Fractional Quantum Hall Effect Measurements at Zero g Factor

D. R. Leadley,[1] R. J. Nicholas,[2] D. K. Maude,[3] A. N. Utjuzh,[4] J. C. Portal,[3] J. J. Harris,[5] and C. T. Foxon[6]
[1]*Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom*
[2]*Department of Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom*
[3]*Grenoble High Magnetic Field Laboratory, MPI-CNRS, 25 Avenue des Martyrs BP 166, F-38042 Grenoble Cedex 9, France*
[4]*Russian Academy of Sciences, Institute of High Pressure Physics, 142092 Troitsk, Moscow Region, Russia*
[5]*Department of Electronic and Electrical Enginering, University College, London, WC1E 7JE, United Kingdom*
[6]*Department of Physics, Nottingham University, University Park, Nottingham, NG7 2RD, United Kingdom*
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Fractional quantum Hall effect energy gaps have been measured as a function of Zeeman energy. The gap at $\nu = 1/3$ decreases as the g factor is reduced by hydrostatic pressure. This behavior is similar to that at $\nu = 1$ and shows that the excitations are spinlike. At small Zeeman energy, the excitation is consistent with the reversal of 3 spins and may be interpreted as a small composite Skyrmion. At 20 kbar, where g has changed sign, the $1/3$ gap appears to increase again. [S0031-9007(97)04626-7]

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The two-dimensional electron gas in a high magnetic field is an excellent test bed for studying electron-electron interactions. In recent years our understanding has been greatly simplified by the composite fermion (CF) model, which maps the fractional quantum Hall effect (FQHE) of electrons onto an integer quantum Hall effect (IQHE) of CFs [1,2]. In this model, the physics of the state at filling factor $\nu = 1/3$, where there is one completely occupied CF Landau level (LL), is explained by analogy with the IQHE state at $\nu = 1$. The other principal FQHE states at $\nu = p/(2p + 1)$ can similarly be explained by the integer states at $\nu = p$. While the ground states are quite well understood, the same is not true for the excited states which are responsible for conduction when the Fermi energy lies in a mobility gap.

The state at $\nu = 1$ is an itinerant ferromagnet with a spontaneous magnetization. Consequently, the activation energy gap deduced from transport measurements is found to be much larger than the single particle Zeeman energy (ZE $= g\mu_B B$) [3] and is instead dominated by the exchange energy $E_c = e^2/4\pi\epsilon l_B$ ($l_B = \sqrt{\hbar/eB}$ is the magnetic length). Furthermore, it has recently been shown optically [4] and electrically [5,6] that the excitations at this point are probably charged spin texture excitations which, in the limit of vanishing ZE, are Skyrmions [7,8]. Here we examine the CF analog $\nu = 1/3$ (the composite fermion ferromagnet). Our measurements suggest that in this limit the composite fermion excitation has a Skyrmion-like character.

Although spin was initially ignored in the CF model it is very important, especially when the Landé g factor is small. This is the case in GaAs where the ZE has a similar magnitude to the energy gaps between CF levels. These gaps arise from electron-electron correlations and scale with E_c, but can be treated as cyclotron gaps due to orbital motion of the CFs in an effective magnetic field $B^* = B - B_{1/2}$. B^* is zero at $\nu = 1/2$, where the gauge field exactly balances the external field of $B_{1/2}$. However, the ZE is determined by the total external field, and at $B^* = 0$ it still has a finite value of $g\mu_B B_{1/2}$. This is an essential difference from the IQHE, where the ZE and cyclotron energy are both zero at $B = 0$. Hence CF LLs of the two spin states may cross as the ZE and magnetic field are varied, leading to the observed disappearance and reemergence of fractions [9–11].

At $\nu = 1/3$ the ground state will always be fully spin polarized, but the states at $\nu = 2/3$ or $2/5$ may either be polarized or unpolarized depending on the relative sizes of the ZE and CF LL gaps. Similarly, the excitations may either involve spin flips or be spin preserving transitions between CF LLs. At $\nu = 1/3$ and small ZE, i.e., very low magnetic fields or small g factor, we expect a spin flip transition to the lowest CF LL state with the opposite spin. The interesting question which we address is whether this is a single spin flip of one CF or a collective phenomenon, i.e., a Skyrmionic excitation of the CFs, which we will refer to as a composite Skyrmion.

In our experiments, g is tuned through zero to favor Skyrmion formation by applying hydrostatic pressure of up to 22 kbar [12]. In GaAs the magnitude of g is reduced from 0.44 and passes through zero at $\sim$18 kbar. Previously, we used this to investigate the changing energy gaps of the mixed spin states around $\nu = 3/2$ [9]. Here we demonstrate that the gap at $\nu = 1/3$ is indeed a spin gap, with excitations consistent with flipping $\sim$3 spins at small ZE. This suggests that composite Skyrmions can be formed at $\nu = 1/3$ when the electron g factor is sufficiently small. By contrast, the gap at $\nu = 2/5$ is consistent with a single particle excitation.

The samples studied were high quality GaAs/$Ga_{0.7}Al_{0.3}As$ heterojunctions grown at Philips Research Laboratories, Redhill. Samples G586, G627, and G902 have undoped spacer layers of 40, 40, and 20 nm. At ambient pressure and 4 K, their respective electron densities after photoexcitation are 3.3, 3.5, and 5.7×10^{15} m^{-2} with corresponding mobilities of

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300, 370, and 200 $m^2/V\,s$. Data from similar samples measured without applied pressure are included from Ref. [13]. The samples were mounted inside a nonmagnetic beryllium copper clamp cell [14], and the pressure was measured from the resistance change of manganin wire. The absolute values quoted are accurate to ± 1 kbar, but between data points the variation is less than ± 0.2 kbar. The pressure cell was attached to a top loading dilution refrigerator probe, allowing temperatures as low as 30 mK to be obtained.

Increasing the pressure reduces the electron density, and above 13 kbar no electrons were present in the dark at low temperature. They could be recovered by illumination with a red LED, but the illumination time required to get a constant density roughly doubled for every 2 kbar increase in pressure. The highest pressure studied was 22 kbar, but no conductivity could be measured despite prolonged illumination. The sample required several hours for the density to stabilize before quantitative measurements could be made, during which it varied by less than 1% over the full temperature range. Above 13 kbar the data from G586 was recorded with a density of $0.44 \pm 0.06 \times 10^{15}$ m^{-2} which puts $\nu = 1/3$ at 5.4 T. At lower pressures where the sample was measured in the dark, the density was slightly higher. For G627 and G902 the data was recorded in the range $0.77–1.23 \times 10^{15}$ m^{-2}, i.e., $\nu = 1/3$ at 9–15 T.

The magnetoresistance ρ_{xx} of sample G586 at 40 mK is shown for pressures between 10 and 20 kbar in Fig. 1. The abscissa is $1/\nu$ which removes the remaining small density variation. The feature at $\nu = 1/3$ weakens as the pressure is increased and completely disappears at 18.7 kbar. In the 20 kbar trace a dip in ρ_{xx} is again evident, suggesting the gap at $1/3$ is recovered. Meanwhile, the feature at $\nu = 2/3$ remains approximately constant, which is an important indication that pressure does not denigrate the sample quality and destroy the FQHE.

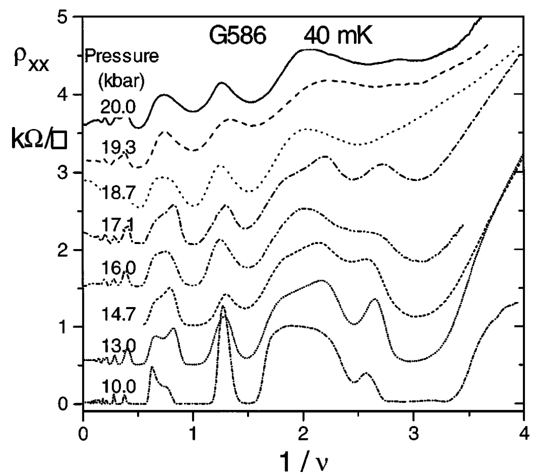

FIG. 1. Magnetoresistance of sample G586 showing $\nu = 1/3$ becoming weaker as the pressure increases, but recovering at 20 kbar.

Figure 2 shows the temperature and pressure variation of the 1/3 minimum, defined as $\Delta\rho = [\rho_{xx}(\infty) - \rho_{xx}(T)]/\rho_{xx}(\infty)$, where $\rho_{xx}(\infty)$ is the resistivity at the same field taken from a high temperature trace where there is no longer a minimum. It is clear that at higher pressures progressively lower temperatures are required to see a $1/3$ minimum, showing that the energy gap E_g decreases strongly with pressure. We obtained values of E_g by fitting the temperature dependence to the Liftshitz-Kosevich (LK) formula, in which $\Delta\rho \propto X/\sinh X$ and $X = 2\pi^2 kT/E_g$. This procedure, described in Ref. [13], measures the gap between LL centers and so is less sensitive to changes in disorder. The LK formula is only valid at relatively higher temperatures before the resistivity minima approach zero, and is typically used in the temperature range $E_g/15 < kT < E_g/5$. For $\nu = 1/3$, we have also measured the activation energy Δ from an Arrhenius plot of $\rho_{xx} = \rho_0 \exp(-\Delta/2kT)$. By contrast, this only uses data at the lowest temperatures. The pressure variation of both E_g and Δ is shown for $\nu = 1/3$ in Fig. 3(a). This shows good agreement between the two methods measured in different temperature ranges. There is a constant difference between the two values such that $E_g = \Delta + \Gamma$, which we ascribe to a constant LL broadening of $\Gamma = 1.3$ K. A similar value of Γ was previously found by extrapolating the activation energy gaps for a series of fractions [15]. At pressures above 16 kbar the value of Δ deduced approaches zero since the minima in ρ_{xx} do not reach zero and cease to be activated at the lowest temperatures. At this point the energy gaps have become comparable to the broadening, and only the LK method is able to measure the gap values.

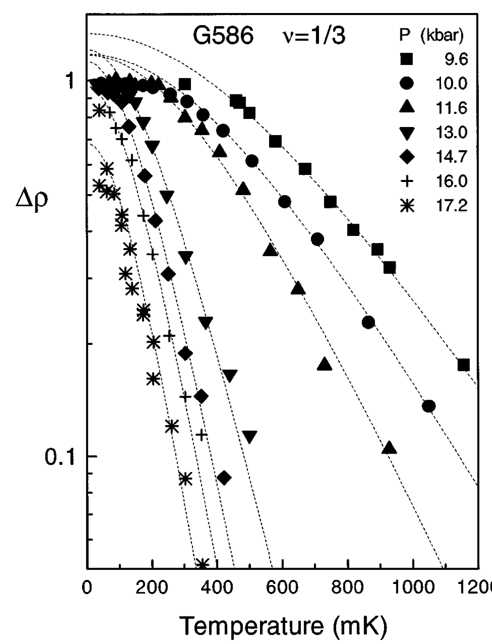

FIG. 2. Temperature dependence of the $\nu = 1/3$ minimum. E_g is obtained from fits to the LK formula (dashed lines).

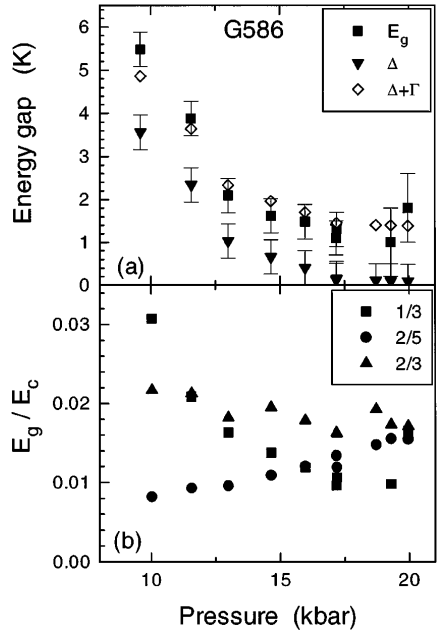

FIG. 3. (a) E_g deduced from fitting to the LK formula compared with the activation energy Δ for sample G586 at $\nu = 1/3$. (b) E_g scaled by E_c, showing how the gap at $\nu = 1/3$ decreases, $2/5$ increases, and $2/3$ remains almost constant as the pressure is increased.

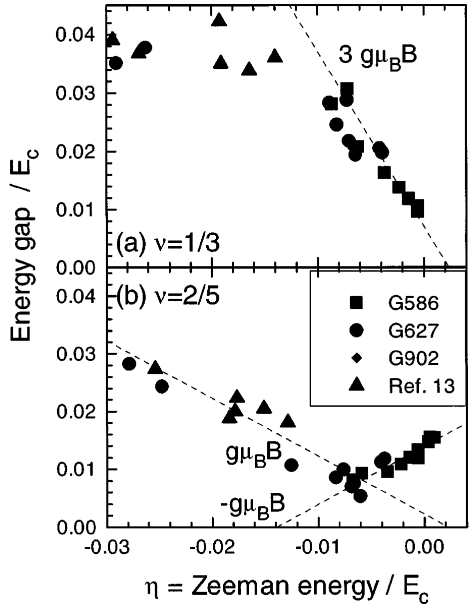

FIG. 4. (a) Energy gap at $\nu = 1/3$ for all the samples as a function of the Zeeman energy. The line shows the energy required to flip 3 spins. (b) The energy gap at $\nu = 2/5$. The slope of these lines corresponds to a single spin flip.

In Fig. 3(b) values of E_g at $\nu = 1/3$, $2/3$, and $2/5$ are shown in units of E_c to allow comparison with theory. This scaled data shows the same trends as the raw data and it is seen that the gaps at $1/3$ ($2/5$) decrease (increase) with pressure over this range. Experimentally the feature at $1/3$ vanishes between 17 and 19 kbar, which is just where g is predicted to pass through zero. By vanishing, we mean that $1/3$ is weaker than $2/5$ and a separate minimum cannot be observed, although the $2/5$ minimum has a pronounced tail on the high field side from the residual $1/3$ feature. While an upper limit can be set on the $1/3$ gap, we cannot tell if it has completely collapsed. At 20 kbar a $1/3$ feature could be seen in the lowest temperature data, but it was not possible to obtain an accurate value for the energy gap as the minimum could not be followed to higher temperatures. From the temperature dependence of ρ_{xx} at the field of $1/3$, an energy gap of $0.017E_c$ results which is consistent with the fraction being established again once g has changed sign.

Since g varies with both pressure and density, the ZE must also be scaled to compare data from different samples. Figure 4 shows the gaps at $1/3$ and $2/5$ for all the samples studied as a function of ZE. Both axes are scaled by E_c making the abscissa $\eta = g\mu_B B/E_c$, the ratio which determines the Skyrmion size and energy [16]. The data for $1/3$ falls into two distinct groups. With $|\eta| > 0.01$, mostly from ambient pressure data, the gap scales only with the Coulomb energy. This behavior is similar to that observed at $\nu = 1$ [5] and shows that the FQHE state at $\nu = 1/3$ has a Coulomb gap, which may correspond to either the spin wave or more probably the CF gap. For $|\eta| < 0.01$, using data taken above 9 kbar, there is a spin gap proportional to ZE. The line on Fig. 4(a), with a gradient of 3, fits the data very well at small η. This corresponds to an energy gap of $3g\mu_B B$ and indicates an excitation involving three spin reversals.

This excitation could be a small composite Skyrmion, as predicted by theory. In a rough estimate Sondhi *et al.* [8] suggested that a Skyrmion formed at $\nu = 1/3$ and occurring at 1 T should contain "a couple of reversed spins." They also estimate the Skyrmion–anti-Skyrmion pair gap as $0.024E_c$ at $g = 0$. The minimum gap we obtain is $0.01E_c$, which compares well when account is taken of the typical 50% reduction in Coulomb energies found in calculations where finite thickness is included [17]. In a more detailed calculation the energy required to create an anti-Skyrmion at $\nu = 1/3$, i.e., the energy to remove one spin at fixed magnetic field, was found to be $E_{1/3}/E_c = 0.069 + 0.024\exp(-0.38R^{0.72}) + |\eta|R$ [18]. The number of reversed spins R in the composite Skyrmion can be found by minimizing this expression, and we see that $R = 1$ for $|\eta| > 0.004$; $R = 3$ at $|\eta| = 0.002$ and $R = 6$ at $|\eta| = 0.001$. These numbers cannot be directly compared with our experiments at a fixed particle number, where the excitation is a Skyrmion–anti-Skyrmion pair, because they do not include creation of the quasiparticle Skyrmion or finite thickness effects. Nonetheless, they allow us to estimate relevant energy and size scales. It is clear that composite Skyrmions will always be small for experimentally accessible parameters and that a size of 3 spins provides good agreement between experiment and theory in the region of $|\eta| = 0.002$. The experiment suggests, however, that the minimum gap for Skyrmionic CF excitations is much less than half of the gap at large ZE. This is substantially different from the prediction of a 50% reduction in the gap due to infinite sized Skyrmions for the analogous IQHE state at $\nu = 1$ [8], showing that analogies between these ferromagnetic states must be treated carefully.

Turning to the data obtained at $\nu = 2/5$ [Fig. 4(b)], there are two distinct regions that cross over at $\eta \simeq -0.006$. For $|\eta| > 0.006$ the gap decreases as the size of the spin splitting decreases, and for $|\eta| < 0.006$ the gap increases again. This suggests a level crossing and finds a straightforward explanation in the CF picture. The $\nu = 2/5$ FQHE gap occurs when two CF LLs are full. When the ZE is small these will be the lowest LLs of the two opposite spin ladders, thus the excitation at $\nu = 2/5$ is a spin flip from an unpolarized ground state. As the ZE increases, the spin reversed ladder moves up relative to the other spin and the $2/5$ gap decreases. When the second and third levels cross over there is a transition to a fully polarized ferromagnetic ground state, and the gap might be expected to vanish. A further increase of ZE opens the $\nu = 2/5$ gap again, until the spin flip is no longer the lowest excitation and the gap eventually saturates at $\hbar\omega_c^*$. The slopes of unity observed on Fig. 4(b) show that this model describes the data well, although we have not accessed large enough $|\eta|$ to reach the saturation region. The exception is in the immediate neighborhood of $\eta = -0.006$ where a finite gap remains.

The position of the crossover is somewhat puzzling since in a single particle picture it would be expected at $g\mu_B B = \hbar\omega_c^*$. This is clearly not the case as our previous work [13] shows $\hbar\omega_c^* \sim 0.03E_c$ at $\nu = 2/5$, putting the cross over at $\eta = -0.03$. We observe this at much smaller $|\eta|$ which suggests that the exchange contribution may stabilize the ferromagnetic ground state compared to the unpolarized state even at very small ZE [19]. It may also lead to a finite gap at the crossover between ferromagnetic and unpolarized states due to differences in the nature and energy of the excitations from the two different ground states.

While the gap at $\nu = 2/3$ appears to be approximately constant over the range of pressure in Fig. 3, the field at $2/3$ is only half that at $1/3$ which makes the range of ZE insufficient to draw definitive conclusions. When the scaled data at large ZE from other samples with $|\eta| > 0.01$ is included, the gap decreases by $g\mu_B B$ in a manner similar to $2/5$. In the CF model, $2/3$ and $2/5$ are expected to behave in a very similar way as they both have the same CF LLs structure. We do not see an obvious minimum in the region $-0.01 < \eta < 0$, although the scatter is larger than for $2/5$. While we cannot see the levels cross over for $2/3$, this has previously been observed when the Zeeman energy is increased by tilting the magnetic field, but only for the lowest density samples [20]. Interestingly, the tilted field measurements did not see the crossover for $2/5$, so it can be seen that a combination of experimental techniques is required for the complete study of the FQHE.

In summary, we have measured the FQHE gaps at $\nu = 2/3$, $2/5$, and $1/3$ under conditions where the Zeeman energy can be tuned through zero. For the ferromagnetic state at $\nu = 1/3$ the energy gap decreased dramatically as the ZE was reduced. At small ZE, the excitation appears to consist of 3 reversed spins which we interpret as a small composite Skyrmion. The behavior is similar to that of the most easily accessible quantum Hall ferromagnet state at $\nu = 1$, and is in general agreement with theoretical predictions. These experiments lend support to the existence of Skyrmionic composite fermion excitations within the two-dimensional electron gas.

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