Unconventional Anisotropic Even-Denominator Fractional Quantum Hall State in a System with Mass Anisotropy

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The fractional quantum Hall state (FQHS) observed at a half-filled Landau level in an interacting two-dimensional electron system (2DES) is among the most exotic states of matter as its quasiparticles are expected to be Majoranas with non-Abelian statistics. We demonstrate here the unexpected presence of such a state in a novel 2DES with a strong band-mass anisotropy. The FQHS we observe has unusual characteristics. While its Hall resistance is well-quantized at low temperatures, it exhibits highly-anisotropic in-plane transport resembling compressible stripe/nematic charge-density-wave phases. More striking, the anisotropy sets in suddenly below a critical temperature, suggesting a finite-temperature phase transition. Our observations highlight how anisotropy modifies the many-body phases of a 2DES, and should further fuel the discussion surrounding the enigmatic even-denominator FQHS.

A hallmark of a high-quality, interacting two-dimensional electron system (2DES) is the mysterious even-denominator fractional quantum Hall state (FQHS) [1–7], which is expected to harbor Majorana excitations obeying non-Abelian statistics and be of potential use in topological quantum computing [8–11]. Here we expose some remarkable properties of this state in a 2DES, confined to an AlAs quantum well, where the electrons possess an anisotropic in-plane effective mass. When the first-excited ($N = 1$) Landau level (LL) is half filled, the ground state has highly-anisotropic longitudinal resistances, very much reminiscent of the compressible stripe phases [12–19] reported in GaAs 2DESs for the $N > 1$ LLs but, surprisingly, the Hall resistance is well-quantized at the half-integer value. Remarkably, the 2DES appears to make a sudden transition to this incompressible, anisotropic phase below a critical temperature. In addition, the quantized Hall plateau is robust even at very large in-plane magnetic fields. The surprises continue away from the half filling, where another state resembling bubble phases [18–20] emerges but its Hall resistance approaches an unexpected quantized value.

We performed experiments on a 2DES confined to a 20-nm-wide, AlAs quantum well where two conduction-band minima (or valleys) centered at the edges of the Brillouin zone are occupied [21]. Each of these valleys, which we denote by X and Y, has an elliptical Fermi contour with anisotropic effective masses $m_l = 1.0$ and $m_t = 0.20$ (in units of free electron mass) along their principal longitudinal and transverse directions; X has its longitudinal axis along the [100] crystal direction, and Y along [010] (see Fig. 1(a)). Our sample has a density of $n \simeq 3.2 \times 10^{11}$ cm^{-2} and a mobility of $\simeq 1.4 \times 10^6$ cm^2/Vs which is extremely high, considering the very large electron effective mass in the system [22]. We tune the valley occupancy via the application of uniaxial strain (ε); see Fig. 1(a) [21, 23]. For $\varepsilon > 0$, electrons are transferred from X to Y while the reverse happens for $\varepsilon > 0$ [21].

Figure 1(b), which shows the sample's piezo-resistance as a function of ε at zero magnetic field, demonstrates how we tune and monitor the valley occupancy. At $\varepsilon = 0$ (point **B**), because X and Y are equally populated, the 2DES exhibits isotropic transport, namely, the resistances measured along the [100] and [010] directions (R_{xx} and R_{yy}, respectively) are equal, even though the individual valleys are anisotropic. For $\varepsilon > 0$, as electrons transfer from X to Y, R_{xx} decreases (black trace in Fig. 1(b)) because the electrons in Y have a small effective mass and therefore higher mobility along [100] [21]. (Note that the total 2DES density remains fixed as strain is applied.) The resistance eventually saturates
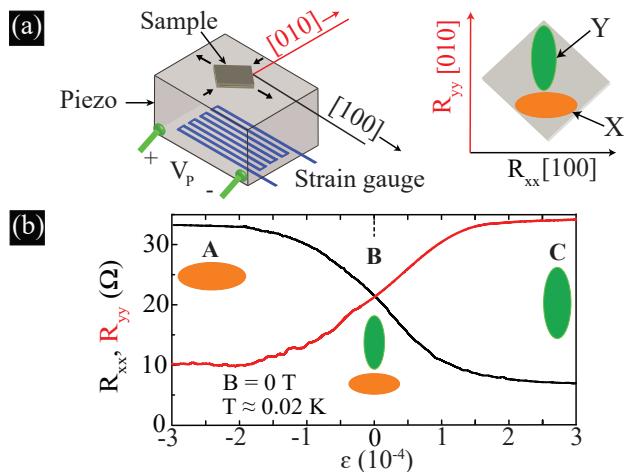

FIG. 1. (a) Schematic of the experimental setup for applying in-plane strain (ε). The sample and a strain gauge are glued to the opposite sides of a piezo-actuator, and strain is introduced when a bias voltage (V_P) is applied to the actuator's leads. The sample geometry, including the orientation of the two occupied valleys (X and Y) and the measured resistances (R_{xx} and R_{yy}) are shown on the right; [100] and [010] refer to the crystallographic directions. (b) Piezo-resistance of the sample as a function of ε. Points **A** - **C** mark the valley occupation.
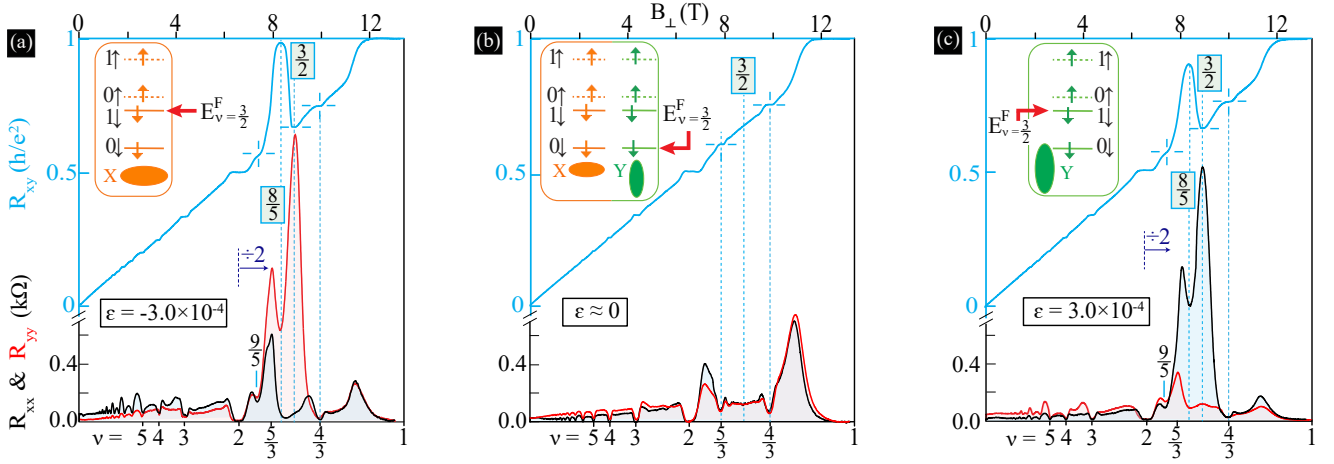
FIG. 2. Exotic phases in the $N = 1$ LL. Plotted are the magneto-resistance traces, R_{xx} (black), R_{yy} (Red) and R_{xy} (blue), taken at $T \simeq 0.02$ K and at three strain values as indicated. Insets show the LLs for X (orange) and Y (green) valleys; the validity of these LL diagrams is discussed in the Supplemental Material [23]. In (a) only X is occupied and $E_{3/2}^F$ resides in the X1↓ LL, while in (c) only Y is occupied and $E_{3/2}^F$ lies in the Y1↓ LL. In both cases R_{xx} and R_{yy} are highly anisotropic near $\nu = 3/2$, with the hard axis along the low-mass (transverse) direction of the occupied valley, but there is an R_{xy} Hall plateau at $\nu = 3/2$ quantized at $(2/3)(h/e^2)$. Transport is also highly anisotropic near $\nu = 8/5$, with an R_{xy} that approaches h/e^2. None of these anomalies are seen in (b) where E^F lies in an $N = 0$ LL.

(point **C**), when all electrons are in the Y valley [21, 51]. For $\varepsilon < 0$, R_{xx} increases and eventually saturates (point **A**) as the electrons are transferred to X which has a large mass and a low mobility along [100]. As expected, the behavior of R_{yy} is opposite to that of R_{xx}.

In Fig. 2 we show R_{xx}, R_{yy}, and R_{xy} traces taken as a function of perpendicular magnetic field ($B_\perp$) at three values of strain, corresponding to points **A**, **B** and **C** in Fig. 1(b). The lower scales show the LL filling factor defined as $\nu = hn/eB$. The most striking features are seen in the range $2 > \nu > 1$. In particular, near $\nu = 3/2$ the 2DES becomes strongly anisotropic at large magnitudes of strain when the electrons occupy the X (left panel) or Y (right panel) valleys. The LL diagrams shown in Fig. 2 help unravel the origin of these unusual features. Here the LLs are indicted by their orbital index ($N = 0, 1$) followed by the spin orientation (↓ and ↑). Note that, thanks to the large spin-susceptibility of our 2DES, the Zeeman energy is $\simeq 1.35$ times the cyclotron energy, as these LL diagrams indicate [23]. When both valleys are occupied (panel (B)) the Fermi energy at $\nu = 3/2$ ($E_{3/2}^F$) lies in the 0↓ LL of X and Y. As expected for an $N = 0$ LL, there are well-developed FQHSs at odd-denominator fillings $\nu = 5/3$, and $4/3$, with hints of a developing FQHS at $8/5$, and transport is nearly isotropic, i.e., $R_{xx} \simeq R_{yy}$ [23]. However, for single-valley occupancy, $E_{3/2}^F$ moves to the 1↓ LL of X (left panel) or Y (right panel), and leads to the dramatic resistance anisotropy near $\nu = 3/2$, which is the highlight of our work.

Focusing on data at $\nu = 3/2$, magneto-transport becomes highly anisotropic, exhibiting $R_{xx} << R_{yy}$ when

electrons occupy X and $R_{xx} >> R_{yy}$ for Y. Note that this anisotropy is opposite to the anisotropy seen at $B = 0$ in Fig. 1(b). The anisotropic behavior in Figs. 2(a) and 2(c) is highly reminiscent of data in high-quality GaAs 2DES in the higher LLs ($N \geq 2$) in a purely perpendicular field, and generally interpreted to signal stripe phases [18, 19]. Here we observe such anisotropy in the $N = 1$ LL where normally an isotropic FQHS is seen [1, 4, 18–20]. At first sight, our data are consistent with recent theories [52, 53] which predict that, unlike the $N = 0$ LL [23], the incompressible FQHSs in the $N = 1$ LL should give way to compressible stripe phases [53]. Similar to the stripe phases in the higher ($N \geq 2$) LLs, such phases are expected to consist of stripes with fillings of the two nearby integer QHSs [18, 19]. In fact, Ref. [53] concludes that the stripes should orient themselves along the direction of the larger mass, rendering this direction as the "easy axis," consistent with our observation. In sharp contrast to this prediction, however, we observe a well-quantized Hall plateau at $(2/3)(h/e^2)$; this is best seen in Fig. 3(c) which zooms in on R_{xy} near $\nu = 3/2$. The quantized Hall resistance is also observed if the current and voltage leads are exchanged (see the R_{yx} trace shown in Fig. 3(d)) [23]. We are therefore observing an incompressible anisotropic FQHS and not a compressible stripe phase.

The state we observe might be a *striped FQHS* composed of alternating Pfaffian and anti-Pfaffian stripes, as theoretically discussed recently [54], although it is unclear how to link the anisotropies seen in our data to the anisotropic mass in our 2DES. On the other hand, several key characteristics of our data match those
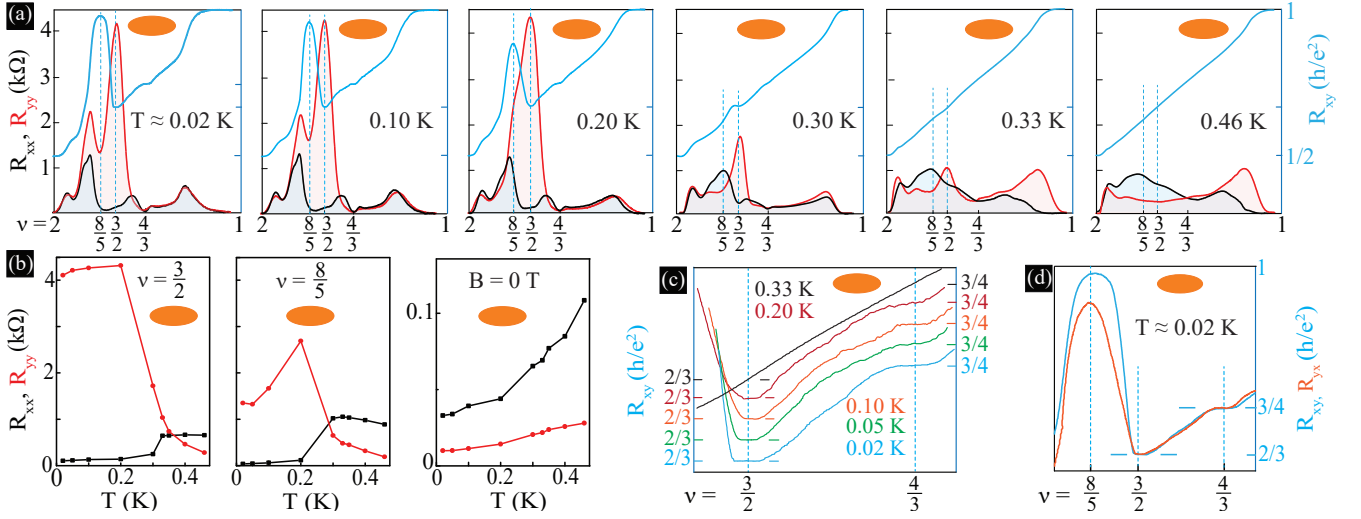
FIG. 3. Temperature dependence of data for $N = 1$ LL taken at $\varepsilon = -3 \times 10^{-4}$ where the 2D electrons occupy only the X valley. (a) Plots of R_{xx}, R_{yy}, and R_{xy} vs filling for six different temperatures ranging from $\simeq 0.02$ to 0.46 K. (b) Evolution of R_{xx} and R_{yy} at $\nu = 3/2$, 8/5, and $B = 0$ with temperature. (c) T-dependence of R_{xy}, near Hall plateaus at $\nu = 3/2$ and 4/3. The traces are shifted vertically for clarity, and the horizontal lines mark the expected positions of the Hall plateaus at $\nu = 3/2$ and 4/3. (d) R_{xy} and R_{yx}, the latter taken after switching the current and voltage leads.

of an anisotropic FQHS proposed by Mulligan, Nayak, and Kachru (MNK) [55] to explain some features of an anisotropic FQHS observed in a GaAs 2DES in the $N = 1$ LL at $\nu = 7/3$ when a parallel magnetic field ($B_{\parallel}$) is applied [23, 56]. MNK report that, subtle changes in the electron-electron interaction in the presence of a $B_{\parallel}$ can lead to a *nematic FQHS* with anisotropic transport coefficients below a critical temperature (T_C) whose magnitude depends on $B_{\parallel}$ and the details of the sample's structure and transport coefficients. Above T_C, the 2DES should exhibit isotropic longitudinal resistances while below T_C the resistance along the hard axis should show an abrupt rise while along the easy axis it should abruptly drop. For $T < T_C$, both resistances should drop with decreasing T, as expected for a FQHS (see Fig. 1 of MNK). MNK also predict that the sudden transition could be somewhat rounded depending on the experimental details (Fig. 3 of MNK).

Our T-dependent data, summarized in Fig. 3, qualitatively show many of the features predicted by MNK. Considering the low-temperature traces in Fig. 3(a), we associate R_{xx} with the easy axis of the low-temperature nematic phase and R_{yy} with the hard axis. Now, starting from high temperatures, we observe that the anisotropy is reversed at the highest T, i.e., $R_{xx} > R_{yy}$ at $\nu = 3/2$ (Fig. 3(b)). This is different from the prediction of MNK which states that the 2DES should be isotropic at high T, but is reasonable given that our 2DES has an intrinsic (mass) anisotropy in the absence of any interaction (see the $B = 0$ panel in Fig. 3(b)). As T is lowered from $\simeq 0.33$ K to $\simeq 0.20$ K, R_{xx} drops rather suddenly while R_{yy} increases significantly. For lower T, both R_{xx} and R_{yy} drop with decreasing T, consistent with the charac-

teristics of a FQHS, although we cannot reliably extract an energy gap because of the limited ranges of T and the resistance values. It is clear, however, that the ground state is a FQHS as indicted by the robust quantization of R_{xy} at $(2/3)(h/e^2)$ for $T \lesssim 0.2$ (Fig. 3(c)).

We emphasize that the theory of MNK was developed for the $\nu = 7/3$ FQHS in the $N = 1$ LL in titled magnetic fields, and it is not obvious if it would apply to the *even-denominator* FQHS we observe in the $N = 1$ LL of a 2DES with anisotropic effective mass without the application of $B_{\parallel}$. It is worth mentioning, however, that an anisotropic FQHS also develops at $\nu = 5/2$ at relatively small tilt angles in the GaAs 2DES $N = 1$ LL; see, e.g., [57], and references therein. This state was also interpreted as a nematic FQHS, although no critical temperature or abrupt changes in resistances were observed [57]. We hope that our results would stimulate new theoretical work on anisotropic even-denominator FQHSs in 2DESs with anisotropic masses and, in particular, whether nematicity in such systems would set in below a critical temperature.

Figures 2 and 3 reveal that in our 2DES another highly anisotropic state emerges near $\nu = 8/5$ in the $N = 1$ LL. Its low-temperature R_{xx} and R_{yy} have the same anisotropy as the $\nu = 3/2$ FQHS, but its R_{xy} rises well above the classical Hall line and approaches the quantized value for an *integer* QHS, namely (h/e^2). Such data closely resemble those for bubble phases seen in GaAs in high LLs away from half fillings [20]. However, the conventional signature of a bubble phase is an R_{xy} quantized at the value for the *nearest* integer QHS. Moreover, the longitudinal resistance are *isotropic*. In contrast, we observe an anisotropic phase near $\nu = 8/5$ with an R_{xy}
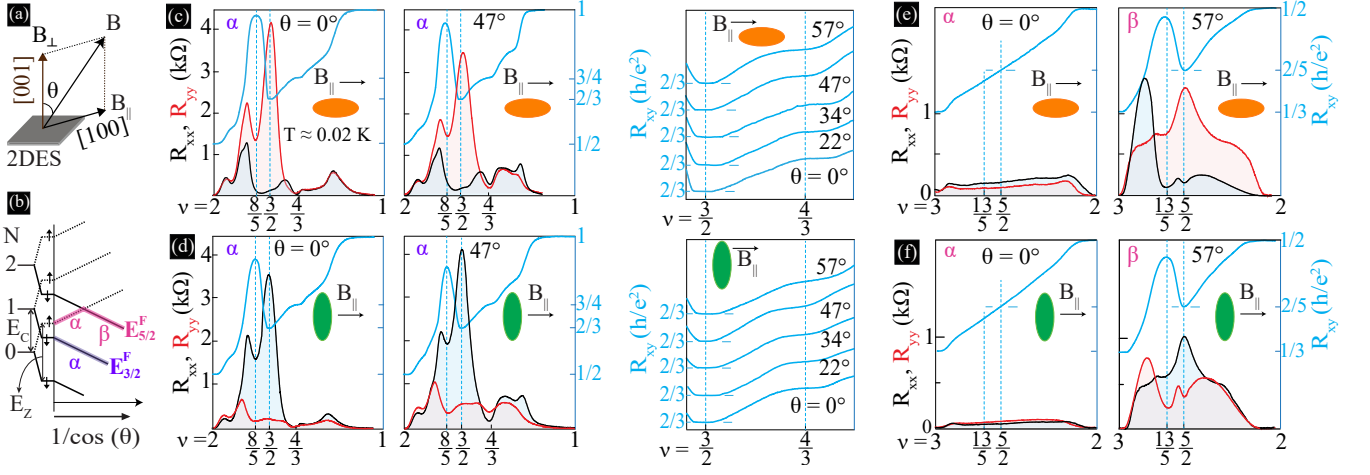
FIG. 4. Tilt-dependence of data, all taken at $T \simeq 0.02$ K. (a) The sample is mounted on a rotating stage to support *in situ* tilt. The direction of $B_{\parallel}$ is along [100], i.e., along R_{xx}. (b) LL diagram as a function of tilt. Thick purple and pink lines represent $E^F_{\nu=3/2}$ and $E^F_{\nu=5/2}$, respectively. In (c) and (d) data are shown for $2 > \nu > 1$ and in (e) and (f) for $3 > \nu > 2$. (c) and (e) contain data for when the 2D electrons occupy X, and (d) and (f) when they are in Y.

which is approaching (h/e^2) instead of $(1/2)(h/e^2)$, implying an unconventional bubble phase comprised of electrons even though the LL is more than half filled. Moreover, we do not see any signs of a bubble phase when the $N = 1$ LL is less than half filled in our AlAs 2DES, suggesting a breakdown of particle-hole symmetry. This conjecture is reasonable as the large effective mass in our 2DES can lead to severe LL mixing, which is known to break particle-hole symmetry [58].

Next we present data, taken in tilted magnetic fields where θ denotes the angle between the total field and its perpendicular component (Fig. 4(a)). The additional $B_{\parallel}$ is a useful tuning knob to study the stripe/nematic phases. In GaAs 2DESs, e.g., $B_{\parallel}$ initially turns the isotropic $\nu = 5/2$ FQHS in the $N = 1$ LL to an anisotropic FQHS, with the hard axis typically along $B_{\parallel}$ [57, 59–63]. At sufficiently large $B_{\parallel}$ there is no quantized R_{xy}, and the anisotropic state is believed to be a compressible stripe or nematic phase. In our tilt experiments (Fig. 4) we observe very different phenomena: $B_{\parallel}$ does not change the direction of the anisotropy at $\nu = 3/2$, even for $B_{\parallel} = 12$ T, the largest $B_{\parallel}$ achieved in our measurements. More remarkably, the Hall plateau at $\nu = 3/2$ stays well developed up to the highest $B_{\parallel}$ (Figs. 4(c) and 4(d), right panels). This is unusual because the $\nu = 5/2$ FQHS in GaAs 2DESs is quite sensitive to $B_{\parallel}$ and its Hall plateau disappears for $B_{\parallel} \gtrsim 5$ T [64]. The insensitivity of the direction of the anisotropy to the direction of $B_{\parallel}$ and the persistence of the quantized R_{xy} at very large $B_{\parallel}$ suggest that the robustness of the anisotropic $\nu = 3/2$ FQHS in our sample is linked to the mass anisotropy.

In Fig. 4 we also show data near $\nu = 5/2$ as a function of θ for the cases when 2D electrons occupy X (panel (e)) or Y (panel (f)). At $\theta = 0$, when $E^F_{\nu=5/2}$ lies in 0↑ (see Fig. 4(b) LL diagram), transport near $\nu = 5/2$ is

anisotropic with the same anisotropy as at $B = 0$, i.e., resistance is higher along the larger mass direction. At $\theta = 57^o$, however, when $E^F_{\nu=5/2}$ moves to the 2↓ LL, the anisotropy direction changes and becomes similar to the $\nu = 3/2$ case (i.e., $R_{xx} < R_{yy}$ for X-occupation and $R_{xx} > R_{yy}$ for Y-occupation). There is, however, no clear signature of a Hall plateau, although R_{xy} assumes a value very close to $(2/5)(h/e^2)$. The fact that the anisotropy direction at $\nu = 5/2$ in the $N = 2$ LL follows the direction of $\nu = 3/2$ anisotropy regardless of the direction of $B_{\parallel}$ again attests to the role of mass anisotropy in dictating the orientation of the anisotropic phases in the excited LLs. Note also in the right panels of Figs. 4(e) and 4(f) the emergence of a bubble-like phase near $\nu = 13/5$ in the $N = 2$ LL. Similar to the phase near $\nu = 8/5$, R_{xy} here is again heading toward an unexpected value, namely $(h/e^2)/2$ instead of $(h/e^2)/3$.

Our results presented here reveal that, unlike in the $N = 0$ LL [23, 52], effective mass anisotropy strongly affects the ground states in higher LLs and induces exotic anisotropic phases, beyond theoretical expectations. They should stimulate further studies of the even-denominator FQHS and, more generally, the many-body physics, in anisotropic systems.

[1] R. L. Willett, J. P. Eisenstein, H. L. Stormer, D. C. Tsui, A. C. Gossard, and J. H. English, Observation of an even-denominator quantum number in the fractional quantum Hall effect, Phys. Rev. Lett. **59**, 1776 (1987).

[2] Y. W. Suen, L. W. Engel, M. B. Santos, M. Shayegan, and D. C. Tsui, Observation of a $\nu = 1/2$ fractional quantum Hall state in a double-layer electron system, Phys. Rev. Lett. **68**, 1379 (1992).

[3] H. C. Manoharan and M. Shayegan, Wigner crystal versus Hall insulator, Phys. Rev. B **50**, 17662 (1994).

[4] R. L. Willett, The quantum Hall effect at 5/2 filling factor, Rep. Prog. Phys. **76**, 076501 (2013).

[5] J. Falson, D. Maryenko, B. Friess, D. Zhang, Y. Kozuka, A. Tsukazaki, J. H. Smet, and M. Kawasaki, Even-denominator fractional quantum Hall physics in ZnO, Nature Physics **11**, 347 (2015).

[6] J. I. A. Li, C. Tan, S. Chen, Y. Zeng, T. Taniguchi, K. Watanabe, J. Hone, and C. R. Dean, Even denominator fractional quantum Hall states in bilayer graphene, Science **358** 648 (2017).

[7] A. A. Zibrov, C. Kometter, H. Zhou, E. M. Spanton, T. Taniguchi, K. Watanabe, M. P. Zaletel, and A. F. Young, Tunable interacting composite fermion phases in a half-filled bilayer-graphene Landau level, Nature **549**, 360 (2017).

[8] G. Moore and N. Read, Nonabelions in the fractional quantum Hall effect. Nucl. Phys. B **360**, 362 (1991).

[9] M. Greiter, X. G. Wen, and F. Wilczek, Paired Hall states in double-layer electron systems, Phys. Rev. B **46**, 9586 (1992).

[10] C. Nayak, S. H. Simon, A. Stern, M. Freedman, and S. Das Sarma, Non-abelian anyons and topological quantum computation, Rev. Mod. Phys. **80**, 1083 (2008).

[11] W. Zhu, Z. Liu, F. D. M. Haldane, and D. N. Sheng, Fractional quantum Hall bilayers at half filling: Tunneling-driven non-Abelian phase, Phys. Rev. B 94, 245147 (2016).

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

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

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

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

[16] E. Fradkin, S. A. Kivelson, E. Manousakis, and K. Nho, Nematic phase of the two-dimensional electron gas in a magnetic field, Phys. Rev. Lett. **84**, 1982 (2000).

[17] E. Fradkin, S. A. Kivelson, M. J. Lawler, J. P. Eisenstein, and A. P. Mackenzie, Nematic Fermi fluids in condensed matter physics, Annu. Rev. Condens. Matter Phys. **1**, 153 (2010).

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

[19] R. R. Du, D. C. Tsui, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Strongly anisotropic transport in higher two-dimensional Landau levels, Solid State Commun. **109**, 389 (1999).

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

[21] M. Shayegan, E. P. De Poortere, O. Gunawan, Y. P. Shkolnikov, E. Tutuc, and K. Vakili, Two-dimensional electrons occupying multiple valleys in AlAs, Phys. Stat. Sol. (b) **243**, 3629 (2006).

[22] Y. J. Chung, K. A. Villegas Rosales, H. Deng, K. W. Baldwin, K. W. West, M. Shayegan, and L. N. Pfeiffer, Multivalley two-dimensional electron system in an AlAs quantum well with mobility exceeding 2×10^6 cm^2/Vs, Phys. Rev. Materials **2**, 071001(R) (2018).

[23] See Supplemental Material for sample details, extended data, and supporting discussions which includes Refs. [24–50].

[24] E. P. De Poortere, Y. P. Shkolnikov, E. Tutuc, S. J. Papadakis, and M. Shayegan, Enhanced electron mobility and high order fractional quantum Hall states in AlAs quantum wells, Appl. Phys. Lett. **80**, 1583 (2002).

[25] Y. J. Chung, K. W. Baldwin, K. W. West, D. Kamburov, M. Shayegan, and L. N. Pfeiffer, Design rules for modulation-doped AlAs quantum wells, Phys. Rev. Materials **1**, 021002 (2017).

[26] M. Shayegan, K. Karrai, Y. P. Shkolnikov, K. Vakili, E. P. De Poortere, and S. Manus, Low-temperature, in situ tunable, uniaxial stress measurements in semiconductors using a piezoelectric actuator, Appl. Phys. Lett. **83**, 5235 (2003).

[27] K. Vakili, Y. P. Shkolnikov, E. Tutuc, E. P. De Poortere, and M. Shayegan, Spin susceptibility of two-dimensional electrons in narrow AlAs quantum wells, Phys. Rev. Lett. **92**, 226401 (2004).

[28] T. Gokmen, M. Padmanabhan, and M. Shayegan, Contrast between spin and valley degrees of freedom, Phys. Rev. B **81**, 235305 (2010).

[29] O. Gunawan, Y. P. Shkolnikov, K. Vakili, T. Gokmen, E. P. De Poortere, and M. Shayegan, Valley susceptibility of an interacting two-dimensional electron system, Phys. Rev. Lett. **97**, 186404 (2006).

[30] N. C. Bishop, M. Padmanabhan, K. Vakili, Y. P. Shkolnikov, E. P. De Poortere, and M. Shayegan, Valley polarization and susceptibility of composite fermions around a filling factor $\nu = 3/2$, Phys. Rev. Lett. **98**, 266404 (2007).

[31] M. Padmanabhan, T. Gokmen, and M. Shayegan, Density dependence of valley polarization energy for composite fermions, Phys. Rev. B **80**, 035423 (2009).

[32] J. Falson, D. Tabrea, D. Zhang, I. Sodemann, Y. Kozuka, A. Tsukazaki, M. Kawasaki, K. V. Klitzing and J. H. Smet, A cascade of phase transitions in an or-

bitally mixed half-filled Landau level, Science Advances **4**, eaat8742 (2018).

[33] F. D. M. Haldane, Geometrical description of the fractional quantum Hall effect, Phys. Rev. Lett. **107**, 116801 (2011).

[34] H. Wang, R. Narayanan, X. Wan, and F. Zhang, Fractional quantum Hall states in two-dimensional electron systems with anisotropic interactions, Phys. Rev. B **86**, 035122 (2012).

[35] D. A. Abanin, S. A. Parameswaran, S. A. Kivelson, and S. L. Sondhi, Nematic valley ordering in quantum Hall systems, Phys. Rev. B **82**, 035428 (2010).

[36] D. Kamburov, Y. Liu, M. Shayegan, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Composite fermions with tunable Fermi contour anisotropy, Phys. Rev. Lett. **110**, 206801 (2013).

[37] D. Kamburov, M. A. Mueed, M. Shayegan, L. N. Pfeiffer, K. W. West, K. W. Baldwin, J. J. D. Lee, and R. Winkler, Fermi contour anisotropy of GaAs electron-flux composite fermions in parallel magnetic fields, Phys. Rev. B **89**, 085304 (2014).

[38] B. E. Feldman, M. T. Randeria, A. Gyenis, F. Wu, H. Ji, R. J. Cava, A. H. MacDonald, and A. Yazdani, Observation of a nematic quantum Hall liquid on the surface of bismuth, Science **354**, 316 (2016).

[39] I. Jo, K. A. Villegas Rosales, M. A. Mueed, L. N. Pfeiffer, K. W. West, K. W. Baldwin, R. Winkler, M. Padmanabhan, and M. Shayegan, Transference of Fermi contour anisotropy to composite fermions, Phys. Rev. Lett. **119**, 016402 (2017).

[40] J. Maciejko, B. Hsu, S. A. Kivelson, Y. Park, and S. L. Sondhi, Field theory of the quantum Hall nematic transition, Phys. Rev. B **88**, 125137 (2013).

[41] R. Regnault, J. Maciejko, S. A. Kivelson, and S. L. Sondhi, Evidence of a fractional quantum Hall nematic phase in a microscopic model, Phys. Rev. B **96**, 035150 (2017).

[42] K. Lee, J. Shao, E. A. Kim, F. D. M. Haldane, and E. H. Rezayi, Pomeranchuk instability of composite Fermi liquids, Phys. Rev. Lett. **121**, 147601 (2018).

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

[44] M. J. Manfra, R. De Picciotto, Z. Jiang, S. H. Simon, L. N. Pfeiffer, K. W. West, and A. M. Sergent, Impact of spin-orbit coupling on quantum Hall nematic phases, Phys. Rev. Lett. **98**, 206804 (2007).

[45] S. P. Koduvayur, Y. Lyanda-Geller, S. Khlebnikov, G. A. Csáthy, M. J. Manfra, L. N. Pfeiffer, K. W. West, and L. P. Rokhinson, Effect of strain on stripe phases in the quantum Hall regime, Phys. Rev. Lett. **106**, 016804 (2011).

[46] N. Samkharadze, K. A. Schreiber, G. C. Gardner, M. J. Manfra, E. Fradkin, and G. A. Csáthy, Observation of a transition from a topologically ordered to a spontaneously broken symmetry phase, Nat. Phys. **12**, 191 (2016).

[47] R. Winkler, Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems (Springer, Berlin, 2003).

[48] Y. You, G. Y. Cho, and E. Fradkin, Nematic quantum phase transition of composite Fermi liquids in half-filled Landau levels and their geometric response, Phys. Rev. B **93**, 205401 (2016).

[49] K. A. Schreiber, N. Samkharadze, G. C. Gardner, Y. Lyanda-Geller, M. J. Manfra, L. N. Pfeiffer, K. W. West, and G. A. Csáthy, Electron-electron interactions and the paired-to-nematic quantum phase transition in the second Landau level, Nature Communications **9**, 2400 (2018).

[50] Q. Qian, J. Nakamura, S. Fallahi, G. C. Gardner and M. J. Manfra, Possible nematic to smectic phase transition in a two-dimensional electron gas at half-filling, Nature Communications **8**, 1536 (2017).

[51] T. Gokmen, M. Padmanabhan, and M. Shayegan, Transference of transport anisotropy to composite fermions, Nat. Phys. **6**, 621 (2010).

[52] B. Yang, Z. Papić, E. H. Rezayi, R. N. Bhatt, and F. D. M. Haldane, Band mass anisotropy and the intrinsic metric of fractional quantum Hall systems, Phys. Rev. B **85**, 165318 (2012).

[53] Z. Zhu, I. Sodemann, D. N. Sheng, and L. Fu, Anisotropy-driven transition from the Moore-Read state to quantum Hall stripes, Phys. Rev. B **95**, 201116(R) (2017).

[54] X. Wan and K. Yang, Striped quantum Hall state in a half-filled Landau level, Phys. Rev. B **93**, 201303(R) (2016).

[55] M. Mulligan, C. Nayak, and S. Kachru, Effective field theory of fractional quantized Hall nematics, Phys. Rev. B **84**, 195124 (2011).

[56] J. Xia, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Evidence for a fractionally quantized Hall state with anisotropic longitudinal transport, Nature Physics **7**, 845848 (2011).

[57] Y. Liu, S. Hasdemir, M. Shayegan, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Evidence for a $\nu = 5/2$ fractional quantum Hall nematic state in parallel magnetic fields, Phys. Rev. B **88**, 035307 (2013).

[58] Y. Zhang, A. Wójs, and J. K. Jain, Landau-level mixing and particle-hole symmetry breaking for spin transitions in the fractional quantum Hall effect, Phys. Rev. Lett. **117**, 116803 (2016).

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

[60] W. Pan, R. R. Du, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, 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).

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

[62] E. H. Rezayi and F. D. M. Haldane, Incompressible paired Hall state, stripe order, and the composite fermion liquid phase in half-filled Landau levels, Phys. Rev. Lett. **84**, 4685 (2000).

[63] Q. Shi, M. A. Zudov, J. D. Watson, G. C. Gardner, and M. J. Manfra, Evidence for a new symmetry breaking mechanism reorienting quantum Hall nematics, Phys. Rev. B **93**, 121411(R) (2016).

[64] J. P. Eisenstein, R. L. Willett, H. L. Stormer, D. C. Tsui, A. C. Gossard, and J. H. English, Collapse of the even-denominator fractional quantum Hall effect in tilted fields, Phys. Rev. Lett. **61**, 997 (1988).