Direct Measurement of the *g* Factor of Composite Fermions

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The activation gap Δ of the fractional quantum Hall states at constant fillings $\nu = 2/3$ and $2/5$ has been measured as a function of the perpendicular magnetic field B. A linear dependence of Δ on B is observed while approaching the spin-polarization transition. This feature allows a direct measurement of the g factor of composite fermions which appears to be heavily renormalized by interactions and strongly sensitive to the electronic filling factor.

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In recent years the role of spin in the fractional quantum Hall (FQH) regime has been the subject of increasing interest. The ever improving mobility of the samples allows the observation of the FQH effect in the low magnetic field regime, where the typical energy scale associated with the electronic interactions competes with the Zeeman splitting and thereby mixes different spin channels. The early observations of a reentrant FQHE at various fillings [1–3] in a tilted field configuration were the first signs of spin-polarization transitions in the ground state. Finally, FQH states with partial (or vanishing) spin polarization have been directly observed [4,5], in contrast to the fully polarized nature of the states in the high field regime.

From a theoretical point of view our understanding of the FQHE has been deepened by the introduction of composite fermions (CF) [6], quasiparticles made of one electron bound to an even number of magnetic flux quanta. Many experiments have confirmed the extreme versatility of CF in treating the collective nature of the FQH states in terms of almost-free quasiparticles. The issue of the effective mass of CF has attracted a lot of interest and several theoretical predictions have been made [7–9].

Much less has been said about the spin-related properties of CF. CF theory was extended for the first time in 1993 to states which are not fully polarized [10]. The spin-polarization transitions of the FQH ground state have been the subject of numerical investigations [11,12] prior to their experimental observations [4]. However, a simultaneous direct measurement of the parameters entering the CF mass and g factor is still essentially lacking.

A simple model of CF Landau levels with an interaction-dependent cyclotron gap ($\propto \sqrt{B}$) and Zeeman spin splitting ($\propto B$) is suitable to describe the main structure of the ground state spin-polarization transitions. The activation gap approaching the transition is essentially linear in B with a slope depending *uniquely* on the CF g factor (see Fig. 1 and the following text). Previous experimental analysis of the magnetic fields, where the spin transition occurs, produced the filling factor scaling of the product $m^* g$ [3,13], with m^* the CF mass to be extracted from the high field activation gap. The information on the CF g factor was therefore indirect.

In this paper we present an experimental analysis of the activation gap Δ at *constant* filling $\nu = 2/3$ and $\nu = 2/5$ in the *purely perpendicular field* configuration. In the CF picture, these two fractions are equivalent and correspond to occupying the *two* lowest CF Landau levels. The sharp linear magnetic field scaling of Δ while approaching the spin-polarization transition yields a *direct* measurement of the CF g factor alone.

Composite fermions [6] are introduced via the Chern-Simons gauge transformation on the many-electron wave

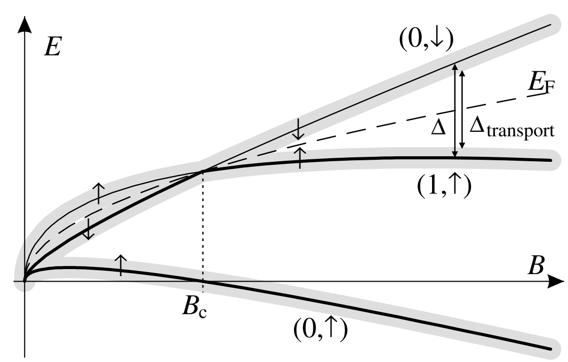

FIG. 1. The qualitative magnetic field scaling of CF Landau levels (n, s), with n the Landau level index and $s = \uparrow, \downarrow$ the spin. The zero temperature ground states at $\nu = 2/3$ and $2/5$ are obtained by occupying the lowest two CF Landau levels with spin (thick black lines), with the Fermi energy (dashed line) lying midway between the ground state and the first excitation (thin line). A quantum phase transition occurs between a spin-unpolarized and fully polarized ground state at the critical magnetic field B_c, with a corresponding activation gap Δ vanishing linearly as $|B - B_c|$. The grey regions show the disorder broadening of the CF Landau levels. Transport measurements are affected by this disorder and the measured gap $\Delta_{transport}$ is systematically smaller than Δ. However, the broadening depends only weakly on the magnetic field, and therefore the *slope* of both gaps versus B is *the same.*

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function [14]. The transformation depends only on the positions of the electrons and is equivalent to attaching an *even* number ϕ of flux quanta $\Phi_0 = h/e$ to each particle, corresponding to an additional magnetic field $b(\mathbf{r}) = \phi\Phi_0 n_e(\mathbf{r})$ [$n_e(\mathbf{r})$ the local electron density] opposite to the external one. CFs are then subject to an effective magnetic field $B^*(\mathbf{r}) = B - b(\mathbf{r})$ that vanishes for $\nu \equiv n_e\phi_0/B = 1/\phi$, on the spatial average (mean-field approximation). Near this filling factor the cancellation is not exact. The residual $B^* = B(1 - \phi\nu)$ yields CF Landau levels with an effective cyclotron energy $\hbar eB^*/m_b$ (m_b the electron band mass) and with a CF-filling factor $p = n_e\phi_0/B^*$. The electronic and CF fillings are related by $\nu = p/(\phi p \pm 1)$ which allows the mean-field mapping of the principal sequence of the electronic FQH states into integer QHE of CF. In the following we will consider states around half filling of the lowest Landau level, thereby choosing $\phi = 2$.

In the nonfully spin-polarized case it has been shown that an independent flux attachment for the two spin channels produces the correct principal sequence of FQH states at $\nu = (p_\uparrow + p_\downarrow)/2[(p_\uparrow + p_\downarrow) \pm 1]$ ($p_{\uparrow/\downarrow}$ the numbers of filled spin-up/spin-down CF Landau levels and $p = p_\uparrow + p_\downarrow$) [15,16]. At mean field we have equal cyclotron gaps for the two spin channels.

The mean-field assumption has the problem of generating the energy gaps scaling incorrectly. The dimensional analysis of the spinless case by Halperin, Lee, and Read [7] yields an activation cyclotron gap at fixed p,

$$\hbar\omega_c^* \propto \frac{1}{2p \pm 1}\frac{e^2}{\varepsilon l}, \tag{1}$$

since the Coulomb term $e^2/\varepsilon l$ ($\approx 51\sqrt{B[\mathrm{T}]}$ K) is the only relevant energy scale for electrons in the lowest Landau level, with the dielectric constant ε ($\approx$12.8 for GaAs) and $l = (\hbar/eB)^{1/2}$ the magnetic length. The scaling law (1) has been confirmed analytically in the large-p limit [9] and by numerical diagonalization of small 2D systems on a sphere [17]. Equation (1) can be obtained by assuming an effective CF mass $m^* \propto \sqrt{B}$ [7,8] with the activation gap as the smallest energy needed to excite a CF from the ground state into the first unoccupied CF Landau level.

Estimates for the magnitudes of the resulting energy gaps have been obtained without taking into account disorder, finite thickness of the sample, and Landau level mixing. Thus, in experiments typically smaller gaps than the theoretically predicted ones are observed [18,19]. In order to discuss the results of our experiments, we introduce the dimensionless parameter α via $m^*/m_0 = \alpha\sqrt{B[\mathrm{T}]}$ (m_0 the electron mass in vacuum). The considerations above suggest the following form of the effective cyclotron gap at CF-filling p:

$$\hbar\omega_c^*(p, B) = \frac{\hbar eB^*}{m^*} = \frac{\hbar eB}{m^*(2p \pm 1)}, \tag{2}$$

consistent with recent numerical investigations [20].

The Chern-Simons transformation does not couple to the electronic spin degree of freedom. Therefore the Zeeman term can easily be included and it depends only on B. Thus,

$$E_{nps}(B) = \left(n + \frac{1}{2}\right)\hbar\omega_c^*(p, B) + sg\mu_B B \tag{3}$$

are the energies of spin-up/spin-down ($s = \pm 1/2$) CF Landau levels with $\mu_B = \hbar e/2m_0 = 0.67$ K/T (see Fig. 1).

The zero-temperature ground state at a given B is obtained by occupying the lowest p CF Landau levels. The corresponding spin polarization is $\gamma(B) = [p_\uparrow(B) - p_\downarrow(B)]/p$. Because of the different B scaling of the cyclotron and Zeeman terms in (3), CF Landau levels with opposite spins cross. The transitions between differently polarized ground states are then given by the crossings between CF Landau levels at the Fermi energy. For example, the critical magnetic field B_c at which the transition to the completely spin-polarized ground state takes place is obtained as the crossing point between the ($n = 0, s =\downarrow$) and the ($n = p - 1, s =\uparrow$) CF Landau levels. It can be expressed in terms of the parameter α as

$$B_c(p) = \left[\frac{2(p-1)}{|g|\,\alpha(2p \pm 1)}\right]^2 \tag{4}$$

in Tesla. From the measurement of B_c we can therefore extract the product $|g|\,\alpha$. If we linearize the B dependence of $E_{nps}(B)$ near the crossing we can define the "slope" $S_{nps}(B) = \partial_B E_{nps}(B)$. It is then easy to check that

$$|S_{np\uparrow}(B_{nn'}) - S_{n'p\downarrow}(B_{nn'})| \equiv \partial_B\Delta|_{B_{nn'}} = \frac{1}{2}|g|\mu_B, \tag{5}$$

with $B_{nn'}$ the magnetic field where the two levels $E_{np\uparrow}$ and $E_{n'p\downarrow}$ cross. The energy gap Δ approaching the transition is therefore linear and its slope (5) *uniquely* depends on the CF g factor. Moreover, the relative slopes of the two CF Landau levels at the crossing are the same for all the possible crossings at a given filling factor. Thus, a measurement of the linear gap while approaching the spin transition *directly* yields the CF g factor and the value of the critical field B_c finally determines the effective mass parameter α.

The model above neglects CF-CF interactions which become relevant *very close* to the spin-polarization transition. They are responsible for the fascinating partly polarized state occurring in the middle of the transition [4,21]. The typical energy scale involved in the formation of this state is $\delta \cong 0.2$ K, so that the gap linearization is suitable for energies typically larger than δ, as we have in our measurements.

In what follows we will concentrate on the activation gap measurement for fixed $\nu = 2/3$ and $2/5$ (i.e., $p = 2$) and deduce the CF g factor in consistence with the depicted model.

Many activation measurements around the spin-polarization transitions were made in a tilted field geometry [1–3]. The consequent in-plane field couples to the finite thickness of the two-dimensional electron system (2DES), modifying the effective 2D Coulomb interaction [22] and thereby affecting the mass parameter α. In our measurement the magnetic field is *purely perpendicular*. We believe this geometry allows a cleaner determination of the CF parameters.

The 2DES used in our experiments was realized in an AlGaAs/GaAs heterostructure and the carrier density was modulated by illumination. The base carrier density and mobility are $n_e = 0.89 \times 10^{15}$ m^{-2} and $\mu_e = 102$ m^2/V s. With maximal illumination $n_e = 1.50 \times 10^{15}$ m^{-2} and $\mu_e = 193$ m^2/V s are achieved. The sample was patterned into a long meandering bar with length $l = 10$ mm and width $w = 90$ μm. The large aspect ratio $l/w = 111$ allows us to measure small resistance changes at the resistance minima. Contacts to the bar were realized by standard Au/Ge/Ni alloy annealing, yielding negligible contact resistances $R_c < 10\Omega$.

The sample is mounted onto the cold finger of a He^3/He^4 dilution refrigerator and is placed at the center of a superconducting solenoid capable of producing fields up to $B = 13$ T. An infrared light-emitting diode allows us to change the carrier density n_e using the persistent photoconductivity. From the two-point resistance R_{2p} we calculate the longitudinal resistivity $\rho_{xx} = (R_{2p} - R_H) \cdot w/l$ with $1/R_H = \nu e^2/h$ at integer and fractional filling factors ν. Starting with the unilluminated sample with lowest carrier density, we change n_e stepwise by illumination at zero magnetic field. Monitoring the resistance during the illumination allows a good control of the increase in n_e. For different n_e we measure the resistivity ρ_{xx} as a function of the magnetic field B, which allows one to determine carrier density and mobility. Figure 2 shows ρ_{xx} for the smallest and largest densities.

For each density we measured the temperature dependence of the resistivity $\rho_{xx}(T)$ while fixing the magnetic field corresponding to filling factors $\nu = 2/3$ and $2/5$. The result is shown in Fig. 3. As expected for these fractional filling factors we observe activated transport $\rho_{xx} \propto \exp(-\Delta/2T)$ with Δ the activation gap (lines in Fig. 3). At lowest temperatures we observe a crossover to variable-range hopping with $\rho_{xx} \propto \exp(-\sqrt{T_0/T})$. From the fits in the regime of activated transport, shown as solid lines in Fig. 3, we extract Δ at $\nu = 2/3$ and $\nu = 2/5$ for different densities, respectively, magnetic fields. The dependence of the activation gap $\Delta(B)$ on the magnetic field is shown in Fig. 4.

A remarkably linear behavior is observed over a large magnetic field range, in agreement with the theoretical

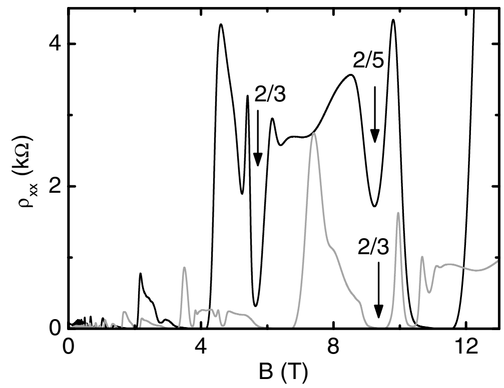

FIG. 2. Resistivity $\rho_{xx}(B)$ without illumination ($n_e = 0.89 \times 10^{15}$ m^{-2}, black line) and for maximal illumination ($n_e = 1.50 \times 10^{15}$ m^{-2}, grey line). Arrows mark the positions of the filling factors $\nu = 2/3$ and $\nu = 2/5$ at which activation measurements are performed.

expectation. Here we want to point out that activation gaps measured by transport are typically reduced by disorder. However, as this effect is expected to be only weakly depending on B the measured $\Delta_{\text{transport}}$ (see Fig. 1) differs from Δ only by a constant. Therefore the *slope* $\partial_B \Delta(B)$ is essentially *the same*. From the slope $\partial_B \Delta(B)$ in formula (5) we extract the CF g factor. Our measurement yields $|g_{2/5}| = 0.92$ and $|g_{2/3}| = 2.80$.

Two important considerations come out. First, the value of g indicates a strong renormalization due to interactions (the bulk g factor for GaAs being -0.44). Second, the CF g factor depends *strongly* on the *electronic* filling factor. In fact, although both the two fractions $\nu = 2/3$ and $2/5$ are mapped into the same CF filling $p = 2$ (symmetrically with respect to $\nu = 1/2$) their g factors differ by more than a factor 3.

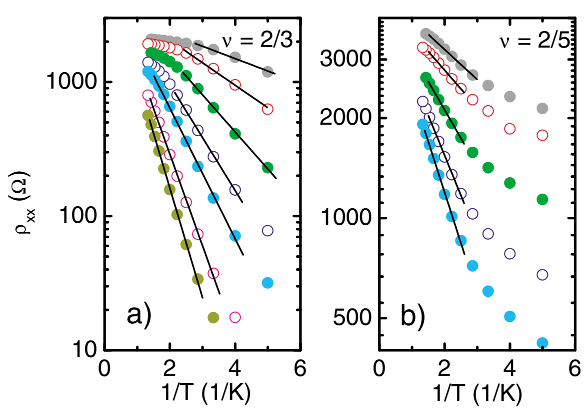

FIG. 3 (color online). Temperature dependence of the resistivity $\rho_{xx}(T)$ for filling factors $\nu = 2/3$ and $\nu = 2/5$ at different densities, respectively, different magnetic fields shown as an Arrhenius plot. The lines show fits of activated transport $\rho_{xx}(T) \propto \exp(-\Delta/2T)$ to our data. (a) Filling factor $\nu = 2/3$ at magnetic fields ranging from $B = 5.64$ T (topmost) to $B = 9.08$ T (bottom curve). (b) Filling factor $\nu = 2/5$ at magnetic fields ranging from $B = 9.23$ T (topmost) to $B = 12.55$ T (bottom curve).

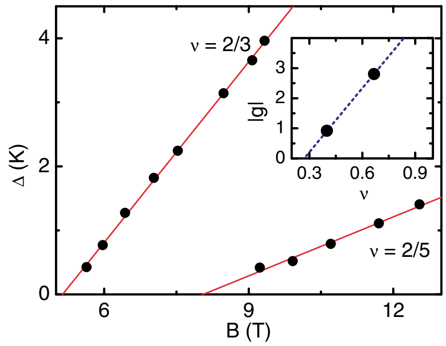

FIG. 4 (color online). Activation gaps $\Delta(B)$ at filling factors $\nu = 2/3$ and $\nu = 2/5$ as a function of the magnetic field. Δ is determined from the fits displayed in Fig. 3. The activation gaps are nicely fitted by a linear dependence as shown by the solid lines. The slopes of these lines are directly related to the CF g factor by $0.5|g|\mu_B$. Inset: g factor extracted from the linear dependence of the activation energy Δ. The two values of $|g| = 0.92$ and 2.80 are obtained at $\nu = 2/5$ and $\nu = 2/3$. The dashed line shows a linear interpolation [23].

The determination of the slope $\partial_B\Delta(B)$ yields a precious experimental information since it is essentially unaffected by disorder broadening of the CF Landau levels. On the contrary, the activation measurement is not extremely accurate for the determination of the critical field B_c, since disorder tends to "close the gap" before the spin-polarization transition occurs.

Since our CF form around $\nu = 1/2$ it is interesting to estimate $g_{1/2}$. From a linear interpolation of our measurement depicted in the inset of Fig. 4 we obtain $|g_{1/2}| = 1.65$, in excellent agreement with the data by Kukushkin *et al.* [4] which yield $|g_{1/2}| = 1.6$ when using their $\alpha \approx 0.2$ (see [13] for details). In contrast, NMR experiments in *tilted fields* found $|g_{1/2}| \approx 0.39$ [24]. The g factor measured in the NMR experiments seems to be roughly consistent with the bare g factor of 2D electrons in GaAs, whereas our measured g value seems to be related to the exchange enhanced electronic g factor. For the exchange enhanced electronic g factor a linear scaling with filling factor is expected from theory [23].

Using this linearization of the g vs ν dependence, we could extrapolate to get $|g_{\nu=1}| = 5.2$, which would be roughly consistent with the experimental results of the exchange enhanced electronic g factor at $\nu = 1$ [25]. In the small ν regime ($\nu < 1/3$) we should be more careful since the range of the four-flux CF ($\phi = 4$) would be explored with the relative (probably different) g factor.

In conclusion, we performed a *direct* measurement of the CF g factor for $\nu = 2/5$ and $2/3$. Although the two fractions are *equivalent* in the CF picture, their g factor is significantly different, showing interaction renormalization and a strong dependence on the *electronic* filling factor ν.

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