PHYSICAL REVIEW B **93**, 121411(R) (2016)

Evidence for a new symmetry breaking mechanism reorienting quantum Hall nematics

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(Received 16 December 2015; revised manuscript received 8 March 2016; published 24 March 2016)

We report on the effect of in-plane magnetic field $B_\parallel$ on stripe phases in higher ($N = 2,3$) Landau levels of a high-mobility two-dimensional electron gas. In accord with previous studies, we find that a modest $B_\parallel$ applied parallel to the native stripes aligns them perpendicular to it. However, upon further increase of $B_\parallel$, stripes are reoriented back to their native direction. Remarkably, applying $B_\parallel$ perpendicular to the native stripes also aligns stripes parallel to it. Thus, regardless of the initial orientation of stripes with respect to $B_\parallel$, stripes are ultimately aligned *parallel* to $B_\parallel$. These findings provide evidence for a $B_\parallel$-induced symmetry-breaking mechanism which challenge current understanding of the role of $B_\parallel$ and should be taken into account when determining the strength of the native symmetry-breaking potential. Finally, our results might indicate nontrivial coupling between the native and external symmetry-breaking fields, which has not yet been theoretically considered.

DOI: 10.1103/PhysRevB.93.121411

Electronic liquid crystal-like phases, termed electron nematics or stripes, are expected to form in a wide variety of condensed matter systems [1–5]. A two-dimensional electron gas in GaAs/AlGaAs hosts the first, and perhaps the most striking, realization of such phases [6–11]. Stripes in a two-dimensional electron gas form due to interplay between exchange and direct Coulomb interactions [6,7,10,11] and are manifested by the resistivity minima (maxima) in the easy (hard) transport direction near half-integer filling factors, $\nu = 9/2, 11/2, 13/2, \ldots$ when the system is cooled below $T \approx 0.1$ K. With very few exceptions [12–14], stripes in GaAs are aligned along the $\langle 110 \rangle$ direction, but what exactly causes such orientation remains unknown [13,15,16].

While the origin of the native symmetry-breaking potential responsible for preferred stripes orientation remains elusive, its magnitude was routinely obtained from experiments employing in-plane magnetic field $B_\parallel$ which provides an external symmetry-breaking field competing with and overcoming the native one. Our current understanding of $B_\parallel$-induced symmetry-breaking potential is based on finite thickness effects [17,18], which favor stripes perpendicular to $B_\parallel$, consistent with previous experiments [13,19–23]. The same approach successfully explains $B_\parallel$-induced stripes in both single-subband [19,20,24–26] and double-subband [27] systems.

In this Rapid Communication we reexamine the effect of in-plane magnetic field on quantum Hall stripes in ultrahigh-quality GaAs quantum wells. In agreement with early experiments [19–21], we find that a $B_\parallel \lesssim 0.4$ applied parallel to the native stripes aligns stripes perpendicular to it. Remarkably, upon further increase of $B_\parallel$, stripes are reoriented back to their native direction, i.e., *parallel* to $B_\parallel$. When $B_\parallel$ is applied perpendicular to the native stripes, we also find that stripes are reoriented *parallel* to $B_\parallel$. We thus conclude that there exist a new $B_\parallel$-induced symmetry-breaking potential which challenge our understanding of the role of $B_\parallel$ and must be taken into account when determining the strength of the native symmetry-breaking potential. In contrast to the well-established $B_\parallel$-induced symmetry-breaking potential originating from finite thickness effects, new symmetry-breaking potential exhibits high sensitivity to spin and Landau level indices. Finally, our results suggest a nontrivial coupling between the native and external symmetry-breaking fields, which has not yet been theoretically considered and might provide an important clue to unveiling the origin of the native symmetry-breaking potential.

The sample used in our study is a 4×4 mm square cleaved from a symmetrically doped, 30-nm-wide GaAs/AlGaAs quantum well. Electron density and mobility were $n_e \approx 2.9 \times 10^{11}$ cm^{-2} and $\mu \approx 1.6 \times 10^7$ cm^2/V s, respectively. Eight indium contacts were fabricated at the corners and mid-sides of the sample. The longitudinal resistances, R_{xx} and R_{yy}, were measured using four-terminal, low-frequency lock-in technique; the current (typically 10 nA) was sent through the mid-side contacts and the voltage drop was recorded between the corner contacts. An in-plane magnetic field was introduced by tilting the sample about $\hat{x}$ or $\hat{y}$ axis, in two separate cooldowns. The data were taken at $T \approx 20$ mK.

In Fig. 1(a) we present an example of stripes in perpendicular magnetic field near $\nu = 9/2$, characterized by $R_{xx} \gg R_{yy}$, indicating stripes oriented along $\hat{y} \equiv \langle 110 \rangle$ direction. When $B_\parallel$ is applied parallel to the native stripes ($B_\parallel = B_y$), at $\theta_y = 12^\circ$ stripes reorient along the $\hat{x}$ direction (perpendicular to $B_\parallel$), as anticipated [see Fig. 1(b)]. Surprisingly, upon further increase of B_y, at $\theta_y = 46^\circ$ stripes are reoriented again, back to their native direction and are now aligned *parallel* to $B_\parallel$ [see Fig. 1(c)]. When $B_\parallel$ is applied perpendicular to the native stripes ($B_\parallel = B_x$), at $\theta_x = 42^\circ$ stripes are reoriented along the $\hat{x}$ direction, again aligning *parallel* to $B_\parallel$ [see Fig. 1(d)]. We thus conclude that, regardless of the orientation of $B_\parallel$, ultimately, stripes align *parallel* to $B_\parallel$.

Figure 1(e) shows the resistance anisotropy $A_R \equiv (R_{xx} - R_{yy})/(R_{xx} + R_{yy})$ vs B_x (left panel) and B_y (right panel). Starting from $A_R \approx 1$, with increasing B_y, A_R vanishes at $B_y \approx 0.4$ T, reaches $A_R \approx -1$, turns around, disappears again

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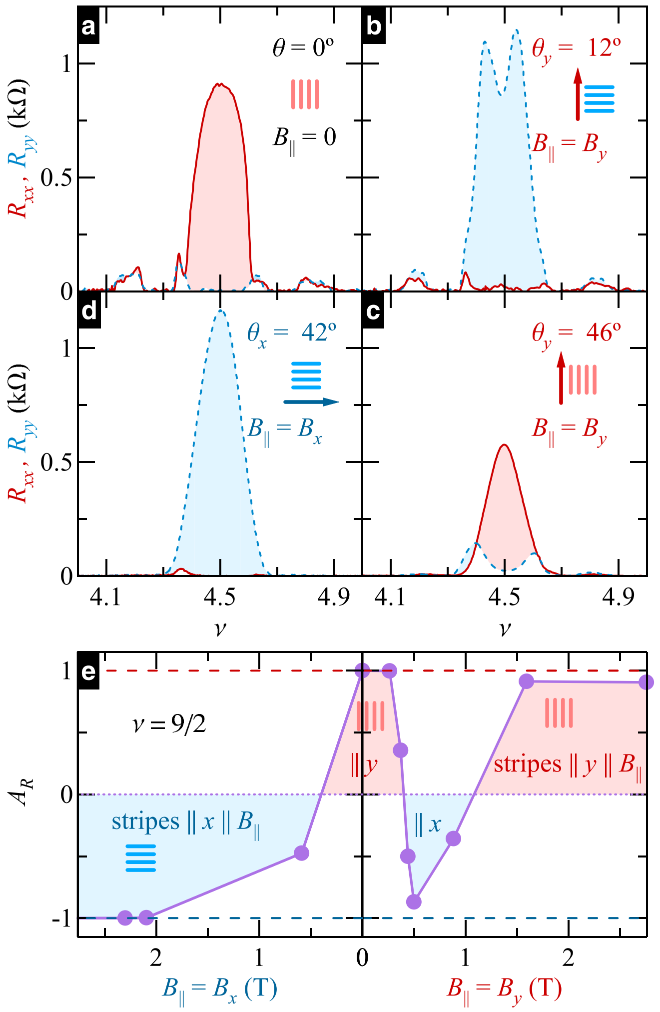

FIG. 1. R_{xx} (solid line) and R_{yy} (dotted line) versus ν at (a) $\theta = 0^\circ$, (b) $B_\parallel = B_y$ and $\theta_y = 12^\circ$, (c) $B_\parallel = B_y$ and $\theta_y = 46^\circ$, and (d) $B_\parallel = B_x$ and $\theta_x = 42^\circ$. (e) Resistance anisotropy $A_R \equiv (R_{xx} - R_{yy})/(R_{xx} + R_{yy})$ as a function of $B_\parallel = B_x$ (left) and $B_\parallel = B_y$ (right) at $\nu = 9/2$. The inset shows the stripes orientation and the direction of $B_\parallel$.

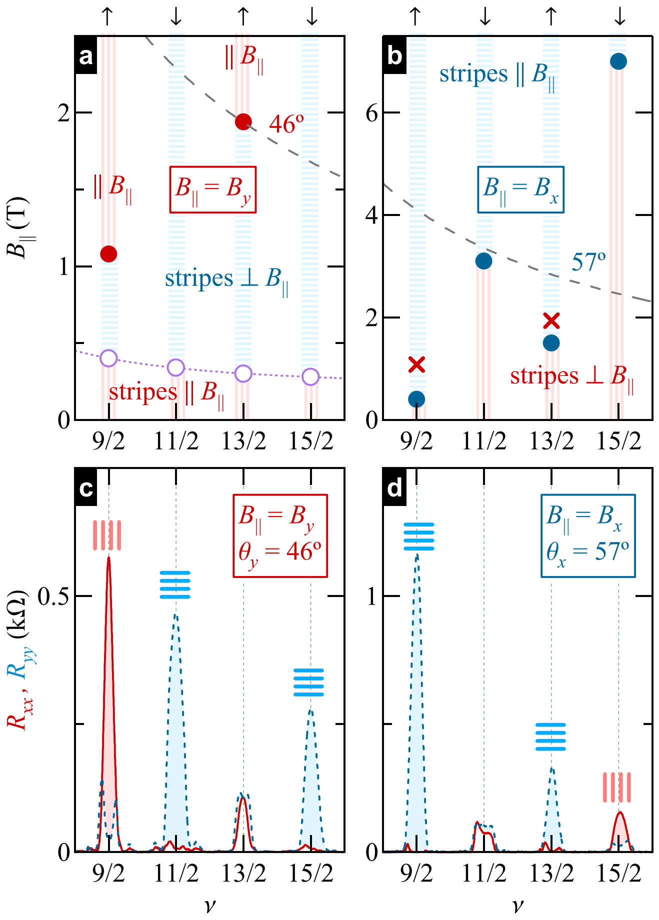

FIG. 2. Evolution of stripe orientation at $\nu = 9/2$, $11/2$, $13/2$, and $15/2$ for (a) $B_\parallel = B_y$ and (b) $B_\parallel = B_x$. The regions with vertical (horizontal) lines represent stripes along $\hat{y}$ ($\hat{x}$), demarcated by the characteristic fields B_{1y} (open dots), B_{2x} [panel (b)] and B_{2y} [panel (a)] (solid dots). For comparison, B_{2y} (crosses) are added to panel (b) at $\nu = 9/2$ and $13/2$. Dashed lines represent $B_\parallel$ at marked tilt angles. R_{xx} (solid line) and R_{yy} (dotted line) vs ν at (c) $\theta_y = 46^\circ$ and (d) $\theta_x = 57^\circ$.

at $B_y \approx 1.1$ T, and finally returns to $A_R \approx 1$. With increasing B_x, A_R vanishes at $B_x \approx 0.4$ T and then approaches $A_R \approx -1$. Taken together, the data in Fig. 1 clearly demonstrate the existence of a mechanism which favors stripes along $B_\parallel$. As we show next, this mechanism is relevant at other filling factors although it shows sensitivity to both the spin index σ and the Landau level index N.

Figure 2 shows the phase diagram of stripe orientations at $\nu = 9/2$, $11/2$, $13/2$, and $15/2$ for (a) $B_\parallel = B_y$ and (b) $B_\parallel = B_x$. The regions representing stripes along $\hat{y}$ ($\hat{x}$), marked by vertical (horizontal) lines, are demarcated by the characteristic fields (circles) where $A_R \approx 0$. We define B_{1y} as the field at which stripes reorient perpendicular to B_y, and B_{2x} (B_{2y}) as the field at which stripes reorient parallel to B_x (B_y). The dashed lines represent $B_\parallel$ at select tilt angles and the resistances at these angles are shown in Figs. 2(c) and 2(d). First, we notice that both B_{2x} and B_{2y} increase with N for a given σ, while B_{1y} decreases with N. Second, strong sensitivity to σ renders the overall dependencies of B_{2x} and B_{2y} on ν nonmonotonic; indeed, both B_{2x} and B_{2y} are always considerably smaller for $\sigma = +1/2$ than $\sigma = -1/2$.

The sensitivity of B_{2x} and B_{2y} to σ and N is also evident in the raw data presented in Figs. 2(c) and 2(d). For $B_\parallel = B_y$ and $\theta_y = 46^\circ$ [see Fig. 2(c)], the stripes at $\nu = 9/2$ have reoriented back to their native direction (along the $\hat{y}$ axis) as manifested by $R_{xx} \gg R_{yy}$. The data at $\nu = 13/2$ suggest that the (second) reorientation is about to happen at this filling factor as well. However, stripes at $\nu = 11/2$ and $15/2$ are still oriented along the $\hat{x}$ direction, as $R_{xx} \ll R_{yy}$. For $B_\parallel = B_x$ and $\theta_x = 57^\circ$ [see Fig. 2(d)], stripes both at $\nu = 9/2$ and $13/2$ have reoriented along the $\hat{x}$ axis, stripes at $\nu = 11/2$ are undergoing the reorientation, while stripes at $\nu = 15/2$ are still oriented along the $\hat{y}$ direction.

To compare the magnitudes of B_{2x} and B_{2y} we add B_{2y} (crosses) to Fig. 2(b) and observe that B_{2y} is close to B_{2x} at both $\nu = 9/2$ and $13/2$. Combined with qualitatively identical dependence on σ and N, this observation suggests that the reorientations characterized by B_{2x} and B_{2y} are of similar origin. We can now classify the reorientations into two types.

The first type, which aligns stripes perpendicular to $B_\parallel$, is characterized by B_{1y} that is not sensitive to σ and decreases with N. The second type aligns stripes parallel to $B_\parallel$ and is characterized by B_{2x} and B_{2y} that depend on σ [28] and increase with N. The data at $\nu = 9/2$ also suggest that the mechanism responsible for reorientation of the first (second) type dominates at lower (higher) $B_\parallel$.

The reorientation of the first type is well understood in terms of finite thickness effects [17,18]. The $B_\parallel$-induced anisotropy energy can be defined as $E_{1A} = E_{1\parallel} - E_{1\perp}$, where $E_{1\parallel}$ and $E_{1\perp}$ are optimized energies per electron of a stripe state parallel and perpendicular to $B_\parallel$, respectively. For a single-subband system, $E_{1A} > 0$ and increases monotonically with $B_\parallel$ [17,21]. While E_{1A} could change sign in systems with two occupied subbands, such systems do not exhibit native stripes at $B_\parallel = 0$ and E_{1A} is insensitive to σ [17,27]. We thus conclude that reorientations of the second type, favoring stripes parallel to $B_\parallel$, have a distinct physical origin.

Furthermore, since $E_{1A}(B_x) = E_{1A}(B_y)$ for $B_x = B_y$ [17,18], we can conclude that the mechanism responsible for reorientation of the second type lacks such symmetry. Indeed, if we assume that the anisotropy energy due to the second mechanism, E_{2A}, is the same for $B_\parallel$ applied along the $\hat{x}$ or $\hat{y}$ directions, one would expect, in the absence of native symmetry-breaking potential, $B_{2x} = B_{2y}$ at a given ν; a native symmetry-breaking potential favoring stripes along the $\hat{y}$ direction would then lead to $B_{2x} > B_{2y}$. In contrast, our data show exactly the opposite and, e.g., at $\nu = 9/2$, $B_{2y} \approx 1.0$ T is considerably larger than $B_{2x} \approx 0.4$ T. We thus conclude that E_{2A} must depend on the direction of $B_\parallel$, suggesting possible coupling of $B_\parallel$ to native symmetry-breaking potential [29]. A proposal considering a combination of Rashba and Dresselhaus spin-orbital interactions as the origin of the native symmetry-breaking potential [15,30,31] seems to indicate that the effects of $B_\parallel$ on such native stripe states should be sensitive to its orientation with respect to the crystal axes. However, a study of the interplay between $B_\parallel$ and spin-orbital interactions was left for future work.

Despite our lack of understanding of the mechanism responsible for the second type of reorientation, our experimental results unambiguously demonstrate that two competing mechanisms must be incorporated in any complete theory of reorientation of quantum Hall nematics. Another important implication of our findings is related to the identification of the native symmetry-breaking potential, whose strength was traditionally obtained by calculating E_{1A} at $B_\parallel = B_{1c}$. In light of clear evidence for the second mechanism and its possible coupling to the native symmetry-breaking potential and/or E_{1A}, this approach must be reexamined.

We thank G. Csathy, L. Engel, Y. Liu, B. Skinner, M. Shayegan, B. Shklovskii, and I. Sodemann for discussions. We thank G. Jones, S. Hannas, T. Murphy, J. Park, and A. Suslov for technical support. The work at Minnesota (Purdue) was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, under Award No. ER 46640-SC0002567 (DE-SC0006671). Q.S. acknowledges The University of Minnesota Doctoral Dissertation Fellowship. Experiments were performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-0654118, by the State of Florida, and by the DOE.

[1] 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).

[2] R. A. Borzi, S. A. Grigera, J. Farrell, R. S. Perry, S. J. S. Lister, S. L. Lee, D. A. Tennant, Y. Maeno, and A. P. Mackenzie, Formation of a nematic fluid at high fields in $Sr_3Ru_2O_7$, Science **315**, 214 (2007).

[3] R. Daou, J. Chang, D. LeBoeuf, O. Cyr-Choiniere, F. Laliberte, N. Doiron-Leyraud, B. J. Ramshaw, R. Liang, D. A. Bonn, W. N. Hardy *et al.*, Broken rotational symmetry in the pseudogap phase of a high-T_c superconductor, Nature (London) **463**, 519 (2010).

[4] J.-H. Chu, J. G. Analytis, K. De Greve, P. L. McMahon, Z. Islam, Y. Yamamoto, and I. R. Fisher, In-plane resistivity anisotropy in an underdoped iron arsenide superconductor, Science **329**, 824 (2010).

[5] R. Okazaki, T. Shibauchi, H. J. Shi, Y. Haga, T. D. Matsuda, E. Yamamoto, Y. Onuki, H. Ikeda, and Y. Matsuda, Rotational symmetry breaking in the hidden-order phase of URu_2Si_2, Science **331**, 439 (2011).

[6] 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).

[7] 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).

[8] 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).

[9] 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).

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

[11] 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).

[12] J. Zhu, W. Pan, H. L. Stormer, L. N. Pfeiffer, and K. W. West, Density-Induced Interchange of Anisotropy Axes at Half-Filled High Landau Levels, Phys. Rev. Lett. **88**, 116803 (2002).

[13] J. Pollanen, K. B. Cooper, S. Brandsen, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Heterostructure symmetry and the orientation of the quantum Hall nematic phases, Phys. Rev. B **92**, 115410 (2015).

[14] Y. Liu, D. Kamburov, M. Shayegan, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Spin and charge distribution symmetry dependence of stripe phases in two-dimensional electron systems confined to wide quantum wells, Phys. Rev. B **87**, 075314 (2013).

[15] I. Sodemann and A. H. MacDonald, Theory of native orientational pinning in quantum Hall nematics, arXiv:1307.5489.

[16] S. P. Koduvayur, Y. Lyanda-Geller, S. Khlebnikov, G. Csathy, 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).

[17] 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).

[18] T. D. Stanescu, I. Martin, and P. Phillips, Finite-Temperature Density Instability at High Landau Level Occupancy, Phys. Rev. Lett. **84**, 1288 (2000).

[19] 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).

[20] 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).

[21] K. B. Cooper, M. P. Lilly, J. P. Eisenstein, T. Jungwirth, L. N. Pfeiffer, and K. W. West, An investigation of orientational symmetry-breaking mechanisms in high Landau levels, Solid State Commun. **119**, 89 (2001).

[22] H. Zhu, G. Sambandamurthy, L. W. Engel, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Pinning Mode Resonances of 2D Electron Stripe Phases: Effect of an In-Plane Magnetic Field, Phys. Rev. Lett. **102**, 136804 (2009).

[23] Q. Shi, M. A. Zudov, J. D. Watson, G. C. Gardner, and M. J. Manfra, Reorientation of quantum Hall stripes within a partially filled Landau level, Phys. Rev. B **93**, 121404(R) (2016).

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

[25] J. Xia, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Evidence for a fractionally quantized Hall state with anisotropic longitudinal transport, Nat. Phys. **7**, 845 (2011).

[26] B. Friess, V. Umansky, L. Tiemann, K. von Klitzing, and J. H. Smet, Probing the Microscopic Structure of the Stripe Phase at Filling Factor 5/2, Phys. Rev. Lett. **113**, 076803 (2014).

[27] W. Pan, T. Jungwirth, H. L. Stormer, D. C. Tsui, A. H. MacDonald, S. M. Girvin, L. Smrčka, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Reorientation of Anisotropy in a Square Well Quantum Hall Sample, Phys. Rev. Lett. **85**, 3257 (2000).

[28] Qualitatively consistent with our observations, early experiments [19] have found that, when $B_\parallel$ is applied perpendicular to stripes, the anisotropy is affected more at $\nu = 9/2$ and $13/2$ than at $\nu = 11/2$ and $15/2$.

[29] An alternative senario is that the effect of $B_\parallel$ is modified by disorder which is anisotropic along the two crystal axes [22]. However, effect of disorder on stripes orientation has not been studied theoretically and it seems unlikely that such a mechanism would depend on σ.

[30] We note that the anisotropy energy due to this mechanism also shows oscillating behavior with σ.

[31] Recent experiments [13] have found that the quantum well symmetry has a minor role in deciding the stripes orientation, suggesting that spin-orbital interaction [15] is unlikely to be the major mechanism for the native symmetry breaking.