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

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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. Remarkably, the resistance 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.

The origin and properties of the fractional quantum Hall state (FQHS) at the even-denominator Landau level (LL) filling factor $\nu = 5/2$ have become of tremendous current interest. This is partly because the quasiparticle excitations of the $5/2$ FQHS are expected to obey non-Abelian statistics and be useful for topological quantum computing. 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 and quantum well width, disorder, and a parallel magnetic field ($B_{||}$) applied in the 2DES plane. Recent measurements have demonstrated that the $\nu = 5/2$ FQHS is stable when the Fermi level lies in the excited-state ($N = 1$) LL of the symmetric electric subband but turns into a compressible state if the Fermi level moves to the ground-state ($N = 0$) LL of the anti-symmetric electric subband. The role of $B_{||}$ is also important and has been used to shed light on the spin polarization of the 5/2 state, which in turn has implications for whether or not the state is non-Abelian. The application of $B_{||}$ in fact has more subtle consequences. It often induces anisotropy in the 2DES transport properties in the $N = 1$ LL and, at sufficiently large values of $B_{||}$, leads to an eventual destruction of the $\nu = 5/2$ FQHS, 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.

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 strong anisotropy in transport as the resistance along $B_{||}$ becomes more than 30 times larger than in the perpendicular direction. Nevertheless, at low temperatures ($T < 100$ mK), the resistances along these 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 ($\Delta$) for the 5/2 FQHS along the two in-plane directions. Despite the enormous transport anisotropy, $\Delta$ has the same magnitude along both directions. We interpret our data in terms of 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 AlGaAs spacer layers and Si $\delta$-doped layers. The 2DES has a density of $n = 3.0 \times 10^{15}$ m$^{-2}$ and a very high mobility, $\mu \approx 2,500$ m$^2$/Vs. It has a very strong $\nu = 5/2$ FQHS, with an energy gap of $\Delta \approx 0.4$ K, when $B_{||} = 0$. The sample is 4 mm $\times$ 4 mm with alloyed InSn contacts at four corners. For the low-temperature measurements, we used a dilution refrigerator with a base temperature of $T \approx 20$ 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. We use $\theta$ 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 $T = 0$, i.e., for $B_{||} = 0$, and exhibit a very strong $\nu = 5/2$ FQHS with an energy gap of $\geq 0.4$ K and an $R_{xy}$ which 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 $\theta = 26^\circ$, e.g., $R_{xx}$ is about 30 times $R_{yy}$. 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.

In Fig. 2 we show the temperature dependence of $R_{xx}$ and $R_{yy}$ at $\nu = 5/2$ for different values of $\theta$. 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 $\Delta$ 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 ($|\theta| \lesssim 5^\circ$), the anisotropy reverses so that $R_{xx}$ exceeds $R_{yy}$. This trend continues with increasing $\theta$ and, at $\theta = 26^\circ$, $R_{xx}$ becomes 30 times larger than $R_{yy}$. Remarkably, however, despite the very large anisotropy, both $R_{xx}$ and $R_{yy}$ remain activated and yield very similar values for $\Delta$.

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 denote the energy gaps deduced from the temperature-dependence of $R_{xx}$ and $R_{yy}$ by $\Delta_{xx}$ and $\Delta_{yy}$, 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 $\rho_{xx}$ and $\rho_{yy}$ following the formalism presented in Ref. [22], 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 $\Delta_{xx}$ and $\Delta_{yy}$, however, exhibit a very steep drop at small $B ||$, followed by a more gradual and monotonic decrease at higher $B ||$. For $\theta > 36^\circ$ ($B || \gtrsim 3.6$ T) we cannot measure the gap for the 5/2 FQHS as it becomes too weak.

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, $\theta = 6^\circ$, 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 $\theta$ increases. All traces were recorded at the base temperature of our measurements, $T \simeq 20$ mK.

FIG. 2. (color online) Temperature-dependence of $R_{xx}$ (red) and $R_{yy}$ (black) at $\nu = 5/2$, measured at different tilting angles, $\theta$. The excitation gap deduced from the slopes of these plots decreases as $\theta$ is increased, while the transport anisotropy increases.
FIG. 3. (color online) Measured excitation gaps, $\Delta_{xx}$ (red circles) and $\Delta_{yy}$ (black squares), are shown as a function of the in-plane magnetic field $B_{||}$. $\Delta_{xx}$ and $\Delta_{yy}$ are nearly equal each other and decrease with increasing $B_{||}$. Also plotted (blue triangles is the transport anisotropy factor, $\alpha$, defined as the ratio between the resistivities $\rho_{xx}$ and $\rho_{yy}$). Note the logarithmic scale on the right: $\alpha$ grows exponentially with increasing temperature, while $R_{xx}$ shows a downturn at high temperatures $T \gtrsim 120$ mK, indicating a smaller anisotropy.

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. We note that in a 2DES with finite (non-zero) electron layer thickness, such as ours, $B_{||}$ 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. Recently it was indeed demonstrated experimentally that such an anisotropy is qualitatively transmitted to the quasiparticles at high magnetic fields, for example to composite Fermions. It is therefore plausible that $B_{||}$ which breaks the rotational symmetry in our 2DES would lead a FQH nematic phase at $\nu = 5/2$.

A FQH nematic phase was in fact recently proposed theoretically to explain the experimental observations of Xia et al. for another FQHS in the $N = 1$ LL, namely at $\nu = 7/3$. In the model of Ref. [27], 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 [27].

 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. [27]). As mentioned above, our data at low temperatures are qualitatively consistent with the predictions of Ref. [27] for the 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. [27] predictions. However, up to the highest temperatures achieved in our measurements ($\simeq 0.2$ K, which is comparable to the excitation gap), we do not see a transition to a truly isotropic state.

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. 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 fractional quantum Hall 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.

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