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Evidence for a $\nu = 5/2$ Fractional Quantum Hall Nematic State in Parallel Magnetic Fields

Yang Liu, S. Hasdemir, M. Shayegan, L.N. Pfeiffer, K.W. West, and K.W. Baldwin
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544
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We report magneto-transport measurements for the fractional quantum Hall state at filling factor $\nu = 5/2$ as a function of applied parallel magnetic field ($B_{||}$). As $B_{||}$ is increased, the 5/2 state becomes increasingly anisotropic, with the in-plane resistance along the direction of $B_{||}$ becoming more than 30 times larger than in the perpendicular direction. Despite the very large resistance anisotropy, the anisotropy ratio remains constant over a relatively large temperature range, yielding an energy gap which is the same for both directions. Our data are qualitatively consistent with a fractional quantum Hall *nematic* phase.

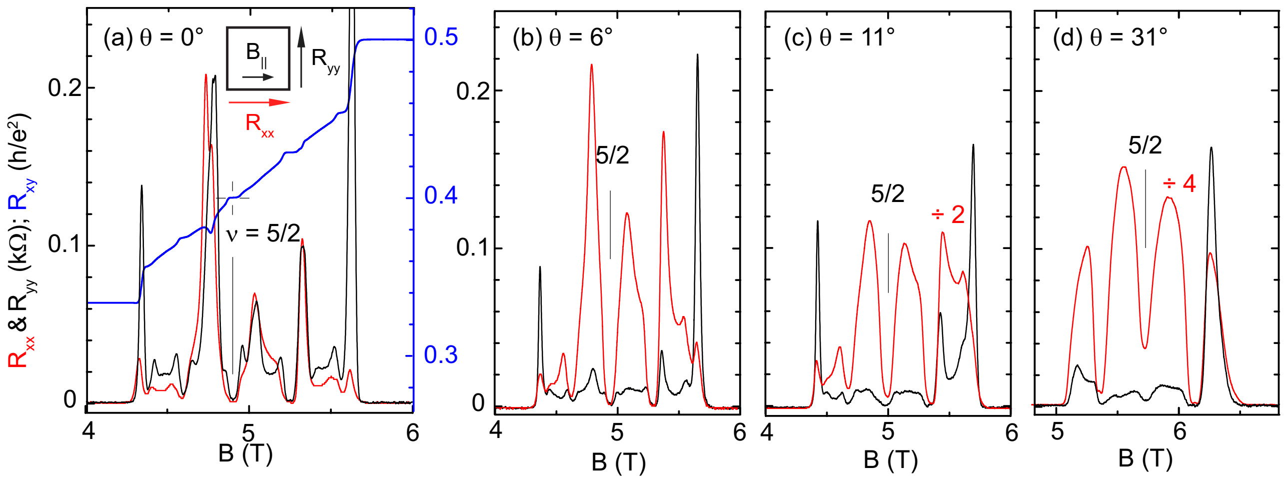

FIG. 1. (color online) (a) Longitudinal resistances R_{xx} (red) and R_{yy} (black), and Hall resistance R_{xy} (blue) measured as a function of perpendicular magnetic field. The deep minima in R_{xx} and R_{yy}, as well as the well-quantized R_{xy} plateau, indicate a strong FQHS at $\nu = 5/2$. (b-d) R_{xx} and R_{yy} measured at finite tilting angles, $\theta = 6°$, $11°$ and $31°$ are shown as a function of total magnetic field. The in-plane component of the magnetic field ($B_{||}$) is along the x-direction. Note that the R_{xx} traces in (c) and (d) are divided by factors of 2 and 4. Strong transport anisotropy near $\nu = 5/2$ grows as θ increases. All traces were recorded at the base temperature of our measurements, $T \simeq 20$ mK.

The origin and properties of the fractional quantum Hall state (FQHS) at the even-denominator Landau level (LL) filling factor $\nu = 5/2$[1] have become of tremendous current interest. This is partly because the quasi-particle excitations of the 5/2 FQHS are expected to obey non-Abelian statistics[2] and be useful for topological quantum computing[3]. The stability and robustness of the 5/2 state, and its sensitivity to the parameters of the hosting two-dimensional electron system (2DES) are therefore of paramount importance. This stability has been studied as a function of 2DES density, quantum well width, disorder, and a parallel magnetic field ($B_{||}$) applied in the 2DES plane[4–18]. The role of $B_{||}$ is particularly important. It has been used to shed light on the spin polarization of the $\nu = 5/2$ state, which in turn has implications for whether or not the state is non-Abelian[4,8,14]. But the application of $B_{||}$ in fact has more subtle consequences. It often induces anisotropy in the 2DES transport properties in the excited-state (N=1) LL and, at sufficiently large values of $B_{||}$, leads to an eventual destruction of the $\nu = 5/2$ FQHS[5,6,12], replacing it by a *compressible*, anisotropic ground state. This anisotropic state is reminiscent of the non-uniform density, stripe phases seen at half-integer fillings in the higher ($N > 1$) LLs[19,20].

Here we study the $\nu = 5/2$ FQHS as a function of $B_{||}$ in a very high-quality 2DES. We find that the application of $B_{||}$ leads to a quick weakening of the 5/2 FQHS and a strong anisotropy in transport as the resistance along $B_{||}$ becomes much larger than in the perpendicular direction. Specifically, the resistance anisotropy ratio grows exponentially with $B_{||}$ up to $B_{||} \simeq 1.5$ T where it reaches about 30. For $B_{||} > 1.5$ T, the anisotropy remains constant up to $B_{||} \simeq 3.6$ T, the $B_{||}$ above which the FQHS at $\nu = 5/2$ disappears and the system turns into a compressible state. Remarkably, for $B_{||} \lesssim 3.6$ T and at low temperatures ($T \lesssim 100$ mK), the resistances along the two in-plane directions monotonically decrease with decreasing temperature while the anisotropy ratio remains nearly constant. From the temperature-dependence of the resistances, we are able to measure the energy gap (Δ) for the 5/2 FQHS along the two in-plane directions. Despite the enormous transport anisotropy, Δ has the same magnitude along both directions. Our data therefore strongly suggest that the ground state of the system is an *anisotropic* FQHS. We discuss possible interpretation of such a ground state, including a FQH *nematic* phase.

In our sample, which was grown by molecular beam epitaxy, the 2DES is confined to a 30-nm-wide GaAs quantum well, flanked by undoped $Al_{0.24}Ga_{0.76}As$ spacer layers and Si δ-doped layers. The 2DES has a density of $n = 3.0 \times 10^{15}$ m^{-2} and a very high mobility, $\mu \simeq 2{,}500$ m^2/Vs. It has a very strong $\nu = 5/2$ FQHS, with an energy gap of $\Delta \simeq 0.4$ K, when $B_{||} = 0$. The sample is 4 mm × 4 mm with alloyed InSn contacts at four corners. For the low-temperature measurements, we used a dilution refrigerator with a base temperature of $T \simeq 20$ mK, and a sample platform which could be rotated *in-situ* in the magnetic field to induce a parallel field component $B_{||}$ along the x-direction (the $[1\bar{1}0]$ crystal direction)[21]. We use θ to express the angle between the field and the normal to the sample plane, and denote the longitudinal resistances measured along and perpendicular to the direction of $B_{||}$ as R_{xx} and R_{yy}, respectively.

Figure 1 shows the R_{xx} (red) and R_{yy} (black) measured as a function of the total magnetic field in the filling range $2 < \nu < 3$; the Hall resistance R_{xy} is also shown (in blue) in Fig. 1(a). The traces in Fig. 1(a) were taken at $\theta = 0$, i.e., for $B_{||} = 0$, and exhibit a very strong $\nu = 5/2$ FQHS with an energy gap of $\simeq$0.4 K and an R_{xy} which

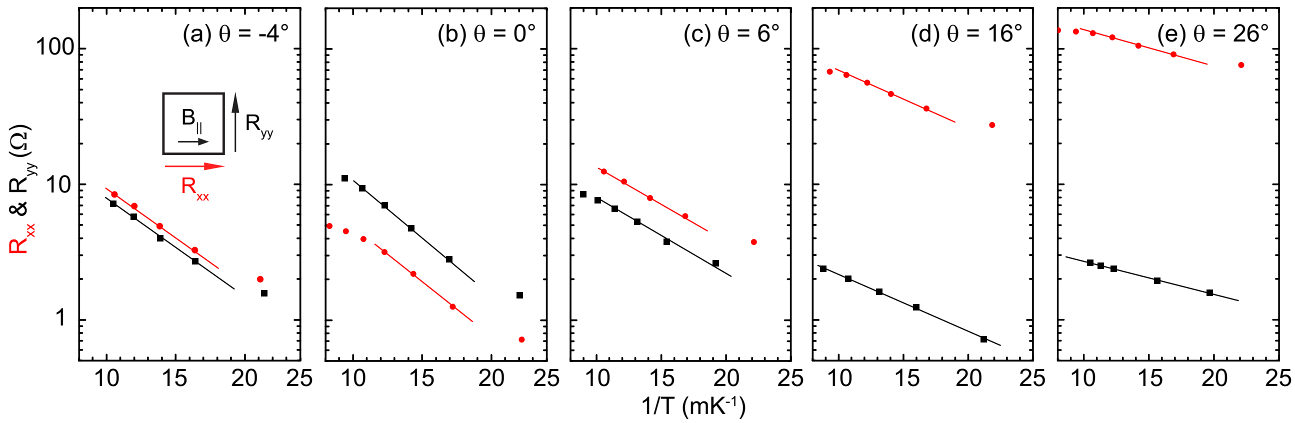

FIG. 2. (color online) Temperature-dependence of R_{xx} (red circles) and R_{yy} (black squares) at $\nu = 5/2$, measured at different tilting angles, θ. The excitation gap deduced from the slopes of these plots decreases as θ is increased, while the transport anisotropy increases.

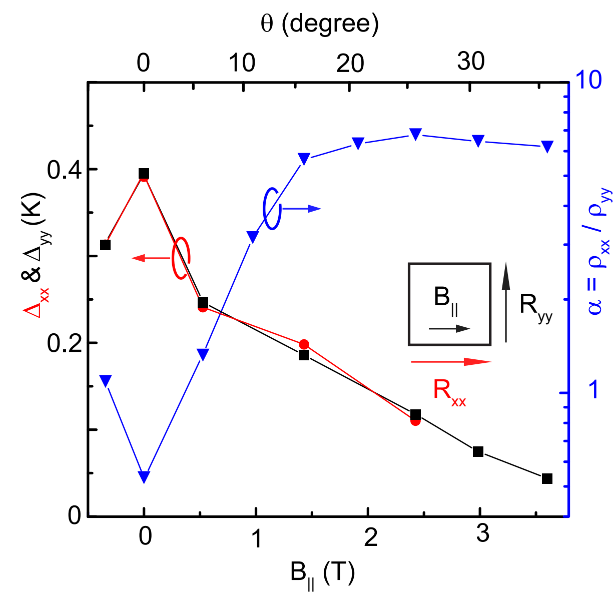

FIG. 3. (color online) Measured excitation gaps, Δ_{xx} (red circles) and Δ_{yy} (black squares), are shown as a function of the in-plane magnetic field $B_{||}$. Δ_{xx} and Δ_{yy} nearly equal each other and decrease with increasing $B_{||}$. Also plotted (blue triangles is the transport anisotropy factor, α, defined as the ratio between the resistivities ρ_{xx} and ρ_{yy}). Note the logarithmic scale on the right: α grows exponentially with $B_{||}$ at small $B_{||}$, and saturates at large $B_{||} \gtrsim 1$ T.

is well-quantized at $0.4h/e^2$. As seen in Figs. 1(b-d), the application of $B_{||}$ causes a very pronounced anisotropy in the in-plane transport at and near $\nu = 5/2$, and R_{xx} becomes much larger than R_{yy}. At $\theta = 26°$, e.g., R_{xx} is about 30 times R_{yy}[23]. Note that in our experiments $B_{||}$ is applied along the x-direction so that the "hard"-axis we observe for in-plane transport is along the direction of $B_{||}$. This is consistent with previous reports on $B_{||}$-induced resistance anisotropy near 5/2[5,6,12,21].

In Fig. 2 we show the temperature dependence of R_{xx} and R_{yy} at $\nu = 5/2$ for different values of θ. In the temperature range $50 < T < 100$ mK, both R_{xx} and R_{yy} are activated and follow the relation $R \sim \exp(-\Delta/2k_BT)$, where Δ is FQH energy gap. At $\theta = 0$ R_{yy} is larger than R_{xx} by about a factor of two. This anisotropy is caused by a mobility anisotropy, as the latter is often seen in very high-mobility samples. With the application of a very small $B_{||}$ along the x-direction ($|\theta| \lesssim 5°$), the anisotropy reverses so that R_{xx} exceeds R_{yy}. This trend continues with increasing θ and, at $\theta = 26°$, R_{xx} becomes 30 times larger than R_{yy}. However, despite the very large anisotropy, both R_{xx} and R_{yy} remain activated and yield very similar values for Δ[24].

The transport energy gaps at $\nu = 5/2$ measured as a function of $B_{||}$ up to $\simeq 3.6$ T are summarized in Fig. 3. We

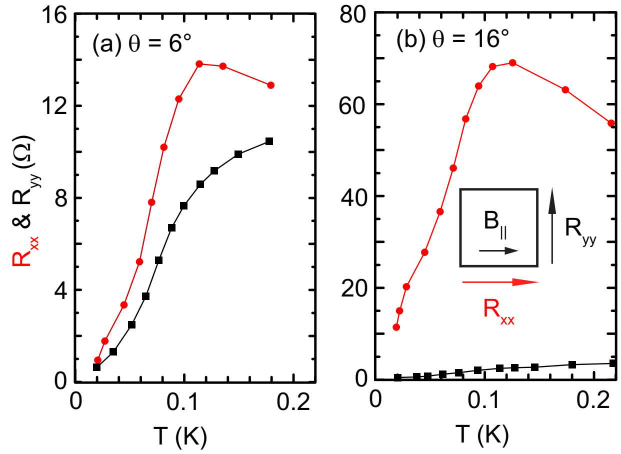

FIG. 4. (color online) R_{xx} and R_{yy} are shown vs. temperature for two values of tilt angle. R_{yy} monotonically increases with increasing temperature, while R_{xx} shows a downturn at high temperatures $T \gtrsim 120$ mK, indicating a smaller anisotropy.

denote the energy gaps deduced from the temperature-dependence of R_{xx} and R_{yy} by Δ_{xx} and Δ_{yy}, respectively. It is clear in Fig. 3 that $\Delta_{xx} \simeq \Delta_{yy}$ despite the large anisotropy observed in R_{xx} and R_{yy}. In Fig. 3 we also plot the observed transport anisotropy as a function of $B_{||}$. Here we used the values of R_{xx} and R_{yy} resistances at $T = 60$ mK, converted them to *resistivities* ρ_{xx} and ρ_{yy} following the formalism presented in Ref.[25], and plot the ratio $\alpha = \rho_{xx}/\rho_{yy}$. As a function of $B_{||}$, this ratio grows very quickly, approximately exponentially up to $B_{||} \simeq 1$ T, and then saturates at higher $B_{||}$. The energy gaps Δ_{xx} and Δ_{yy}, however, exhibit a very steep drop at small $B_{||}$, followed by a more gradual and monotonic decrease at higher $B_{||}$. For $\theta > 36°$ ($B_{||} \gtrsim 3.6$ T) we cannot measure the gap for the 5/2 FQHS as it becomes too weak.

The data presented above provide clear evidence for a strong $\nu = 5/2$ FQHS whose in-plane transport is very anisotropic in the presence of applied $B_{||}$. And yet its energy gap is the same for the two in-plane directions. These observations imply a $\nu = 5/2$ FQHS whose transport is anisotropic at finite temperatures. A possible interpretation of our data is that we are observing a FQH *nematic* phase. It has been argued in numerous theoretical studies that such liquid-crystal-like FQH phases might exist in 2D systems where the rotational symmetry is broken[26–35]. Now in a 2DES with finite (non-zero) electron layer thickness, such as ours, it is known that $B_{||}$ breaks the rotational symmetry as it couples to the electrons' out-of-plane motion and causes an anisotropy of their real-space motion as well as their Fermi contours[36]. Recently it was demonstrated experimentally that such a $B_{||}$-induced anisotropy is qualitatively transmitted to the quasiparticles at high magnetic fields, for example to the composite Fermions near $\nu = 1/2$ in the lowest LL[37]. It is therefore reasonable to expect that $B_{||}$ also breaks the rotational symmetry in our 2DES in the $N = 1$ LL and induces a FQH nematic phase at $\nu = 5/2$.

A FQH nematic phase was in fact recently proposed theoretically[31] to explain the experimental observations of Xia *et al.*[38] for another FQHS in the $N = 1$ LL, namely at $\nu = 7/3$. In the model of Ref.[31], the ground-state is a FQHS but the dc longitudinal resistance at finite temperatures is anisotropic as it reflects the anisotropic property of the thermally excited quasiparticles. The energy gap for the excitations, however, is predicted to be the same for R_{xx} and R_{yy}. These features are consistent with our experimental data. According to Mulligan *et al.*, the FQH nematic phase with anisotropic transport is stable only at very low temperatures[31]. As temperature is raised above a critical value that depends on the details of the sample's parameters and transport properties, R_{xx} should abruptly drop and R_{yy} suddenly rise so that they have the same value, signaling an isotropic FQH phase. Mulligan *et al.* also report that, thanks to the small symmetry-breaking $B_{||}$ field, this finite-temperature transition might become rounded so that R_{xx} and R_{yy} approach each other more slowly at high temperatures (see Fig. 3 of Ref.[31]). As mentioned above, our data at low temperatures are qualitatively consistent with the predictions of Ref.[31] for a FQH nematic state. At higher temperatures (Fig. 4), our data exhibit a downturn in R_{xx} as temperature is raised above $\simeq 0.1$ K, signaling that transport is becoming less anisotropic, also generally consistent with Ref.[31] predictions. However, up to the highest temperatures achieved in our measurements ($\simeq 0.2$ K, which is comparable to the $\nu = 5/2$ FQHS excitation gaps in our sample for $\theta = 6°$ and $\theta = 16°$), we do not see a transition to a truly isotropic state[39].

While the above interpretation of our data based on a FQH nematic state is plausible, there might be alternative explanations. For example, it has been theoretically suggested that the low-energy charged excitations of the FQHSs in the $N = 1$ LL have a very large size as they are complex composite Fermions dressed by roton clouds[40]. Because of their large size, these excitations are prone to become anisotropic in the presence of $B_{||}$. Such anisotropy, even if small in magnitude, could lead to a much larger *transport* anisotropy of the quasiparticle excitations at finite temperatures because this transport would involve hopping or tunneling of the quasiparticles between the localized regions.

To summarize, our magneto-transport measurements reveal that the application of a $B_{||}$ leads to a $\nu = 5/2$ FQHS whose in-plane longitudinal resistance is highly anisotropic at low temperatures. The resistance anisotropy ratio remains constant over a relatively large temperature range, and the energy gap we extract from the temperature-dependence of the resistances is the same for both directions. Our data are generally consistent with a FQH *nematic* phase, although other explanations might be possible. Regardless of the interpretations, our results attest to the very rich and yet not fully understood nature of the enigmatic $\nu = 5/2$ FQHS.

ACKNOWLEDGMENTS

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