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Anomalous robustness of the $\nu = 5/2$ fractional quantum Hall state near a sharp phase boundary

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We report magneto-transport measurements in wide GaAs quantum wells with tunable density to probe the stability of the fractional quantum Hall effect at filling factor $\nu = 5/2$ in the vicinity of the crossing between Landau levels (LLs) belonging to the different (symmetric and antisymmetric) electric subbands. When the Fermi energy (E_F) lies in the excited-state LL of the symmetric subband, the 5/2 quantum Hall state is surprisingly stable and gets even stronger near this crossing, and then suddenly disappears and turns into a metallic state once E_F moves to the ground-state LL of the antisymmetric subband. The sharpness of this disappearance suggests a first-order transition.

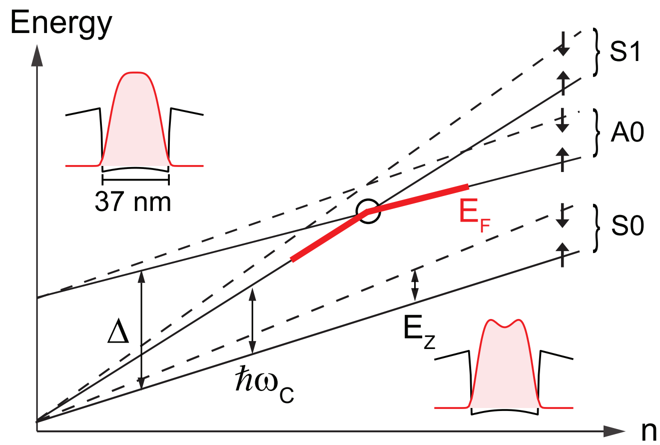

FIG. 1. (color online) Schematic LL diagram for the symmetric (S) and antisymmetric (A) electric subbands as a function of increasing density n. The index 0 or 1 following S and A is the LL quantum number (N), and the up- (↑) and down-spin (↓) levels are represented by solid and dashed lines. The relevant energies are the subband separation (Δ), the cyclotron energy ($\hbar\omega_c$), and the Zeeman energy (E_Z). As we increase n while keeping the QW balanced, $\hbar\omega_c$ increases and Δ decreases. The S1↑ level crosses the A0↑ level when $\hbar\omega_c = \Delta$. The Fermi energy (red line) moves from S1↑ to A0↑ at the crossing (marked by a circle). In our work, we study the evolution of the FQHSs near $\nu = 5/2$ at this crossing. The upper left and lower right insets show the self-consistently calculated electron charge distributions (red curves) and potentials (black curves) at zero magnetic field for a 37-nm-wide QW, with densities of 2.09 and 2.48 $\times 10^{11}$ cm^{-2}, respectively.

There is tremendous interest currently in the origin and properties of the fractional quantum Hall state (FQHS) at the even-denominator Landau level (LL) filling factor $\nu = 5/2$ [1]. This interest partly stems from the expectation that the quasi-particle excitations of the 5/2 FQHS might 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 two-dimensional electron system (2DES) in which it is formed are therefore of paramount importance and have been studied recently both experimentally [4–12] and theoretically [13–16].

Ordinarily, the 5/2 FQHS is seen in very low disorder 2DESs when the Fermi energy (E_F) lies in the spin-up, excited-state ($N = 1$), LL of the ground-state (symmetric, S) electric subband, namely in the S1↑ level (see Fig. 1). It has been theoretically proposed that a non-Abelian (Pfaffian) $\nu = 5/2$ FQHS should be favored in a "thick" electron system confined to a relatively wide quantum well (QW) [13–16]. But in a realistic, experimentally achievable wide QW system, the electrons can occupy the second (antisymmetric, A) electric subband. It was demonstrated very recently that, if the subband energy spacing (Δ) is smaller than the cyclotron energy $\hbar\omega_c$, so that E_F at $\nu = 5/2$ lies in the *ground-state* ($N = 0$) LL of the antisymmetric subband (i.e., in the A0↑ level; see Fig. 1), then the $\nu = 5/2$ FQHS is destroyed and instead the standard, odd-denominator FQHSs characteristic of the $N = 0$ LLs are seen [9, 17]. These observations imply that the node in the *in-plane* wave-function is crucial for the stability of the 5/2 FQHS.

Here we examine the stability of the $\nu = 5/2$ FQHS in relatively wide GaAs QWs in the vicinity of the crossing (at E_F) between the S1↑ and the A0↑ LLs (Fig. 1). We find that, when E_F lies in the S1↑ LL, the 5/2 state is remarkably robust and gets even stronger as the A0↑ LL is brought to within ~ 1 K of the S1↑ LL. As the crossing is reached and E_F moves into the A0↑ LL, the $\nu = 5/2$ state abruptly disappears.

Our samples were grown by molecular beam epitaxy, and each consist of a wide GaAs QW bounded on each side by undoped $Al_{0.24}Ga_{0.76}As$ spacer layers and Si δ-doped layers. We report here data for three samples, with QW widths $W = 37$, 31 and 30 nm, and densities of $n \simeq 2.5$, 3.3 and 3.8 $\times 10^{11}$ cm^{-2}, respectively. The widths and the densities of these samples were carefully designed so that, for each sample, its Δ is close to $\hbar\omega_c$ at the magnetic field position of $\nu = 5/2$. This enables us to make the S1↑ and A0↑ levels cross at E_F by slightly tuning the density (Fig. 1), as we describe below. The low-temperature ($T = 0.3$ K) mobilities of our samples are $\mu \simeq 950$, 480 and 670 m^2/Vs, respectively. These are about a factor of three to four smaller than the mobilities for 2DESs in single-subband QW samples grown in the same molecular beam epitaxy chamber; we believe it is the occupancy of the second electric subband that reduces the mobility in the samples studied here.

Each of our samples has an evaporated Ti/Au front-gate and an In back-gate. We carefully control n and the charge distribution symmetry in the QW by applying voltage biases to these gates [9, 17–19]. For each n, we measure the occupied subband electron densities from the Fourier transforms of the low-field ($B \leq 0.5$ T) Shubnikov-de Haas oscillations. These Fourier transforms exhibit two peaks whose frequencies, multiplied by $2e/h$, give the subband

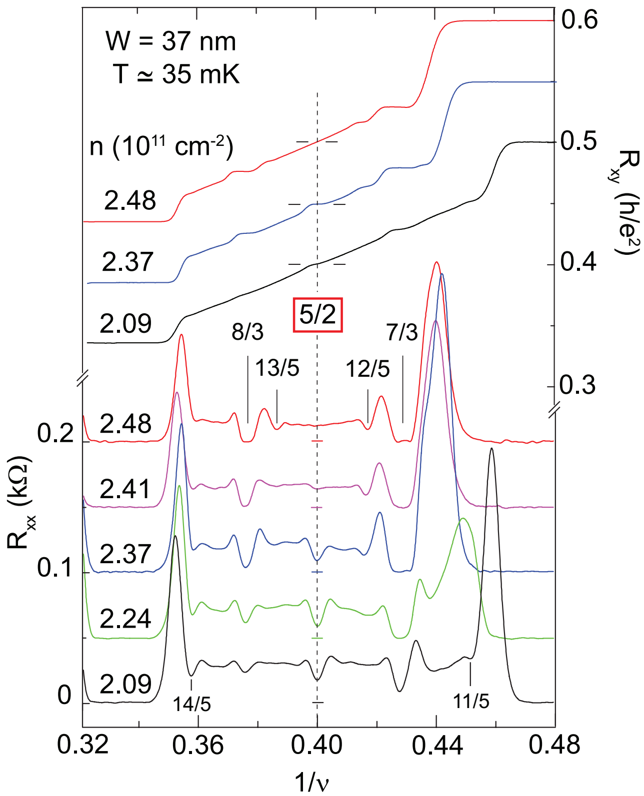

FIG. 2. (color online) Waterfall plots of R_{xx} and R_{xy} magneto-resistances showing the evolution of FQHSs for the 37-nm-wide GaAs QW as the density is changed from 2.09 to 2.48 $\times$ 10^{11} cm^{-2}. Except for the lowest density R_{xx} and R_{xy} traces, for clarity each R_{xx} trace is shifted vertically by 50 Ω, and each R_{xy} trace by 0.05 h/e^2.

densities, n_S and n_A; see, e.g., Fig. 1 in Ref. [19]. The difference between these densities directly gives the subband separation $\Delta = \frac{\pi\hbar^2}{m^*}(n_S - n_A)$, where $m^* = 0.067m_e$ is the GaAs electron effective mass. All the data reported here were taken by adjusting the front- and back-gate biases so that the total charge distribution is symmetric. We add that our measured Δ agree well with the results of calculations that solve the Poisson and Schroedinger equations to obtain the potential energy and the charge distribution self-consistently.

Figure 2 shows a series of longitudinal (R_{xx}) and Hall (R_{xy}) magneto-resistance traces in the filling range $2 < \nu < 3$ for the 37-nm-wide QW sample, taken at different densities ranging from 2.09 to 2.48 $\times 10^{11}$ cm^{-2}. As n is increased in this range, Δ decreases from 83 to 79 K while $\hbar\omega_c$ at $\nu = 5/2$ increases from 69 to 82 K, so we expect a crossing of the S1$\uparrow$ and A0$\uparrow$ levels. This crossing manifests itself in a remarkable evolution of the FQHSs as seen in Fig. 2. At the lowest density, R_{xx} shows reasonably well-developed minima at $\nu = 5/2$, 7/3, and 8/3, as well as weak minima at 11/5 and 14/5. These minima are characteristic of the FQHSs observed in high-quality, standard (single-subband) GaAs 2DESs, when E_F lies in the S1$\uparrow$ LL (see, e.g., Fig. 1(a) of Ref. [9]). At the highest n, the R_{xx} minima at $\nu = 5/2$, 11/5 and 14/5 [20] have disappeared and instead there are fully developed FQHSs at $\nu = 7/3$ and 8/3 as well as developing minima at 12/5 and 13/5 [21]. All these features are characteristic of FQHSs when E_F is in the A0$\uparrow$ LL [9, 17].

To better highlight the evolution of the FQHSs observed in Fig. 2, in Fig. 3 we show an interpolated, color-scale plot of R_{xx} as a function of filling and density. Both Figs. 2 and 3 show that as n is increased, the evolution of the FQHSs takes place from high-field (low ν) to low-field (high ν). The weak R_{xx} minimum at $\nu = 11/5$ observed at the lowest n, e.g., disappears quickly as n is raised and is followed by a strengthening of the 7/3 (and then the 12/5) FQHS at higher n. Then comes the disappearance of the 5/2 FQHS, and eventually the strengthening of the 8/3 (and 13/5) FQHSs and weakening of the 14/5 R_{xx} minimum at the highest n. Such evolution is of course expected: Since the S1$\uparrow$ level crosses the A0$\uparrow$ LL when $\Delta = \hbar\omega_c \propto \frac{n}{\nu}$, we expect the crossing to occur at progressively higher ν as n, and consequently $\hbar\omega_c$ at a given ν, increase. To assess the position of the expected crossing quantitatively, in Fig. 3 we have included a dashed curve, marked $\Delta = \hbar\omega_c$. The value of Δ for this line is based on our measured Δ from low-field Shubnikov-de Haas oscillations which agree with the results of our self-consistent calculations for a

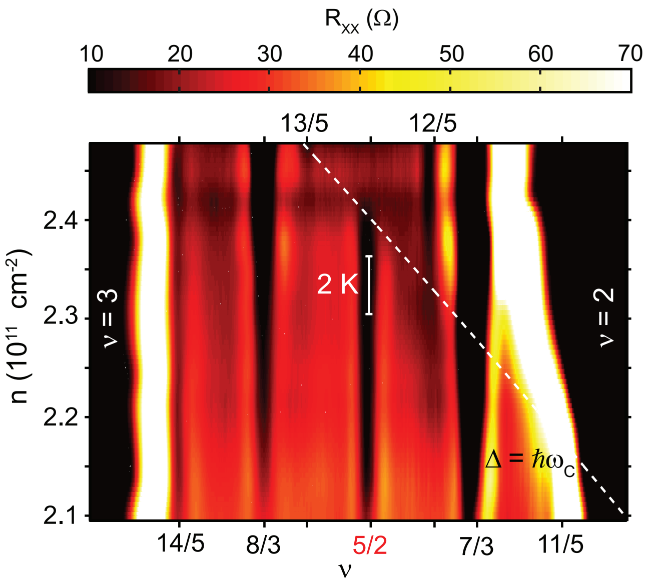

FIG. 3. (color online) A color-scale plot of R_{xx} for the 37-nm-wide QW demonstrating the evolution of the FQHSs as the density is increased from $n = 2.09$ to 2.48×10^{11} cm^{-2}. The bright regions correspond to large R_{xx} values, and the dark regions to small R_{xx} where the quantum Hall states are observed. The white dashed line denotes the condition $\Delta = \hbar\omega_c$. Below (above) this line we expect E_F to lie in the S1↑ (A0↑) level. The vertical bar provides an energy scale for the separation between the S1↑ and A0↑ levels at $\nu = 5/2$.

37-nm-wide QW. While we cannot rule out the possibility that Δ is re-normalized at magnetic fields in the $2 < \nu < 3$ range, it appears that the dashed line corresponds to the position of the LL crossing accurately: the $\nu = 12/5$ and 13/5 FQHSs, which are characteristic of E_F being in the A0↑ level [21], are seen above the dashed line, and the $\nu = 5/2$ FQHS is seen only below this line when E_F lies in the S1↑ LL. Interestingly, the $\nu = 7/3$ FQHS is observed on both sides of the dashed line and becomes stronger monotonically as n is raised.

Having established the crossing of the S1↑ and A0↑ LLs in Figs. 2 and 3, we now focus on our main finding, namely the stability of the $\nu = 5/2$ FQHS in the vicinity of this crossing. The data of Figs. 2 and 3 indicate that as n is raised, the 5/2 FQHS initially becomes stronger. This strengthening is seen from the deepening of the R_{xx} minima, and particularly from the very well developed R_{xy} plateau at $n = 2.37 \times 10^{11}$ cm^{-2} (compared, e.g., to the plateau for $n = 2.09 \times 10^{11}$ cm^{-2}, see Fig. 2). We will return to this intriguing observation later in the paper. Even more striking, however, is that *the $\nu = 5/2$ FQHS, which is most robust at $n = 2.37 \times 10^{11}$ cm^{-2}, suddenly disappears when the density is increased by less than 2% to $n = 2.41 \times 10^{11}$ cm^{-2}*.

Data for the narrower QW samples, presented in Fig. 4, verify the above observations qualitatively. Moreover, they allow us to quantitatively assess, through energy gap measurement, the robustness of the $\nu = 5/2$ FQHS near the LL crossing and the sharpness of its disappearance. The R_{xx} traces shown in Fig. 4(a) corroborate the data of Fig. 2. A very similar evolution of the FQHSs is seen, including a sudden disappearance of the 5/2 state at high n. Note that $\hbar\omega_c$ at which the 5/2 FQHS disappears in Fig. 4(a) is equal to 109 K, very close to the value of $\Delta \simeq 112$ K for this 31-nm-wide QW at $n = 3.31 \times 10^{11}$ cm^{-2}. From the temperature dependence of the 5/2 R_{xx} minimum (Fig. 4(b)), we are also able to deduce an energy gap ($^{5/2}\Delta$) for the $\nu = 5/2$ FQHS. The measured gap, shown in Fig. 4(d) as a function of the magnetic field position of $\nu = 5/2$, exhibits a behavior consistent with the conclusions gleaned qualitatively from the R_{xx} traces of Figs. 2 and 4(a): $^{5/2}\Delta$ increases as n is raised and then suddenly decreases. Note in Fig. 4(d) that $^{5/2}\Delta$ collapses from its maximum value when n is increased by less than 3%. The sharpness of the collapse suggests that the ground state of the 2DES makes a first-order transition from a FQHS to a metallic state as E_F moves from the S1↑ to the A0↑ level.

A remarkable feature of the data in Figs. 2-4 is that the $\nu = 5/2$ FQHS becomes stronger with increasing n before it collapses. This is clearly evident in the plot of $^{5/2}\Delta$ vs. B in Fig. 4(d). A qualitatively similar increase of $^{5/2}\Delta$ with n was seen recently in 2DESs where only one electric subband was occupied [8], and was attributed to the enhancement of the Coulomb energy and the screening of the disorder potential with increasing n. It is possible that our data can be explained in a similar fashion. However, the relatively steep rise of $^{5/2}\Delta$, especially right before the collapse, is puzzling.

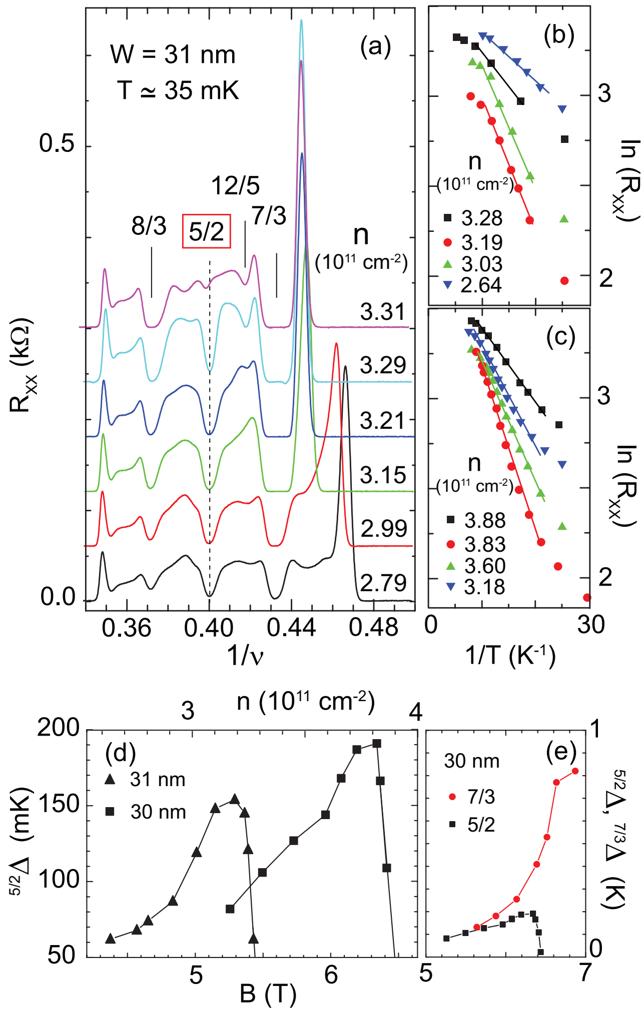

FIG. 4. (color online) (a) Waterfall plot of R_{xx} vs. $1/\nu$ for the 31-nm-wide GaAs QW as n is changed from 2.79 to 3.31×10^{11} cm^{-2}. The traces are shifted vertically (by 60 Ω). (b) and (c) Arrhenius plots of R_{xx} at $\nu = 5/2$ vs. inverse temperature for the 31- and 30-nm-wide QWs at the indicated densities. Data are shifted vertically for clarity. (d) Measured energy gap for the $\nu = 5/2$ FQHS in both samples as a function of magnetic field or density. (e) Measured energy gaps for the $\nu = 5/2$ and 7/3 FQHSs in the 30-nm-wide QW.

We have repeated the gap measurements for a slightly narrower (30-nm-wide) QW and the data, shown in Figs. 4(c) and 4(d), qualitatively confirm this anomalous behavior: ${}^{5/2}\Delta$ increases steeply with increasing n and then suddenly drops once the density exceeds 3.83×10^{11} cm^{-2}. Note that the higher n, and therefore larger $\hbar\omega_c$, at which ${}^{5/2}\Delta$ collapses in the narrowest QW sample are consistent with its larger subband separation. For this QW, at $n = 3.88 \times 10^{11}$ cm^{-2}, we have $\Delta \simeq 130$ K, very close to $\hbar\omega_c = 128$ K. A noteworthy observation in Fig. 4(d) data is that, at a common density of $n = 3.2 \times 10^{11}$ cm^{-2}, ${}^{5/2}\Delta$ for the wider (31 nm) QW is nearly twice larger than ${}^{5/2}\Delta$ for the narrower (30 nm) QW. The observation of a larger gap for a wider QW, which was also reported in Ref. 10, appears to be consistent with the theoretical expectation that a Pfaffian $\nu = 5/2$ FQHS should be favored in a 2DES with larger electron layer thickness [14]. However, according to the available calculations, while for thicker electron layers the overlap between the numerically calculated wavefunction and the Pfaffian state is enhanced, the energy gap is in fact reduced [14]. We conclude that the much larger gap observed in Fig. 4(d) at $n = 3.2 \times 10^{11}$ cm^{-2} for the 31-nm-wide QW sample compared to the 30-nm-wide sample is related to the anomalous, steep rise of the gap before the LL crossing occurs.

In Fig. 4(e), we also show the energy gap of the $\nu = 7/3$ FQHS measured in the 30-nm-wide QW sample. It increases monotonically with increasing B, consistent with our expectation that the 7/3 state should become stronger when E_F moves from the S1↑ to the A0↑ level [22]. We do indeed observe a strong rise in ${}^{7/3}\Delta$ at this field. Note also in Fig. 4(e) that, at the lowest fields and far from the crossing, ${}^{5/2}\Delta$ and ${}^{7/3}\Delta$ in the 30-nm sample are of very similar magnitude, as seen previously is standard single-subband 2DESs when E_F lies in the S1↑ level. However, it appears from Fig. 4(e) data that $^{7/3}\Delta$ much exceeds $^{5/2}\Delta$ even before the crossing occurs.

In conclusion, we studied the stability of the $\nu = 5/2$ FQHS when the lowest LL of the antisymmetric electric subband (A0↑) crosses the second LL of the symmetric subband (S1↑). The 5/2 FQHS is remarkably robust when E_F lies in the S1↑ LL even as the A0↑ level is brought to within $\sim$ 1 K of the S1↑ level. As the crossing is reached the 5/2 state abruptly disappears, suggesting a first-order transition from a FQHS to a metallic state.

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[20] At yet higher n, which we cannot achieve in this sample, we expect the $\nu = 14/5$ R_{xx} minimum to completely disappear once E_F lies in the A0 level at $\nu = 14/5$ (see, e.g., Fig. 1(b) in Ref. 9).
[21] A very weak $\nu = 12/5$ FQHS is observed in ultra-clean, single-subband samples when E_F lies in the S1 level at very low temperatures [J. S. Xia *et al.*, Phys. Rev. Lett. **93**, 176809 (2004)]. We do not see such a FQHS in our samples because of their lower mobilities and the higher temperature of our experiments.
[22] Note that we expect the S1$\uparrow$ and A0$\uparrow$ levels to cross at $\nu = 7/3$ at slightly larger B (~ 0.1 T) compared to $\nu = 5/2$ because of the density dependence of Δ.