisotropy in the longitudinal resistance would emerge from the model. Whether the different temperature dependences of R_{xx} and R_{yy} can also be accomodated is less clear.

In summary, we have demonstrated that an in-plane magnetic field can drive a 2D electron system at filling factor $\nu = 7/3$ into a new state in which its longitudinal resistance is strongly anisotropic and non-linear and yet its Hall resistance remains quantized at $R_{xy} = 3h/7e^2$. This new configuration, bearing strong similarities to both conventional FQHE and anisotropic "stripe" states testifies to the richness of collective phases in 2D electron systems, and calls for further theoretical considerations.

[1] For reviews of the FQHE and related phenomena, see *Perspectives on Quantum Hall Effects*, edited by S. Das Sarma and A. Pinczuk (Wiley, New York, 1997).

[2] Lilly, M. P., Cooper, K. B., Eisenstein, J. P., Pfeiffer, L. N. & West, K. W. Evidence for an anisotropic state of two-dimensional electrons in high Landau levels. *Phys. Rev. Lett.* **82**, 394 (1999).

[3] Du, R. R. *et al.* Strongly anisotropic transport in higher two-dimensional Landau levels. *Solid State Commun.* **109**, 389 (1999).

[4] Koulakov, A. A., Fogler, M. M. & Shklovskii, B. I. Charge density wave in two-dimensional electron liquid in weak magnetic field. *Phys. Rev. Lett.* **76**, 499 (1996)

[5] Fogler, M. M., Koulakov, A. A. & Shklovskii, B. I. Ground state of a two-dimensional electron liquid in a weak magnetic field. *Phys. Rev. B* **54**, 1853 (1996).

[6] Moessner, R. & Chalker, J. T. Exact results for interacting electrons in high Landau levels. *Phys. Rev. B* **54**, 5006 (1996).

[7] Fradkin, E. & Kivelson, S. A. Liquid-crystal phases of quantum Hall systems. *Phys. Rev. B* **59**, 8065 (1999).

[8] Fradkin, E., Kivelson, S. A., Lawler, M. J., Eisenstein, J. P. & Mackenzie, A. P. Nematic Fermi Fluids in Condensed Matter Physics. *Annual Reviews of Condensed Matter Phys.* **1**, 153 (2010).

[9] Alternatives exist; see Read, N. & Rezayi, E. Beyond paired quantum Hall states: Parafermions and incompressible states in the first excited Landau level. *Phys. Rev. B* **59**, 8084 (1999).

[10] Willett, R. *et al.* Observation of an Even-Denominator Quantum Number in the Fractional Quantum Hall Effect. *Phys. Rev. Lett.* **59**, 1776 (1987).

[11] Moore, G. & Read, R. Nonabelions in the Fractional Quantum Hall Effect. *Nucl. Phys. B* **360**, 362 (1991).

[12] Eisenstein, J. P., Cooper, K. B., Pfeiffer, L. N. & West, K. W. Insulating and fractional quantum Hall states in the first excited Landau level. *Phys. Rev. Lett.* **88**, 076801 (2002).

[13] We attribute the small differences between R_{xx} and R_{yy} for $2.85 \lesssim B_\perp \lesssim 3$ T to extrinsic sample-dependent effects of no relevance here.

[14] Anisotropy in the $N = 1$ LL has been observed in 2D *hole* systems by M. Shayegan *et al.* [15] and M.J. Manfra *et al.* [16].

[15] Shayegan, M., Manoharan, H. C., Papadakis, S. J. & De Poortere, E. P. Anisotropic transport of two-dimensional holes in high Landau levels. *Physica E* **6**, 40 (2000).

[16] M.J. Manfra *et al.*, *Phys. Rev. Lett.* **98**, 206804 (2007).

[17] Eisenstein, J. P. *et al.* Collapse of the Even-Denominator Fractional Quantum Hall Effect in Tilted Fields. *Phys. Rev. Lett.* **61**, 997 (1988).

[18] Eisenstein, J. P., Willett, R. L., Stormer, H. L., Pfeiffer, L. N. & West, K. W. Activation energies for the even-denominator fractional quantum Hall effect. *Surf. Sci.* **229**, 31 (1990).

[19] Csathy, G. *et al.* Tilt-Induced Localization and Delocalization in the Second Landau Level. *Phys. Rev. Lett.* **94**, 146801 (2005).

[20] Cooper, K. B., Lilly, M. P., Eisenstein, J. P., Pfeiffer, L. N. & West, K. W. Onset of anisotropic transport of two-dimensional electrons in high Landau levels: Possible isotropic-to-nematic liquid-crystal phase transition. *Phys. Rev. B* **65**, 241313(R) (2002).

[21] Pan, W. *et al.* Strongly anisotropic electronic transport at Landau level filling factor $\nu = 9/2$ and $\nu = 5/2$ under a tilted magnetic field. *Phys. Rev. Lett.* **83**, 820 (1999).

[22] Lilly, M. P., Cooper, K. B., Eisenstein, J. P., Pfeiffer, L. N. & West, K. W. Anisotropic states of two-dimensional electron systems in high Landau levels: Effect of an in-plane magnetic field. *Phys. Rev. Lett.* **83**, 824 (1999).

[23] Dean, C. R. *et al.* Contrasting behavior of the 5/2 and 7/3 fractional quantum Hall effect in a tilted field. *Phys. Rev. Lett.* **101**, 186806 (2008).

[24] Xia, J., Cvicek, V., Eisenstein, J. P., Pfeiffer, L. N. & West, K. W. Tilt-Induced Anisotropic to Isotropic Phase Transition at $\nu = 5/2$. *Phys. Rev. Lett.* **105**, 176807 (2010).

[25] The orienting effect of the in-plane magnetic field on the high LL stripe phases has been studied theoretically by Jungwirth *et al.* [26] and Stanescu *et al.* [27]. In some cases, it is possible for the hard resistance direction to be perpendicular to $B_{||}$.

[26] Jungwirth, T., MacDonald, A. H., Smrcka, L. & Girvin, S. M. Field-tilt anisotropy energy in quantum Hall stripe states. *Phys. Rev. B* **60**, 15574 (1999).

[27] Stanescu, T. D., Martin, I. & Phillips, P. Finite-

temperature density instability at high Landau level occupancy. *Phys. Rev. Lett.* **84**, 1288 (2000).

[28] If the density modulation is too large, this picture will surely break down. However, we note that stripes only appear in the $N = 1$ LL when a tilted field is applied, in contrast to the situation in the $N \geq 2$ LLs. Quantum fluctuations [7] are much stronger in the $N = 1$ LL and it seems plausible that they will limit the density modulation in any tilt-induced stripe phase.

[29] Musaelian, K. & Joynt, R. Broken rotation symmetry in the fractional quantum Hall system. *J. Phys. Cond. Matt.* **8**, L105 (1996).

[30] Mulligan, M., Nayak, C., & Kachru, S. Isotropic to anisotropic transition in a fractional quantum Hall state. *Phys. Rev. B* **82**, 085102 (2010) and arXiv:1104.0256.

[31] The $\nu = 2$ stripes would have to be twice as wide as the $\nu = 3$ stripes for the average filling factor to be $\nu = 7/3$. Such a scenario ignores the known destabilization of stripe phases away from half filling to isotropic "bubble" phases [4–6].

[32] Shimshoni, E. & Auerbach, A. Quantized Hall insulator: Transverse and longitudinal transport. *Phys. Rev. B* **55**, 9817 (1997).

[33] M. Hilke *et al.* Experimental evidence for a two-dimensional quantized Hall insulator. *Nature* **395**, 675 (1998).

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Author contributions

J.X and J.P.E conceived the project. L.N.P and K.W.W fabricated the samples. J.X performed the experiment. J.X and J.P.E discussed the data and co-wrote the manuscript.

Additional information The authors declare no competing financial interests.

Evidence for a fractional quantum Hall state with anisotropic longitudinal transport (Supplementary information)

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The energy gap Δ of a fractional quantized Hall effect (FQHE) state is most often determined via the temperature dependence of the longitudinal resistance, R. Generally, there is some range of temperature over which $R \sim \exp(-\Delta/2T)$. Since ordinary FQHE states are isotropic in the 2D plane, one expects the value of the gap Δ to be independent of whether R_{xx} or R_{yy} is used for its determination. Figure S1 a) shows that this is very nearly the case for the $\nu = 7/3$ FQHE state in our sample when the magnetic field is perpendicular to the plane (tilt angle $\theta = 0$). The simple linear fits to $\log(R)$ *vs.* T^{-1} shown in the figure give gaps of 240 mK and 210 mK for the R_{xx} and R_{yy} data, respectively. We do not believe that the small difference between these values is statistically significant and so give $\Delta \approx 225$ mK as our best estimate of the $\nu = 7/3$ gap at $\theta = 0$.

As our paper reports, tilting the sample relative to the magnetic field induces substantial anisotropy in the longitudinal resistance at $\nu = 7/3$ even though a quantized Hall plateau remains. We find, however, that for tilt angles beyond $\theta \approx 20°$, it is no longer possible to extract a unique energy gap from the temperature dependence of R_{xx} and R_{yy}. This difficulty is illustrated in Fig. S1 b) where $\log(R_{xx})$ and $\log(R_{yy})$ at $\nu = 7/3$ and $\theta = 66°$ are plotted *vs.* T^{-1}. Even leaving aside the dramatic divergence of these two resistances for $T < 50$ mK, it is clear from the figure that in the intermediate temperature range $50 < T < 250$ mK their temperature dependences are significantly different and only weakly resemble simple thermal activation. Figure S1 c) shows the results of separately fitting R_{xx} and R_{yy} at $\nu = 7/3$ in the intermediate temperature range to the standard Arrhenius form $\exp(-\Delta/2T)$. The extracted values of Δ_x and Δ_y (from the R_{xx} and R_{yy} data, respectively) are plotted versus the in-plane magnetic field $B_{||}$ resulting from tilting the sample by an angle θ. As reported previously [1, 2], the energy gap for the $\nu = 7/3$ FQHE state in similar samples initially increases with $B_{||}$. However, beyond about $\theta = 20°$, Δ_x and Δ_y become significantly different, rendering a simple interpretation of them as energy gaps for the FQHE state suspect.

Figure S1 c) demonstrates that the temperature dependence of R_{xx} and R_{yy} at $\nu = 7/3$ is quite complex and not readily interpreted. It is remarkable that in spite of this complexity a robust Hall plateau at $R_{xy} = R_{yx} = 3h/7e^2$ is observed at low temperatures at all tilt angles we have studied ($0 \le \theta \le 76°$). Figure S2 shows these Hall plateaus, along with the associated local minima in R_{xx} and R_{yy} at several tilt angles.

[1] Dean, C. R. *et al.* Contrasting behavior of the 5/2 and 7/3 fractional quantum Hall effect in a tilted field. *Phys. Rev. Lett.* **101**, 186806 (2008).
[2] Xia, J., Cvicek, V., Eisenstein, J. P., Pfeiffer, L. N. & West, K. W. Tilt-Induced Anisotropic to Isotropic Phase Transition at $\nu = 5/2$. *Phys. Rev. Lett.* **105**, 176807 (2010).

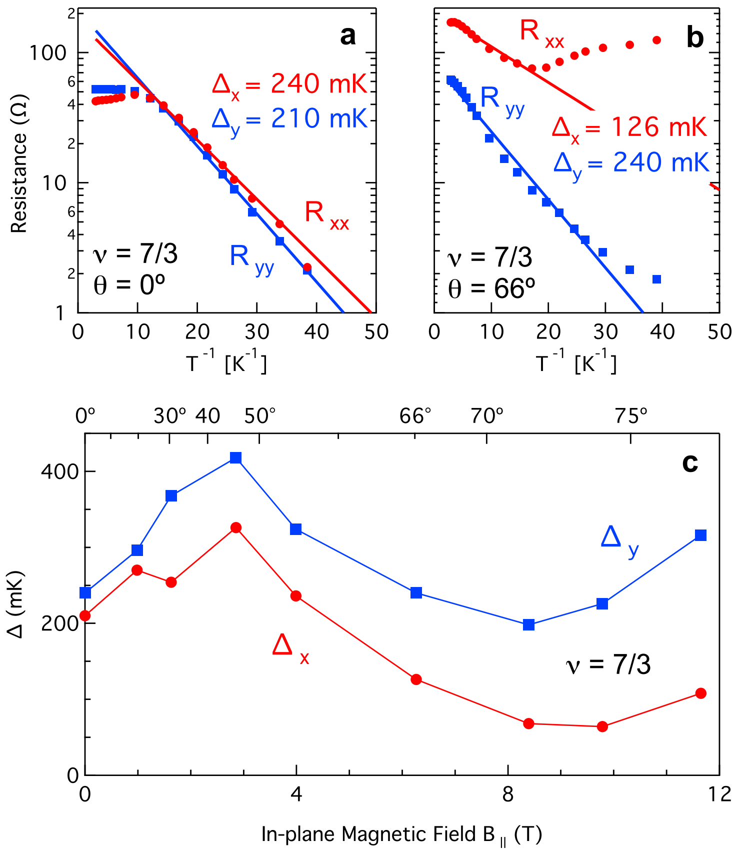

FIG. 1: a) and b) Arrhenius plots of R_{xx} and R_{yy} at $\nu = 7/3$ *vs*. T^{-1} at $\theta = 0^\circ$ and 66°, respectively. Δ_x and Δ_y are the gap parameters extracted from fitting the data in the intermediate temperature range $50 < T < 250$ mK. c) Fitted gap parameters Δ_x and Δ_y *vs*. in-plane magnetic field $B_{||}$ and tilt angle θ.

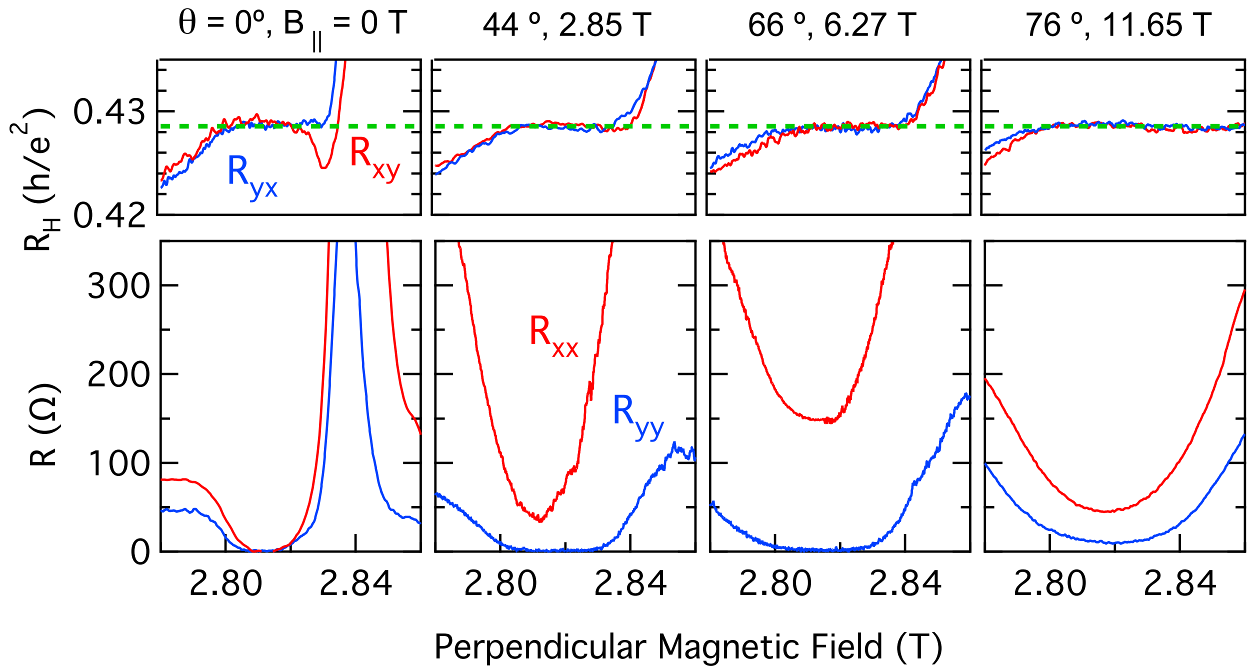

FIG. 2: Hall plateaus and longitudinal resistance minima at $\nu = 7/3$ for various tilt angles and in-plane magnetic fields. All data at $T \approx 15$ mK.