

Measurements of composite Skyrmions at filling factor 1/3

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Abstract

Measurements of the fractional quantum Hall effect energy gaps at high pressures are presented that provide evidence for the existence of composite Skyrmions. Just as charged spin textures known as Skyrmions are thought to be the lowest lying excitations for electrons at $\nu=1$, we show that composite Skyrmions can be formed at $\nu=1/3$ when the electron g -factor is sufficiently small.

Keywords: Fractional quantum Hall effect, Skyrmions, composite Fermions.

The fully polarised fractional quantum Hall effect (FQHE) state at filling factor $\nu=1/3$ consists of exactly one full composite Fermion Landau level (CF LL) and as such is completely analogous to the integer quantum Hall state at $\nu=1$. Indeed the fact that Laughlin's wavefunction for $\nu=1/3$ contains the $\nu=1$ wavefunction as a factor is one of the basis for the composite Fermion model [1]. Thus, as at all odd ν , the ground state at $\nu=1/3$ should be seen as an itinerant ferromagnet. Excitations from these ferromagnetic ground states, which determine the conductivity, are dominated by the Coulomb exchange energy, $E_c=e^2/4\pi\epsilon l_B$ ($l_B = \sqrt{\hbar/eB}$ is the magnetic length) which is much larger than the single particle Zeeman energy $g\mu_B B$. Single spin flips generate spin waves [2], but, if the Zeeman energy is not too large, there may be spin-textured chiral solitons with a multiple of R flipped spins [3,4]. The size and energy of these collective excitation is determined by the ratio $\eta = g\mu_B B / E_c$ and in the limit of $\eta=0$ they become infinite sized Skyrmions. At $\nu=1$ these have been detected optically from the degree of spin polarisation in nuclear magnetic resonance [5] and photoluminescence [6] and in transport measurements [7,8].

In the case of $\nu=1/3$ the lowest excitation may be either a spin preserving transition to the next higher CF LL or a spin flip transition to the lowest CF LL state with the opposite spin. At $\nu=1$ there was no ambiguity since both the Zeeman and Coulomb energies are small compared to the cyclotron energy, but at $\nu=1/3$ it is necessary to compare the exchange energy with gaps between CF LLs, arising from electron-electron correlations which also scale as E_c . At small η i.e. low magnetic fields or small g -factor, the lowest excitation should be the spin flip but the question is whether this is a single spin flip of one CF or a collective phenomenon, i.e. a Skyrmion.

We have measured the magnetoresistance of GaAs/GaAlAs heterojunctions at temperatures between 30 mK and 1.5 K to obtain values of the FQHE energy gap, principally at filling factors 1/3, 2/3 and 2/5. Hydrostatic pressure of up to 22 kbar has been used to change the Landé g -factor, which increases with pressure from the ambient value of -0.44 passing through zero at ~ 18 kbar and ultimately becomes positive at the highest pressures [9]. The Hall bar samples were

mounted inside a liquid clamp cell attached to the tail of a top loading dilution refrigerator [10]. The temperature was measured with a RuO resistor attached to the pressure cell and the pressure was obtained from the change in resistance of manganin wire. The electron density n_e in the samples could be altered in situ with a red LED after which they were left in the dark for several hours to stabilise before recording data. For sample G586, with a 400 Å spacer layer, n_e was adjusted to be $0.44 \pm 0.06 \times 10^{15} \text{ m}^{-2}$ above 13 kbar and slightly higher at lower pressures where data was taken in the dark. The magnetoresistance ρ_{xx} of G586 at 40 mK is shown in Fig. 1 for pressures in the range 10-20 kbar. The abscissa $1/\nu$ is used to remove the small remaining density variation. As the pressure is increased the feature at $\nu=1/3$ gets weaker. It appears to vanish in the 18.7 kbar data, for which pressure we expect g to be close to zero, and then reappears in the 20 kbar data after g changes sign. Meanwhile the feature at $\nu=2/3$ changes very little, demonstrating that the FQHE is not adversely affected by pressure *per se*.

Two procedures have been used to extract values for an energy gap at $\nu=1/3$. The depth of the minimum at $\nu=1/3$, defined by $\Delta\rho = \{\rho_{xx}(\infty) - \rho_{xx}(T)\} / \rho_{xx}(\infty)$, where $\rho_{xx}(\infty)$ is the high temperature resistivity at $\nu=1/3$ when there is no longer a minimum, is fitted to the Lifshitz-Kosevich (LK) formula $\Delta\rho \propto \chi / \sinh\chi$ where $\chi = 2\pi^2 kT/E_g$ as shown in Fig. 2. This procedure, described in more detail in Ref. 11, is valid over the temperature range for which $\Delta\rho < 0.8$. The energy E_g extracted in this way measures the gap between CF LL centres and is not sensitive to the LL broadening due to disorder. The activation energy Δ has also been found from the Arrhenius plot in Fig. 3 using the equation $\rho_{xx}(T) = \rho_0 \exp(-\Delta/kT)$. This energy is the mobility gap in the density of states. At pressures above 16 kbar the value deduced for Δ is very small since the minima in ρ_{xx} do not reach zero and cease to be activated at the lowest temperatures.

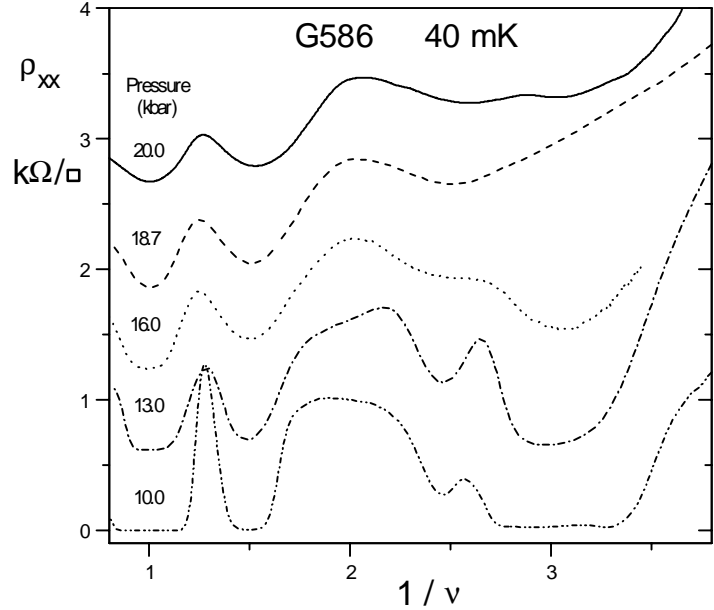


Fig. 1: Magnetoresistance recorded at 40 mK for sample G586 at pressures between 10 and 20 kbar. Note how the feature at $\nu=1/3$ gets weaker relative to $2/5$ with increasing pressure, but is recovered at the highest pressure. The curves are offset for clarity.

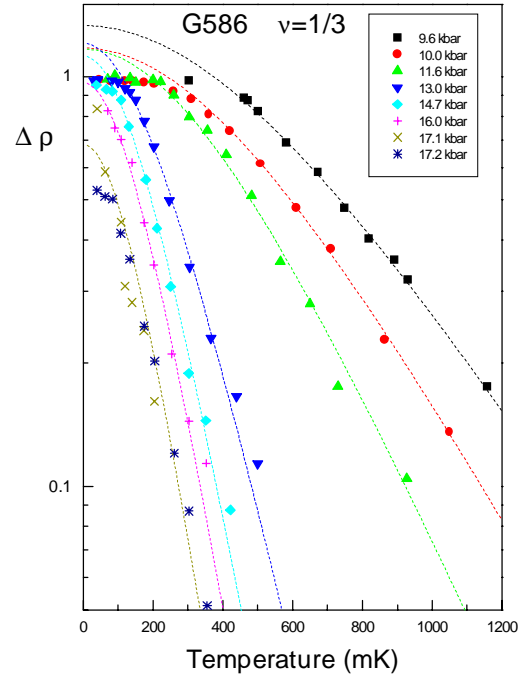


Fig. 2: Depth of the minimum at $\nu=1/3$ fitted to the LK formula to extract the energy gap E_g .

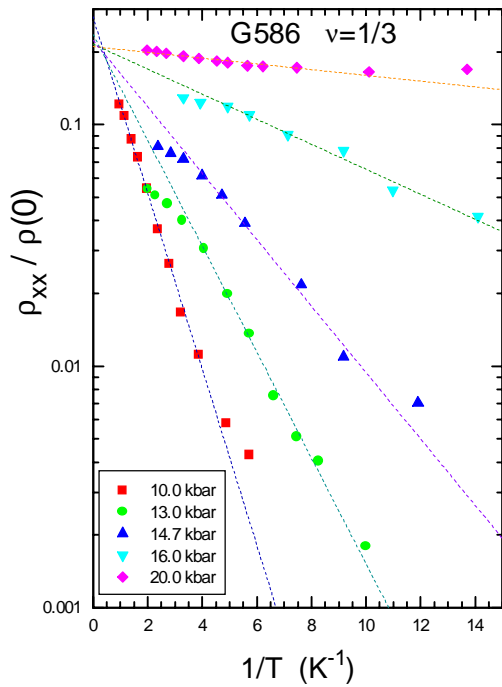


Fig. 3: Resistivity at $\nu=1/3$ from which the activation energy Δ is extracted.

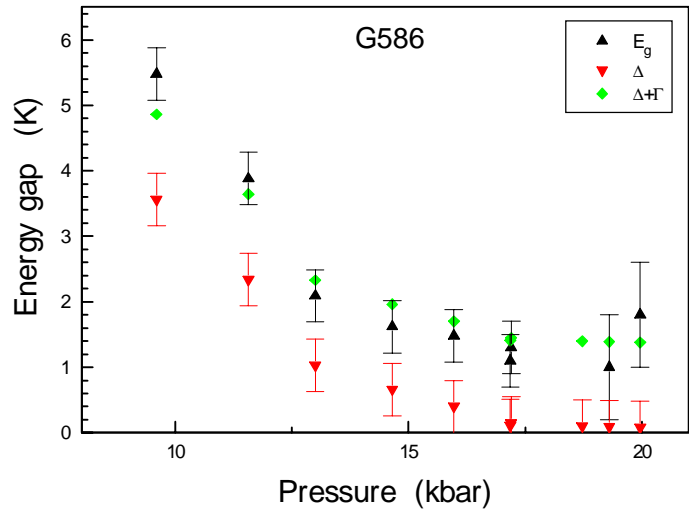


Fig. 4: Energy gap at $\nu=1/3$ as a function of pressure, E_g deduced from fitting to the LK formula compared with the activation energy Δ .

minimum at higher pressures, thus however

This may be due to hopping or parallel conduction at the highest pressures - a problem avoided in the LK approach. From both figures it is clear that lower temperatures are required to see a fully developed the data is analysed we conclude that the energy gap decreases as the pressure increases. The pressure variation of both E_g and Δ is shown in Fig. 4. There appears to be 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.

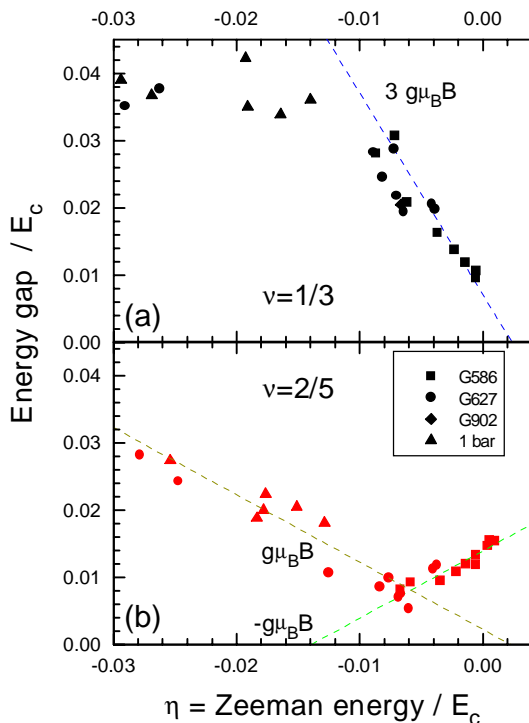


Fig. 5: Energy gaps for all samples at (a) $\nu=1/3$ and (b) $\nu=2/5$ as a function of Zeeman energy, all scaled by the Coulomb energy. Triangles show data taken at ambient pressure from Ref. 11.

In order to compare E_g for different samples where $\nu=1/3$ occurs at quite different magnetic fields all the data has been scaled in Fig. 5 by the interaction energy E_c and plotted as a function of η , the Zeeman energy scaled by E_c . This scaling accounts for the pressure and density variation of g and also allows for comparison with theory. The data in Fig. 5a falls into two groups either side of $\eta \sim 0.01$ which indicates a crossover from spin wave to Skyrmionic excitations. At relatively high densities, and low pressures, such that $|\eta| > 0.01$ the gap just scales with E_c . This is similar to the behaviour seen at $\nu=1$ and shows that the FQHE state at $\nu=1/3$ has a Coulomb gap, which may correspond either to the spin wave or, more probably, the CF LL gap. For pressures above ~ 9 kbar and lower densities, where the Zeeman energy is smaller, there is a spin gap

proportional to $|\eta|$. The line on Fig. 5a with a gradient of $3g\mu_B B$ provides a good fit to the data at small $|\eta|$, which following Refs. 7 & 8 suggests the excitation entails reversing ~ 3 spins. This could be a small composite Skyrmion which is consistent with theoretical predictions [3,12]. The number of spins in the Skyrmion will increase continuously as η decrease, so 3 should be regarded as an average value.

The energy of Skyrmions at $\nu=1$ and $1/3$ with R spins has been calculated in Ref. [12] to be $E_1/E_c = 0.313 + 0.23 \exp(-0.25R^{0.85}) + \eta R$ and $E_{1/3}/E_c = 0.069 + 0.024 \exp(-0.38R^{0.72}) + \eta R$ respectively, where the first term is the energy for an infinite Skyrmion at $\eta=0$ and the third is the Zeeman energy of R spin flips. Comparing these two expressions it is clear that the Zeeman energy will be relatively more important for the composite Skyrmion at $\nu=1/3$, due to the interactions between CFs being weaker than between electrons. Hence the composite Skyrmion at $\nu=1/3$ will be smaller for a given η than the Skyrmion at $\nu=1$. Minimising the composite Skyrmion energy predicts $R=3$ at $|\eta|=0.002$. This theory for creation of an isolated Skyrmion can not be directly compared with the experiments where the excitation consists of a Skyrmion-antiskyrmion pair and finite thickness corrections must be applied, however it allows us estimate the expected energy and size scales.

By contrast Fig. 5b shows the gap at $\nu=2/5$ varying in a manner consistent with a single spin excitation since the lines in this case have gradients of $\pm 1g\mu_B B$. There is also a minimum gap observed at $\eta=-0.007$. This corresponds to the point where the $2/5$ ground state changes from being polarised, with two spin up CF LLs full at large $|\eta|$, to unpolarised at small $|\eta|$ with one full CF LL of each spin. This behaviour is similar to that seen at $\nu=2/3$ in tilted magnetic field experiments [13]. That a finite gap remains as the CF LLs cross suggests the ferromagnetic interactions lift the degeneracy between the polarised and unpolarised ground states.

Acknowledgements

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