The fractional quantum Hall (FQH) effect is reported in a high mobility CdTe quantum well at millikelvin temperatures. Fully developed FQH states are observed at filling factor $4/3$ and $5/3$ and are found to be both spin-polarized ground state for which the lowest energy excitation is not a spin flip. This can be accounted for by the relatively high intrinsic Zeeman energy in this single valley two-dimensional electron gas. FQH minima are also observed in the first excited $(N=1)$ Landau level at filling factor $7/3$ and $8/3$ for intermediate temperatures. In contrast, the $5/2$ FQH state remains absent down to $T \sim 10$ mK.

DOI: 10.1103/PhysRevB.82.081307

PACS number(s): 73.43.Qt, 73.40.Lq, 73.43.Lp

In Fig. 1, we plot the longitudinal resistance $R_{xx}$ for cooldown A as a function of the perpendicular magnetic field for different temperatures. Pronounced FQH states are observed at low temperature at filling factor $\nu=4/3$, and $\nu=5/3$, with the resistance falling to zero, together with well-defined quantized Hall resistance. The role of illumination in improving the sample quality is critical, as the quantum life-

1Laboratoire National des Champs Magnétiques Intenses, CNRS-UJF-UPS-INS, F-38042 Grenoble, France
2Faculty of Mathematics and Physics, Institute of Physics, 12116 Prague, Czech Republic
3Department of Physics, Regensburg University, D-93053 Regensburg, Germany
4Institute of Physics, Polish Academy of Sciences, PL-02668 Warsaw, Poland

©2010 The American Physical Society

081307-1
time \( \tau_q \) extracted from the low-field Shubnikov de Haas (SdH) oscillations is found to increase more than five times, from 0.6 ps in the dark to 3 ± 0.3 ps after illumination. This value of \( \tau_q \) is comparable to the one which can be observed in GaAs samples with several million mobility, despite our moderate measured mobility of 260 000 cm²/V s.⁹

Nevertheless, at low temperature, an important number of electronic states are localized, leading to wide zero resistance states in the integer quantum Hall effect which prevent the observation of any signs of the FQH effect in the first excited (\( N = 1 \)) LL. As the temperature is increased, the fraction of localized states is reduced and weak FQH minima become visible in the \( N = 1 \) LL. These features persist up to relatively high temperature, demonstrating again the quality of the sample.

In Fig. 2 we focus on the FQH effect in the \( N = 0 \) LL. Figure 2(a) shows the temperature dependence of the longitudinal resistance at \( \nu = 5/3 \) and \( 4/3 \), for cooldown A and B as a function of the inverse temperature. The difference in sample quality between cooldowns appears clearly when comparing the low-temperature behavior of the initially similar resistance at filling factor \( 4/3 \). The so-called “activation plots” or Arrhenius plots are generally used to extract an activation gap or mobility gap, corresponding to the energy difference between the edge of the delocalized states of the ground and excited states. However, a simple extraction of this activation gap \( \Delta \) requires the observation of an expanded linear region (typically at least one order of magnitude) where \( R_{xx} \sim e^{-\Delta/2kBT} \), whereas such a region is rather absent in our data. This nonthermally activated behavior is actually expected when a Gaussian or Lorentzian level shape is taken into account, for which one expects the linear behavior in an activation plot to deviate at low temperature in the presence of a broadening which reduces the mobility gap. This effect becomes important when the particles level broadening is non-negligible compared to the total (spectral) gap. To analyze our data, we therefore use the model proposed in Ref. 10 which includes a disorder-induced Gaussian broadening to calculate the temperature dependence of the resistance. The LL broadening is imposed by the one extracted for electrons via SdH measurements. The results of these simulations are plotted as dotted lines in Fig. 2(a) and show a very good agreement with the experimental behavior. From this model we estimate the total FQH gap in cooldown B to be 3.15 K and 3.0 K for \( \nu = 4/3 \) and \( \nu = 5/3 \), respectively.

In Fig. 2(b) we focus on the FQH effect in the \( N = 0 \) LL. At \( \nu = 5/3 \), the resistance rapidly decreases from 0.6 ps in the dark to 3 ps after illumination. This nonthermally activated behavior is actually observed in GaAs samples with several million mobility, despite our moderate measured mobility of 260 000 cm²/V s.⁹

Expected evolution of the gaps for different ground states (dotted lines) (see text). Inset: corresponding total FQH gaps at \( \nu = 4/3 \) and \( \nu = 5/3 \) as a function of the total field \( B_{\text{total}} \). Expected evolution of the gaps for different ground states (dotted lines) (see text). (b) Angular dependence of magnetotransport in the upper spin branch of the \( N = 0 \) LL at fixed temperature \( T \approx 390 \) mK. Increasing tilting angle \( \theta \) indicated by the arrow. (c) Schematic representation of the CF fan diagram at fixed CF cyclotron energy as a function of the Zeeman energy (see text). \( E_{\text{CF}}(N) \) is the energy of the \( N \)th CF level. The arrows depict the spin orientation of each subband. (d) Position of the CF level crossings in the \( (|E_{\text{CF}}|, B_{\text{total}}) \) plane (see text). The arrows depict the spin polarization of the ground state in different region.

FIG. 1. (Color online) Hall resistance \( R_{xy} \) and longitudinal resistance \( R_{xx} \) versus perpendicular magnetic field for different temperatures.

FIG. 2. (Color online) (a) Longitudinal resistance \( R_{xx} \) at \( \nu = 4/3 \) as a function of inverse temperature for cooldown A (stars) and for cooldown B at \( \theta = 0° \) (circles) and \( \theta = 55.6° \) (triangles). Same data for cooldown B at \( \nu = 5/3 \) (open symbols). Simulations of the thermally activated resistance (dashed lines) (see text). Inset: corresponding total FQH gaps at \( \nu = 4/3 \) and \( \nu = 5/3 \) as a function of the total field \( B_{\text{total}} \).
ngetic length, this corresponds to 0.013 and 0.014, respectively.

Activation data was also collected when tilting the 2DEG plane in the total magnetic field with an in situ rotation stage at an angle of $\theta=55^\circ$. This data, also plotted in Fig. 2(a), is very similar to the $\theta=0^\circ$ behavior for $\nu=4/3$ and $\nu=5/3$. The small difference can be well reproduced for both fractions either by introducing a small increase ($\sim 10\%$) in the level width, while the total gap remains constant, or by using a constant level width and a slightly reduced gap ($\sim 10\%$ also). The total gap extracted from our analysis at $\theta=0^\circ$ and $\theta=55^\circ$ are plotted in the inset of Fig. 2(a) as a function of the total field at fixed perpendicular field (filling factor), the vertical error bar representing the possible gap decrease at $\theta=55^\circ$. Starting with the measured gap value for $\theta=0^\circ$, we show how the gap should evolve as a function of total magnetic field (Zeeman energy) in three different configurations: a spin-polarized ground state with single-particle spin-reversed excitation ($\Delta S=-1$, where $\Delta S$ is the net spin change of the excitation), a spin-polarized ground state with no spin-reversed excitations ($\Delta S=0$), and a spin-unpolarized ground state ($\Delta S=+1$). The bare $g$ factor $g'=1.6$ is taken from Raman-scattering measurements performed on the same sample.

The fact that the $\nu=5/3$ gap remains nearly constant at $\theta=55^\circ$ suggests, as observed in GaAs, a spin-polarized ground state with a lowest energy excitation which is not a spin flip since no increase is observed despite of a significant variation (nearly a factor of 2) of the Zeeman energy. If the $\nu=4/3$ state was to be unpolarized, one would expect a sharp decrease in the gap as well as its disappearance, here around $B_{\text{total}}=16$ T, before reentrance at higher fields due to a change in the ground-state polarization. This transition has been observed in GaAs 2DEG at low electron density and also for higher densities close to the one of our CdTe sample. In Refs. 1 and 11, the $\nu=4/3$ FQH gap for sample G71 with initial electron density $\sim 2.7 \times 10^{11}$ cm$^{-2}$ decreases as the density (total field) is increased and is close to vanishing for magnetic fields of about 12 T. Our observation of a quasiunchanged gap at $\theta=55^\circ$ shows the $\nu=4/3$ FQH state is spin polarized in CdTe. The fact that this gap is not increasing further suggests that the lowest energy excitations in this state do not involve spin reversal.

The qualitative behavior of the gap at different tilt angles between $\theta=0^\circ$ and $\theta=55^\circ$ can be inferred from a detailed angular dependence of $R_{xx}$ measured for a fixed intermediate temperature of $T \sim 390$ mK. At this temperature the gap variation can efficiently be probed as observed when comparing the resistance values at $\nu=4/3$ and $\nu=5/3$ for cooldown A and B [Fig. 2(a)]. This angular dependence plotted in Fig. 2(b) shows only a very weak variation in the resistance at $\nu=5/3$ and $\nu=4/3$ over the entire $\theta$ range studied ($0^\circ < \theta < 55^\circ$). This demonstrates that no significant changes in the $\nu=4/3$ and $\nu=5/3$ FQH gaps are observed upon tilting, as expected for a spin-polarized state with no spin-reversed excitation.

This behavior can actually be understood more quantitatively using the CF theory for FQH effect, where FQH for electron is mapped onto the integer quantum Hall effect for composite fermions. In the upper spin branch of the $N=0$ LL, around $\nu=3/2$, these CF see an effective magnetic field $B_{\text{CF}}^*=3(B_{\perp}-B_{\parallel}/2)$, where $B_{\parallel}/2$ is the magnetic field corresponding to $\nu=3/2$. In this case the $\nu=4/3(5/3)$ FQH effect for electrons is the $\nu_{\text{CF}}^*=2(1)$ integer quantum Hall effect for CF. The scale of the CF cyclotron gap between two CF levels is then given by $\hbar B_{\text{CF}}^*|m_{\text{CF}}|$, where $m_{\text{CF}}$ is the CF effective mass. When the Zeeman energy is added to this simple picture, which is schematically depicted in Fig. 2(b), the lower spin branch of the $N=1$ CF level [(1, 0)] may have a lower energy than the upper spin branch of the $N=0$ CF level [(0, 0)]. In this situation the ground state at $\nu_\text{CF}=2$, initially formed by (0, 1) and (0, 0) CF levels for small Zeeman energies, is now formed by the (1, 0) and (0, 1) CF levels and therefore spin polarized. This picture can be applied to our 2DEG in CdTe, with a $g$ factor of $g'=1.6$ and the composite fermions effective mass experimentally determined in Ref. 13 as a function of $B_{\text{CF}}^*(m_{\text{CF}}=0.51 + 0.074/R_{\text{CF}}^* )$. In Fig. 2(c), we plot in a $(B_{\text{CF}}^*, B_{\text{total}})$ plane the position of the crossing points of the (0, 0) CF level with the (1, 0) and (2, 1) levels. For $\nu=4/3$, these crossings occur for $B_{\text{total}} \sim 3.4$ T and $B_{\text{total}} \sim 6.8$ T, respectively, explaining why the $\nu=4/3$ FQH ground state is spin polarized with no spin-reversed excitations for the total magnetic field range investigated ($14 < B_{\text{total}} < 25$ T). The excitation gap in this domain corresponds to a CF cyclotron gap referred to as “cyclotronlike” in Fig. 2(c). The same conclusions are drawn for the $\nu=5/3$ ($\nu_{\text{CF}}^*=1$) FQH state, provided $B_{\text{total}} > 3$ T. We note that the CF cyclotron gap used in these calculations is larger than the experimentally measured FQH gap discussed above, meaning that the transition to cyclotronlike excitations should occur at even smaller magnetic field.

Finally, we turn to the description of the emerging FQH effect in the $N=1$ LL which can be observed in our sample at intermediate temperatures. As can be seen in Fig. 1, weak minima are emerging at filling factors $\nu=7/3$ and $\nu=8/3$ for temperatures above 400–500 mK. At lower temperatures, the increasing number of localized states leads to the FQH effect being masked by the integer quantum Hall effect. The $T=534$ mK perpendicular field data of Fig. 1 are replotted for clarity in Fig. 3. In the inset of Fig. 3, we focus on the evolution of the local minimum at $\nu=7/3$ and $T=600$ mK.
for different tilt angles. The minimum maintains its strength at low angles before starting to weaken around \(\theta = 24^\circ\) and finally disappearing for \(\theta > 42^\circ\). The relative initial stability with respect to tilt angle is similar to the one observed in the \(N=0\) LL, and suggest that, as for \(\nu = 5/3\) and \(\nu = 4/3\), the \(\nu = 7/3\) state is already in a regime where the ground state is spin polarized with a lowest energy excitation which is not a spin flip. However, the observation of a \(\nu = 7/3\) state at lower temperatures (not possible because of localization) would be necessary to validate this hypothesis. At higher angles however, the minimum clearly disappears and the resistance at the broad maximum in \(R_n\) associated with the \(N=1\) LL starts to increase. Depending on the orientation between the parallel magnetic field and the current flow, the transport was found to be anisotropic, somewhat reminiscent of the anisotropy observed at low temperature in high mobility GaAs-based 2DEG.\(^{15,16}\)

At variance with \(\nu = 7/3\) and \(\nu = 8/3\), no minimum is observed at filling factor \(\nu = 5/2\). This remains true at ultralow temperature (\(T \sim 10\) mK), where we still have delocalized electrons around \(\nu = 5/2\). The absence of a \(\nu = 5/2\) FQH minimum could primarily be attributed to insufficient sample quality. However, it is also possible that the high Zeeman energy in CdTe plays a particular role in the formation of the \(5/2\) FQH state. The present extraordinary interest in the even-denominator \(\nu = 5/2\) FQH state is partly motivated by its possible description using the so-called Moore Read (MR) wave function\(^3\) exhibiting exotic non-Abelian statistics (for a review, see Ref. 18). Despite of a great deal of theoretical evidence for the \(\nu = 5/2\) FQH state to be described by the MR wave function, there is still no direct experimental observation of the full spin polarization expected within this framework. Instead, recent optical measurements\(^9\) point toward a spin-unpolarized state. In our experimental conditions at \(\nu = 5/2\) (\(B = 7.6\) T, \(g^* = -1.6\)), the Zeeman energy is about \(\sim 8\) K, which is more than one order of magnitude larger than the very weak energy gap usually associated with the \(5/2\) FQH state (even in the highest mobility GaAs samples). Under such conditions, the stabilization of an unpolarized ground state is very unlikely. Whether this is the reason or not for the “missing” minimum at \(\nu = 5/2\) in our CdTe sample is a fundamental question which could only be decisively answered provided further significant improvement are made in terms of sample quality.

In conclusion, we have shown that the 2DEG in a CdTe quantum well can have a high quality, leading to the observation of pronounced FQH states in the upper spin branch of the \(N=0\) LL, as well as emergent FQH minima in the \(N=1\) LL. The physics of these FQH state is strongly influenced by the intrinsic Zeeman energy, resulting in the complete spin polarization of the FQH ground state, in agreement with a CF approach for FQH effect. The high quality of the 2D electron gas in CdTe offers a promising single valley “model system” to study delicate many-body effects (e.g., the \(N=1\) LL FQH effect) in the presence of a relatively high Zeeman energy.

Work supported by EC-EuroMagNetII-228043, EC-ITEM under Grant No. MTKD-CT-2005-029671, CNRS-PICS-4340, MNiSW under Grant No. N20205432/1198, and ERDF under Grant No. POIG.01.02.00-008/08.


\(^{9}\) This apparent contradiction is due to the fact that in such high mobility GaAs samples, the long-range scattering by remote donors is even more predominant and leads to a higher mobility, for a comparable \(\tau_r\).


\(^{14}\) The CF effective mass in our sample may differ from the one extracted in Ref. 13, because of the different \(\epsilon_r\). LL mixing (the electron effective mass is \(m^* \sim 0.1 m_0\) in CdTe) and finite-thickness effects.


