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Evidence for a spin transition in the $\nu=\frac{2}{5}$ fractional quantum Hall effect

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We have studied the effects of hydrostatic pressure on a high-quality two-dimensional electron system under high magnetic field. The $\nu=2/5$ and 3/7 fractional quantum Hall effect (FQHE) states dramatically vanish and then subsequently reappear with increasing pressure. In the high-pressure $\nu=2/5$ state, tilting of the magnetic field away from the normal is found to suppress the FQHE state. These results suggest that the high-pressure $\nu=2/5$ FQHE state is spin unpolarized with the spin transition being driven by reduction of Landé g factor experienced by electrons due to application of pressure. [S0163-1829(97)50444-9]

The composite fermion picture of the fractional quantum Hall effect (FQHE) provides a unified approach to understanding the physics of two-dimensional electron system (2DES) under high magnetic field.[1,2] Strong electron-electron interaction in the presence of quantizing magnetic field is thought to produce a strange, new quasiparticle called the composite fermion (CF), which consists of an electron attached to an even number of flux quanta. One of the most remarkable implications of the CF picture is the existence of a Fermi sea of CF's with a well-defined Fermi surface at Landau level filling fraction of $\nu=1/2$.[1] Because the magnetic field is incorporated into these particles as attached magnetic flux tubes in the CF picture, the CF's at $\nu=1/2$ behave as if they are moving under a zero effective magnetic field. In particular, an analogy drawn between the regular electron system in the absence of magnetic field and the CF's at half filling has been instrumental in clarifying many of its properties.

Away from $\nu=1/2$ the CF's experience an effective magnetic field $B_{\text{eff}}=B_{\text{external}}-B_{\nu=1/2}$. A series of geometrical resonance experiments, which demonstrate the semiclassical motion of the CF's around $\nu=1/2$, have provided primary evidence in support of CF's.[3–5] Just as the integral quantum Hall effect occurs as a consequence of the quantization of electrons into Landau levels, the FQHE is interpreted as resulting from the Landau quantization of CF's. Thus, the $\nu=p/(2p\pm1)$ series of FQHE states around $\nu=1/2$ can be viewed as $\nu=p$ integral quantum Hall states of CF's. An interpretation of the magneto-oscillatory data on the FQHE states in terms of a simple, single-particle Shubnikov–de Haas formalism has provided a measure of the effective mass of CF's.[6–9] The temperature dependence of resistivity at $\nu=1/2$ can be understood in terms of scattering of impurities[1,10] and phonons.[11]

While these findings generally lend support for a system of spin-polarized CF's in FQHE, a modest Lande g factor ($g=-0.44$) in GaAs necessitates proper accounting of the spin of 2DES. The relative smallness of the Zeeman energy, $g\mu B_{\text{total}}$, compared to the orbital cyclotron energy, $\hbar\omega_c$, opens a possibility of spin reversals at little or no energetic cost. Experiments have shown that rotation of 2DES with respect to perpendicular magnetic field induces transitions from one spin polarization to another in FQHE states such as $\nu=8/5$ and 4/3.[12–16] Recent angular-dependent transport study of the FQHE states in the vicinity of $\nu=3/2$ has proposed an explanation in terms of CF's with spin whose Landau levels are split into spin levels.[17] The coincidences of these spin levels give rise to the observed spin transitions around $\nu=3/2$ and the spin polarization of the FQHE states are determined from the number of up and down spin levels for a given magnetic field.

While it would be of much interest to study such spin transitions in the primary series of FQHE states about $\nu=1/2$, the Zeeman energy experienced by electrons in the lowest Landau level is deemed sufficiently large to fully polarize the spins of typical 2DES. The Fermi wave vector of CF's at $\nu=1/2$, as determined from various geometrical resonance experiments, has reinforced the notion of spin-polarized 2DES in the lowest Landau level.[3–5] Only in 2DES's with extremely low electron density, signatures of spin transitions have been observed in the $\nu=2/3$ FQHE state.[15,16] Consequently the physics of spin-degenerate 2DES in high magnetic fields has not been experimentally accessible to date, in spite of diverse spin effects predicted in the limit of vanishing Zeeman energy.[18,19] However, the possibility of realizing a 2DES with a vanishingly small g factor via application of pressure has been pointed out previously.[20] Application of hydrostatic pressure is thought to produce variation in the band structure and the spin-orbit coupling, which results in the reduction in the magnitude of the g factor experienced by electrons.[21] Enhancement of the $\nu=4/3$ FQHE under pressure was attributed to the pressure-induced reduction of g factor in 2DES.[20] Similar enhancement of certain FQHE states in the lowest Landau level has been reported recently.[22]

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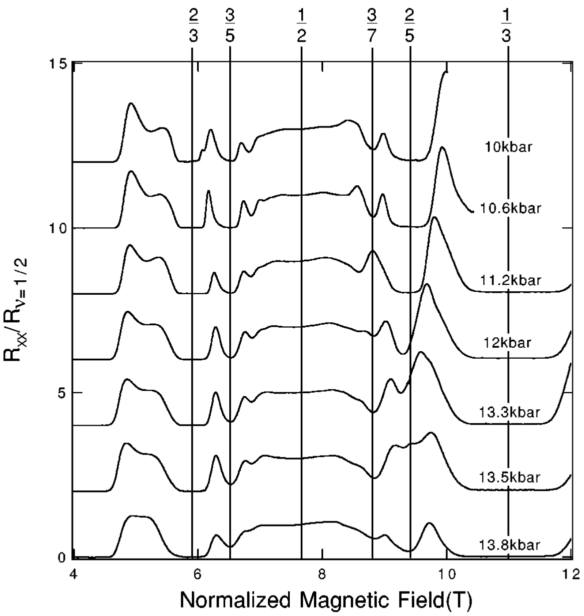

FIG. 1. Magnetoresistance of two-dimensional electron systems at a temperature of 40 mK for various pressures. Magnetoresistance traces have been normalized to the resistance value at $\nu=1/2$ at 13.8 kbar of pressure. The magnetic field for different traces has been normalized to the magnetoresistance data at 13.8 kbar for the sake of comparison. Fractions at the top of the figure indicate the Landau level filling factor.

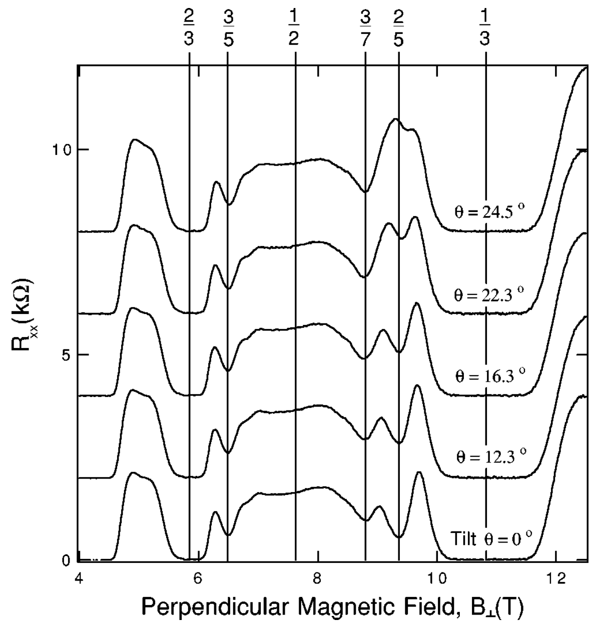

FIG. 2. Magnetoresistance of two-dimensional electron systems under 13.8 kbar of pressure for different tilt angles as a function of perpendicular magnetic field $B_\perp=B\cos\theta$. Fractions at the top of the figure indicate the Landau level filling factor.

In this paper we report on our study of high mobility GaAs/Al$_x$Ga$_{1-x}$As heterostructures up to 14 kbar of pressure. The $\nu=2/5$ and 3/7 FQHE states gradually disappear and then subsequently reappear under increasing pressure. At pressures slightly above the critical pressure necessary for the collapse, a reentrant behavior in the $\nu=2/5$ FQHE may be induced by rotating the sample relative to the external magnetic field. These results imply a transition from a spin-polarized ground state at low pressures to a spin-unpolarized one at high pressures. This transition appears to be driven by reduction in the Zeeman energy experienced by electrons as a result of decrease in the magnitude of g factor that occurs as a result of application of hydrostatic pressure on the GaAs/Al$_x$Ga$_{1-x}$As heterostructure. The observed reentrant behavior of $\nu=2/5$ and 3/7 FQHE states is consistent with the crossing and uncrossing of the CF spin levels around $\nu=1/2$.

The experiments were performed on a high-quality GaAs/Al$_x$Ga$_{1-x}$As heterostructure with an electron density of $n=3.5\times10^{11}$ cm^{-2} and mobility of $\mu=2.4\times10^6$ cm^2/V s. Eight symmetrically placed indium contacts were diffused around the edge of the sample. Hydrostatic pressure was generated using a miniature pressure clamp made of beryllium-copper with a flourinated solvent as the pressure-transmitting medium. The smallness of the pressure cell limited the sample sizes to less than 2×2 mm^2. A small light-emitting diode (LED) chip placed inside the pressure cell was used to illuminate the sample at low temperatures. Compactness of the pressure cell allowed it to be immersed inside the mixing chamber of a top-loading dilution refrigerator. An *in situ* rotating mechanism was used to rotate the pressure cell. Application of pressure resulted in a roughly linear decrease in the electron density of 1.45×10^{10} cm^{-2}/kbar in the region of accessible pressure.

Figure 1 shows the magnetoresistance of a high-quality 2DES at a temperature of 40 mK for the range of pressure between 10 and 13.8 kbar and filling fractions from $\nu=1/3$ to $\nu=1$. Because of pressure-induced reduction in the density of electrons, the magnetic field scale at different pressures has been normalized to the data obtained at the highest pressure of 13.8 kbar in the figure. In the region of pressure shown in the figure, the FQHE states at $\nu=1/3$, 2/3, and 3/5 appear virtually unmodified by application of pressure. In addition, transport features near $\nu=1/2$ remain identical for all the pressures. In contrast, the FQHE states at $\nu=2/5$ and 3/7 exhibit dramatic variation with pressure as magnetoresistance minima turn into maxima with increasing pressure. At $\nu=2/5$ the broad minimum seen at 10 kbar gradually narrows with pressure and turns into a weak doublet at 13.5 kbar of pressure. Addition of about 0.3 kbar of pressure is found to dramatically restore the FQHE state at $\nu=2/5$. A similar behavior albeit at a lower pressure can be seen for the $\nu=3/7$ FQHE. The initial magnetoresistance minimum becomes a maximum and then back to a minimum under increasing pressure. The reentrant FQHE at $\nu=2/5$ under 13.8 kbar of pressure was further studied by rotating the sample with respect to the perpendicular magnetic field.

Figure 2 shows the magnetoresistance under 13.8 kbar of pressure at different tilt angles. The tilt angle was determined from the shift in the transport features of the data and the perpendicular magnetic field is given by $B_\perp=B\cos\theta$. Similar to the data on Fig. 1, addition of parallel magnetic field has no effect on the various FQHE states except at $\nu=2/5$. The magnetoresistance minimum of the $\nu=2/5$ FQHE state becomes progressively weaker and nearly disappears by the maximum tilt angle of 24.5°. Unfortunately, the maximum tilt angle was limited to ~25° due to restricted space inside the mixing chamber and it was not possible to track the evolution of the $\nu=2/5$ state to higher tilt angles. Nonetheless, the collapse of the $\nu=2/5$ state with increasing parallel magnetic field is reminiscent of previous studies of FQHE states under tilted magnetic fields.[12–16] These studies have shown that various FQHE states such as $\nu=8/5$, 4/3, and 2/3 often exhibit reentrant spin transitions under rotating magnetic field upon entering one spin polarization from another.

The evolution of the $\nu=2/5$ FQHE state to both pressure and tilting strongly suggests that the observed transition involves the spin of 2DES. While no direct determination of the spin polarization can be made in the present experiment, circumstantial evidence strongly suggests that the $\nu=2/5$ state below 13.5 kbar of pressure is spin polarized and that it becomes spin unpolarized at higher pressures. With a larger Zeeman energy favoring a spin-polarized ground state over a spin-unpolarized state, destruction of the $\nu=2/5$ FQHE from rotation of the sample over a relatively small range of angles shows that the FQHE state under 13.8 kbar of pressure prior to the collapse is highly sensitive to small increases in the Zeeman energy. Such sensitivity to tilting is expected from the proximity of the spin transition, and the FQHE state above 13.5 kbar is likely to be spin unpolarized. It also follows that the $\nu=2/5$ state below 13.5 kbar of pressure is spin polarized. The gradual weakening of the $\nu=2/5$ and $\nu=3/7$ FQHE states under pressure is consistent with the reduced strength of the spin-polarized ground state from decrease in the Zeeman energy experienced by electrons. Such a reduction in the Zeeman energy is highly indicative of a smaller g factor under hydrostatic pressure.

Tilted-field experiments of the FQHE states at $\nu=8/5$, 4/3, 2/3, and 3/5 have provided evidence suggestive of a transition from partially polarized or unpolarized FQHE states to polarized ground states at higher total magnetic fields.[12–16] In particular the FQHE at $\nu=8/5$, as an electron-hole analog of $\nu=2/5$ ($8/5=2-2/5$), demonstrates a striking reentrant behavior under rotation of the sample away from the normal[13] and provided evidence suggestive of the predicted spin state at $\nu=2/5$.[18,19] Our findings provide convincing evidence of such a spin transition in the $\nu=2/5$ FQHE state. The splitting of magnetoresistance at $\nu=2/5$, as shown in the magnetoresistance data for 13.5 kbar of pressure in Fig. 1, has been previously observed for the case of $\nu=8/5$ (Ref 13) and $\nu=2/3$ (Ref. 16) when both the spin-polarized and spin-unpolarized FQHE states are weakest.

The original theoretical description of FQHE assumed a complete spin polarization and treated the electrons as being ''spinless.'' Based on the smallness of Zeeman energy in $GaAs/Al_xGa_{1-x}As$ heterostructure, the possibility of spin-reversed Hall states at low magnetic fields was initially proposed for the $\nu=2/5$ FQHE state.[18] Comparison of the spin-polarized and unpolarized $\nu=2/5$ Hall states revealed that the unpolarized state has a lower potential energy than the polarized ground state. In the limit of vanishing Zeeman energy, numerical diagonalization of small systems indicates that the $\nu=[2/(2n+1)](\frac{2}{3},\frac{2}{5},\frac{2}{7},\ldots)$ are unpolarized, while the primary Laughlin states $\nu=[1/(2n+1)](\frac{1}{3},\frac{1}{5},\ldots)$ are fully polarized.[19] Other FQHE states such as $\frac{3}{5}$, $\frac{4}{9}$, and $\frac{4}{11}$ have been proposed to be partially polarized.

Recent angular-dependent transport study has proposed spin splitting of CF levels to interpret the FQHE states around $\nu=3/2$.[17] While the Landau level splitting is determined by the effective in-plane magnetic field, the spin splitting of these levels is assumed to be determined by the total external magnetic field. As the total magnetic field is increased while the effective in-plane magnetic field is held fixed, the spin levels from different Landau levels cross one another as the spin splitting increases. When these spin levels coincide, the energy gap disappears and a compressible state may be found. Such a coincidence of CF spin levels provides an elegant explanation for the observed spin transitions in FQHE.

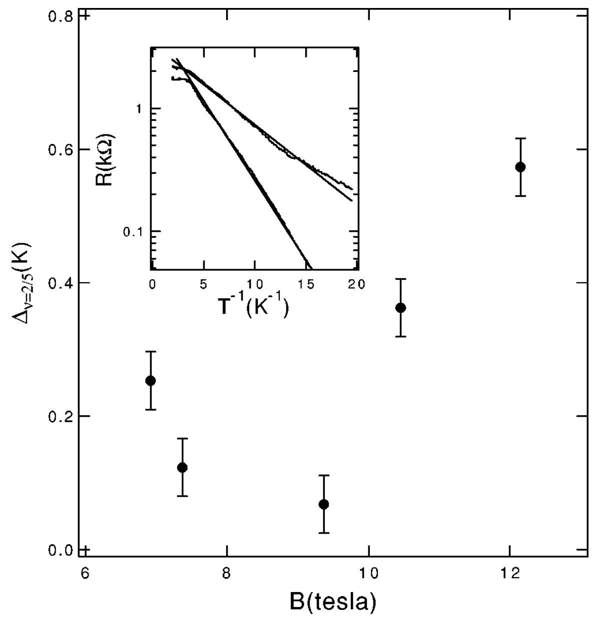

FIG. 3. Energy gap of the $\nu=2/5$ fractional quantum Hall effect under pressure vs magnetic field. Each data point corresponds to different pressures. Variation in magnetic field occurs as a result of change in the electron density brought on by increasing hydrostatic pressure. Inset: Representative Arrhenius plot of magnetoresistivity at $\nu=2/5$ vs inverse temperature. The data correspond to the highest and the lowest magnetic field shown in the figure.

Extending such a level crossing picture to $\nu=2/5$, the observed transition seen in both pressure and rotation then may be viewed as arising from the coincidence of the upper spin level of the lowest CF level with the lower spin level of the second CF level. The reappearance of the $\nu=2/5$ FQHE above 13.5 kbar occurs from occupation of both up and down spin levels of the lowest CF level. Below 13.5 kbar of pressure, the Zeeman energy is greater than the cyclotron energy of CF's and two spin-down levels are occupied. A local minimum in the energy gap of the $\nu=2/5$ FQHE state is expected as a consequence of such evolution of the spin levels.

Figure 3 shows the energy gap of the $\nu=2/5$ FQHE state at different magnetic fields. Assuming that magnetoresistance ρ_{xx} is activated, $\rho_{xx}\propto\exp(-\Delta/2T)$, the energy gap Δ or equivalently the energy required to create a quasiparticle-quasihole pair at the $\nu=2/5$ FQHE state may be determined. Each data point was obtained at different pressures and consequently corresponds to a different g value. The energy gap at the highest and lowest magnetic fields shown correspond to 11.2 and 14.2 kbar of pressure, respectively. The inset of the figure shows the representative Arrhenius plot of the magnetoresistance at these pressures. A minimum in the energy gap is found around 8 T of magnetic field, which corresponds to 13.8 kbar of pressure. Such a behavior of the energy gap is consistent with the competition between the spin-polarized and spin-unpolarized ground states as the total Zeeman energy is varied. Since the Coulomb energy, $e^2/\epsilon l_0$, where l_0 is the magnetic length, is proportional to $\sqrt{B}$ and the Zeeman energy varies linearly with the magnetic field, the major variation in the energy gap near the spin transition is expected to come from the contribution from the Zeeman energy. Variation in the energy gap from the changes in the density of the electrons due to application of pressure is expected to be small.

With the appearance of the spin-unpolarized $\nu=2/5$ state under hydrostatic pressure, a question arises as to the value of the g factor under pressure. We may deduce the g factor from the condition for coincidence of the spin levels when the Zeeman energy of CF's equals its cyclotron energy:

$$g\mu_B B_{\text{total}}=\hbar e B_{\text{eff}}/m^*, \qquad (1)$$

where m^* is the effective mass of CF's. Because of the proximity of the spin transition, we were unable to perform a satisfactory Shubnikov–de Haas analysis of temperature-dependent magnetoresistivity[6–9] at $\nu=2/5$. We instead looked at neighboring FQHE states and obtained an effective mass of $m^*=1.9m_0$ at the $\nu=3/7$ FQHE state. This yields a g value of $g=0.21$ under 13.8 kbar of pressure. While this implies that the application of 13.8 kbar of pressure has resulted in a considerable reduction of the g factor, there remain some questions over the effect of spin degeneracy on the Shubnikov–de Haas formalism and the role of exchange enhancement of the g factor in high magnetic field. At this point it remains unclear what are the relative contributions of the bare g factor under pressure and the exchange enhancement in the the obtained g value of $g=0.21$.

Turning to the transition seen at the $\nu=3/7$ FQHE, a similar but somewhat more complicated behavior is expected due to the presence of three spin levels. In the current study, only one spin transition is observed at 11.2 kbar. A second transition is expected at a somewhat lower pressure. In addition, study of the $\nu=2/3$ state at low pressures ($\sim$6 kbar) shows splitting of the magnetoresistance minimum reported previously.[16]

In summary, we have observed evidence for a spin transition at the $\nu=2/5$ FQHE under hydrostatic pressure. Sensitivity of the $\nu=2/5$ state to both tilting and pressure suggests strongly that the reentrance seen at $\nu=2/5$ involves the spin of electrons. Reduction in the magnitude of g factor under pressure appears to be largely responsible for the emergence of the spin transition in the $\nu=2/5$ FQHE state.

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