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FRACTIONAL QUANTUM HALL EFFECT MEASURED IN A SPIN DEGENERATE ELECTRON GAS

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The influence of spin on the Fractional Quantum Hall Effect is investigated in GaAs-GaAlAs heterojunctions in a filling factor region where both spin states of the lowest Landau level are occupied. When the single particle spin splitting is reduced by hydrostatic pressure features at even numerator fractions are enhanced while those with odd numerators are diminished. This is due to the existence of spin- and Landau gaps in the composite Fermion energy spectrum.

In this paper the influence of spin splitting on the Fractional Quantum Hall Effect (FQHE) is studied experimentally by reducing the energy difference between electron states of spin up and spin down with hydrostatic pressure.[1] The results are interpreted in the composite Fermion (CF) framework. Usually only one spin state is considered, i.e. the electrons are treated as spinless particles or in the limit of infinite spin splitting. Then the FQHE can be interpreted as an integer QHE of spinless CFs and all the features seen at high magnetic fields for filling factors $\nu<1$ can be explained by forming CF Landau levels (LL) in an effective field centred on $\nu=1/2$.[2] However, for $2>\nu>1$ and at low fields both spin states must be considered.

By using hydrostatic pressure to tune the Landé g-factor we can investigate the influence of spin splitting. In bulk GaAs the g-factor is -0.44, which is the result of subtracting band structure effects from the free electron value of 2. At higher pressure the band structure contribution is reduced, and so is the magnitude of the g-factor which is expected to pass through zero at ~16 kbar.[3] Pressure also reduces the conduction band offset between GaAs and GaAlAs leading to a lower electron density, n_e, but this can be increased again through persistent photoconductivity.

The samples studied, G627 & G902, were GaAs-$Ga_{0.67}Al_{0.33}As$ heterojunctions grown by MBE at Philips Research Laboratories with 400Å and 200Å spacer layers respectively. For G627 n_e was maintained at $1.8(\pm0.2)\mathrm{x}10^{15}\mathrm{m}^{-2}$ for pressures up to 13.4 kbar, while for G902 it dropped from $3.1\ \mathrm{x}10^{15}\mathrm{m}^{-2}$ at ambient pressure in the dark to $2.1\mathrm{x}10^{15}\mathrm{m}^{-2}$ after full illumination at 14 kbar. The sample was immersed in oil inside a BeCu pressure cell, loaded into the mixture of a dilution refrigerator in a 17 T superconducting magnet. The temperature was measured with a ruthenium oxide resistor mounted on the pressure cell which accurately followed the sample temperature. The pressure was obtained from the resistance of an InSb sensor.

Figure 1 shows ρ_{xx} at four pressures in the region 2 >ν> 2/3 for G627. At high pressure, where the g-factor approaches zero, even numerator fractions such as ν=2/3, 4/3 and 8/5 are enhanced, while the odd numerator fractions are suppressed. New features also appear at ν=4/5 and 6/5 and the width of the ν=1 minimum is reduced. This is all consistent with removal of the spin degeneracy. For example, with a large spin splitting the state at ν=2/3 is fully spin polarised and consists of two full CF LLs formed only from spin-down electrons. When g→0 the same particles fill one CF LL of each spin and so this state can be considered to be ν=1/3 for the spin-degenerate system. Similarly 4/5 (initially a weak state formed from second generation CFs[4]) becomes a strong feature as it translates to ν=2/5. All the features at odd numerator fractions have half full CF LLs in the degenerate system, without an energy gap at the Fermi energy, and so do not form quantum Hall states. This is similar to observations in bilayer systems[5] where the splitting between symmetric and antisymmetric states is tuned with the separation of adjacent 2DEGs. That situation was modelled by assigning an isospin index to each layer. In the present system, with real spin, there is no spatial separation between the two species of particles and so interaction effects might be expected to be much greater.

We now consider in more detail the mixed spin region around ν=3/2 where the

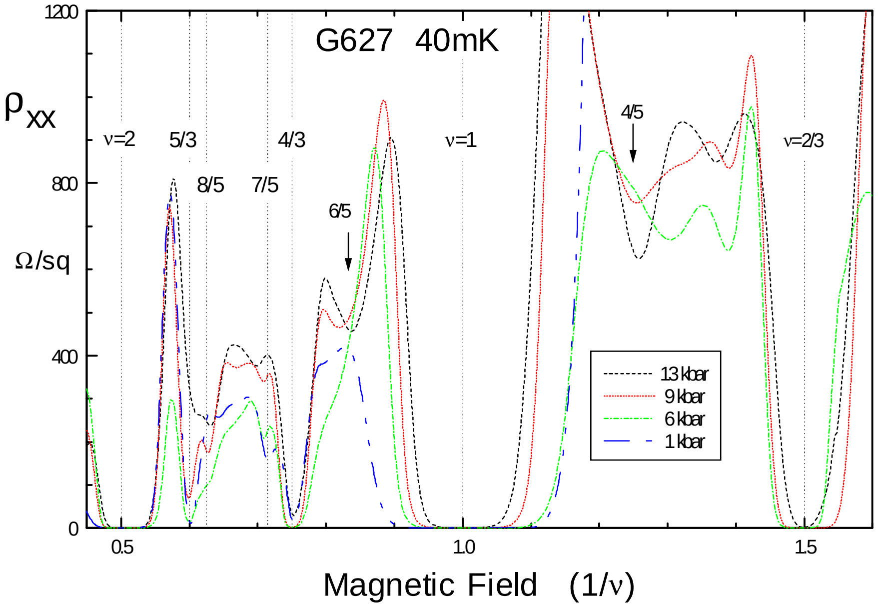

Figure 1: Magnetoresistance of sample G627 for 2>ν>1, showing a decrease in strength of 5/3 and 7/5 relative to 4/3 and 8/5 as the pressure increases. The density was fixed at 1.8 (±0.2) x10^{15}m^{-2}

features at ν=4/3 and 8/5 increase in strength at higher pressures relative to those at 5/3 and 7/5. At ν=3/2 electrons completely fill the lower spin state of the lowest LL 0^- and half fill the upper spin level 0^+. Initially it might be thought that 0^- can be ignored, as it does not contribute to conduction, and CFs formed from the electrons in the half full 0^+ level. However, at fields away from ν=3/2, Landau quantisation in the effective field increases the CF energy by more than the spin splitting and thus CF LLs from both 0^- and 0^+ will overlap. So 0^- can not be ignored and the correct procedure is to make CFs out of *holes* in the complete LL[6] making the state at ν=3/2 the hole analogue of 1/2. FQHE features will appear whenever there is an energy gap at the Fermi level, but we need to know what the initial and final states are to understand how the features change. Considering the two sets of LLs originating from holes in the spin up or down levels the CF energy is:

$$E_{i,N,\sigma} = E_i + \left(N + \frac{1}{2}\right)\hbar eB^*/M^* \pm \frac{1}{2} g^* \mu_B B \, . \qquad (1)$$

*M** is the CF effective mass, which depends *B**, and g* is the Landé g-factor. Note that while the CF cyclotron energy depends on $B^* = 3\left(B\left(\tfrac{3}{2}\right) - B\right)$, the Zeeman term depends on the total magnetic field. In our simple picture each CF consists of a spin 1/2 hole and 2 flux quanta. The flux attachment accounts for the many body Coulomb interaction but the spin part is still essentially that of a single particle. Figure 2 shows a calculation of the CF LLs and the movement of the Fermi energy

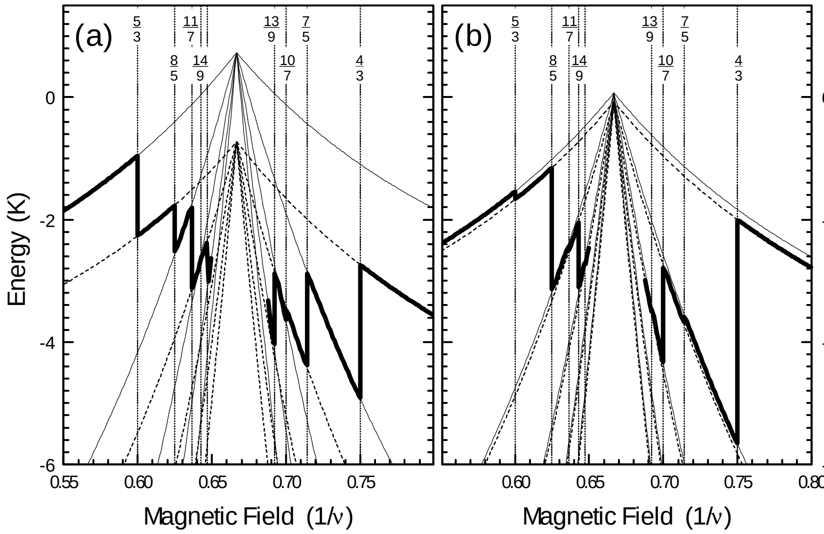

Figure 2: Calculated CF Landau level energies for each spin state (solid and dashed lines), showing the Fermi energy (thick line) as a function of filling factor. Input parameters for G627 are $n_e=1.8\times10^{15}m^{-2}$; M*=0.50+0.08B*; g=0.44. The spin splitting is reduced by a factor of 10 between (a) and (b) giving a dramatic reduction in energy gap at odd- and an enhancement for even-numerator fractions

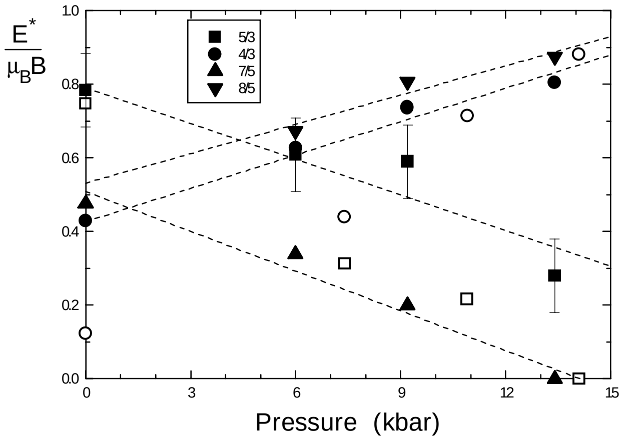

Figure 3: Pressure variation of the FQHE energy gap E* divided by total field B, showing the different behaviour of odd and even numerator fractions. Filled and open symbols are for samples G627 and G902 respectively. Lines are fits to the G627 data and have gradients of ±0.03 kbar^{-1}. Typical error bars are shown for the 5/3 data.

for (a) large and (b) small g*. Even numerator fractions like 4/3 and 8/5 correspond to quasi-cyclotron gaps, whereas the odd numerator fractions 5/3 and 7/5 correspond to spin gaps. Reducing the g-factor, in this case by applying pressure, leads to collapse of the spin gaps and an enhancement of the Landau gaps. These calculations can also explain the changes in spin polarisation brought about by changing the electron density or tilting the sample in a magnetic field.[7]

We have measured the energy gap for each fraction by fitting the temperature dependence of the resistivity to the Ando formula.[8]. The gaps are shown scaled by $\mu_B B$ at each pressure in figure 3 which would be a plot of g* for pure spin gaps. For 5/3 and 7/5 this shows the Zeeman energy of CF holes is reduced along with the single particle g-factor. An additional contribution to the 5/3 gap is seen due to exchange interactions. At 7/5 this is smaller because the spin population difference is less. For both samples the rate of decrease of the gaps with pressure at 5/3 and 7/5 is equal to the rate of increase at 4/3 and 8/5, which is consistent with a simple shift of the two Landau fans as the Zeeman energy is changed by the pressure.

Acknowledgements

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