Hysteresis and Spin Transitions in the Fractional Quantum Hall Effect

H. Cho,[1] J. B. Young,[1] W. Kang,[1] K. L. Campman,[2] A. C. Gossard,[2] M. Bichler,[3] and W. Wegscheider[3]
[1]*James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637*
[2]*Department of Electrical Engineering, University of California at Santa Barbara, Santa Barbara, California 93106*
[3]*Walter Schottky Institut, Technische Universität München, Am Coulombwall, D-85748 Garching, Germany*
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We have observed hysteretic behavior associated with spin transitions in the fractional quantum Hall effect (FQHE). Dramatic hysteresis in up and down sweeps of the magnetic field occurs in the vicinity of the spin-polarized to spin-unpolarized transitions in even-numerator FQHE states. The hysteresis is most pronounced at the lowest temperatures and disappears as the temperature is raised. These results suggest that the FQHE states exhibit metastability in close proximity of the spin transitions. We discuss our findings in terms of a recent proposal of ferromagnetlike ordering associated with nearly degenerate Landau levels. [S0031-9007(98)07139-7]

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The two dimensional electron systems (2DES) at low temperatures and high magnetic fields are notable for novel ground states and phase transitions [1,2]. An incompressible quantum liquid state of fractional quantum Hall effect (FQHE) occurs as a consequence of strong electron-electron interaction in high magnetic fields. While strong magnetic field favors a ground state with electron spins that are aligned parallel to the applied magnetic field, small Zeeman energy, $g\mu B_{\text{total}}$, experienced by electrons in the GaAs/AlGaAs semiconductor heterostructure opens possibilities of FQHE states with mixed spin configurations. In the limit of vanishing Zeeman energy, electron spins can flip at little energetic cost, and a phase transition to a spin-unpolarized FQHE state is possible. This type of spin transition may be induced in semiconductor heterostructures by application of large hydrostatic pressure, which reduces the Lande g factor experienced by electrons [3]. In this paper, we report on our study of hysteretic behaviors associated with such spin transitions in the FQHE.

Because of relatively modest g factor ($g = -0.44$) in GaAs, electronic spin represents an important dynamical degree of freedom in 2DES. Small Zeeman energy opens the possibility for spin reversals, and the existence of FQHE states with reversed spin ground states has been postulated theoretically [4]. Tilted-field experiments have shown that certain FQHE states such as $\nu = 8/5$ and $4/3$ exhibit a transition from a spin-unpolarized state to a spin-polarized state as the magnetic field is rotated away from the normal [5]. Addition of an in-plane magnetic field increases the Zeeman energy, and the spin-polarized FQHE states become energetically favorable over unpolarized or partially polarized states. Recent experiments have sought to study the spin transitions in FQHE by reducing the g factor experienced by electrons through application of large hydrostatic pressure [6–8]. Significant reduction in the Zeeman energy experienced by 2DES in the GaAs/AlGaAs heterostructure under high pressure has resulted in a transition from a spin-polarized to a spin-unpolarized ground state in the $\nu = 2/5$ FQHE [8]. Under increasing pressure, the $\nu = 2/5$ FQHE state gradually weakens and vanishes at a critical pressure. Further increase of the pressure restores the $\nu = 2/5$ FQHE. The tilted-field experiment shows that the $\nu = 2/5$ FQHE state below the critical pressure is spin polarized and that the reentrant $\nu = 2/5$ FQHE state above the critical pressure is spin unpolarized.

In this Letter, we report on our study of hysteretic behavior associated with the spin transitions in certain even-numerator FQHE states. Dramatic hysteresis in up and down magnetic field sweeps is observed in close proximity of the spin transition associated with the FQHE states such as $\nu = 2/5$, $4/7$, and $4/9$. A large difference in the transport features between up and down magnetic field sweeps creates complicated hysteresis loops centered about these FQHE states. The hysteretic behavior is most pronounced at the lowest temperatures and disappears as the temperature is raised. The hysteresis occurs in a small range of pressure around the critical pressure necessary to induce a spin transition. The absence of hysteretic features associated with the spin transitions of odd-numerator FQHE states suggests that the internal symmetry of the FQHE liquids may play an important role in the production of hysteresis.

The experiment was performed on a high quality GaAs/AlGaAs heterostructure and a 250-Å-wide quantum well of densities $n = (3.5 \text{ and } 2.0) \times 10^{11}\ \text{cm}^{-2}$ and mobilities $\mu = (2.4 \text{ and } 4.0) \times 10^{6}\ \text{cm}^2/\text{V sec}$, respectively. Description of the pressure apparatus used for the experiment is described elsewhere [8]. Application of pressure resulted in a roughly linear decrease of the electron density of $(1.45 \text{ and } 0.8) \times 10^{10}\ \text{cm}^{-2}/\text{kbar}$ in heterostructure and quantum well samples, respectively, in the range of pressure studied.

In Fig. 1, we present a typical magnetoresistance trace seen under 12.8 kbar of pressure, slightly below the critical pressure necessary to induce a spin transition in the

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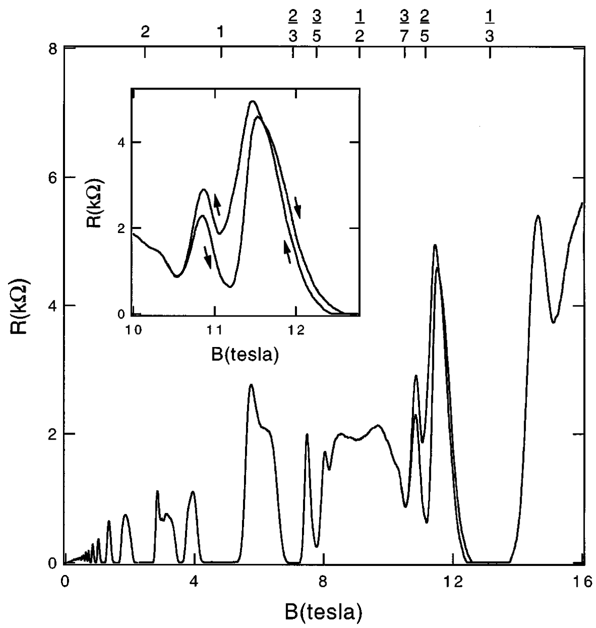

FIG. 1. Magnetoresistance of GaAs/AlGaAs heterostructure under pressure of 12.8 kbar at a temperature of 40 mK. Hysteresis in the magnetoresistance is observed around filling fraction $\nu = 2/5$. Fractions at the top of the figure indicate the Landau level filling factor. Inset: An expanded view of the magnetoresistance about $\nu = 2/5$. Arrows indicate the direction of the field sweeps.

$\nu = 2/5$ FQHE. Well-developed minima in the magnetoresistance are seen for various integer and fractional quantum Hall states. The most remarkable feature of the data is the hysteretic loop centered about filling fraction $\nu = 2/5$ between up and down sweeps of magnetic field. In up sweeps the $\nu = 2/5$ FQHE develops into a reasonably well-developed minimum in magnetoresistance. In down sweeps, various transport features become more resistive, and its locations shift to lower magnetic fields. The $\nu = 2/5$ FQHE is considerably more resistive and appears weaker than the adjacent $\nu = 3/7$ FQHE. Further study reveals that the hysteretic behavior around $\nu = 2/5$ occurs only in close proximity to the critical pressure necessary for the spin transition.

Figure 2 shows the hysteretic behavior in magnetoresistance around $\nu = 2/5$ in the range of pressure from 11.2 to 13.8 kbar. As the pressure is gradually increased, both up and down sweeps of magnetic field show that the $\nu = 2/5$ FQHE becomes progressively weaker and virtually disappears by 13.5 kbar. The reentrant behavior of the $\nu = 2/5$ FQHE at 13.5 kbar of pressure is the signature of the phase transition associated with the change of its spin polarization [8]. The gradual weakening of the $\nu = 2/5$ FQHE with pressure is accompanied by growing hysteresis between the up and down sweeps of magnetoresistance. The general hysteresis profile is that a stronger resistance minimum is produced during up sweeps and a weaker resistance minimum during down sweeps. The hysteresis is initially small or nearly nonexistent at 11.2 kbar of pressure. As the pressure is increased, the hysteretic behavior becomes substantial above 12 kbar and appears most pronounced at 13.3 kbar. The hysteresis persists at 13.5 kbar when the $\nu = 2/5$ FQHE has virtually disappeared and at higher pressures when the unpolarized $\nu = 2/5$ FQHE emerges.

In Fig. 3, we present the temperature dependence of the hysteresis around $\nu = 2/5$ for a heterostructure sample under 12.5 kbar of pressure. The hysteresis is most pronounced at the lowest temperatures of 40 mK shown in the figure. Temperature dependence shows that the hysteresis loops mirror the strength of the $\nu = 2/5$ FQHE. As the temperature is raised to 90 mK, the $\nu = 2/5$ Hall state becomes weaker, and the hysteresis is reduced compared to the data at the lowest temperature. At 200 mK only a weak minima can be seen at $\nu = 2/5$, and the hysteretic behavior appears as a slight shift of magnetoresistance. At higher temperatures there is no trace of the FQHE and hysteresis at $\nu = 2/5$.

In addition to the $\nu = 2/5$ FQHE state, hysteresis is also found in proximity of spin transitions associated with other FQHE states. Figure 4 illustrates the hysteretic behavior observed in the vicinity of the $\nu = 4/7$ and $4/9$ FQHE states in 250-Å-wide quantum well samples. Under 12 kbar of pressure a strong hysteresis is centered

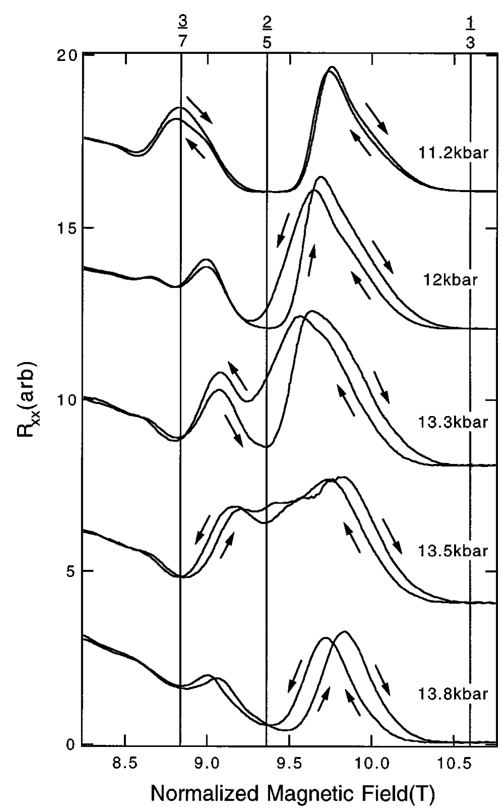

FIG. 2. Magnetoresistance of two-dimensional electron system under pressure in the vicinity of filling fraction $\nu = 2/5$. The resistance data were taken at a temperature of 40 mK. Magnetic field scale has been normalized to the highest pressure shown in the figure for the sake of comparison.

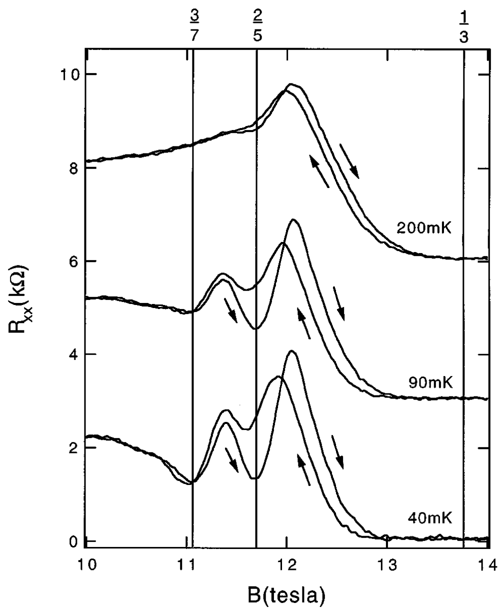

FIG. 3. Temperature dependence of magnetoresistance around $\nu = 2/5$ for a heterostructure sample under 12.5 kbar of pressure.

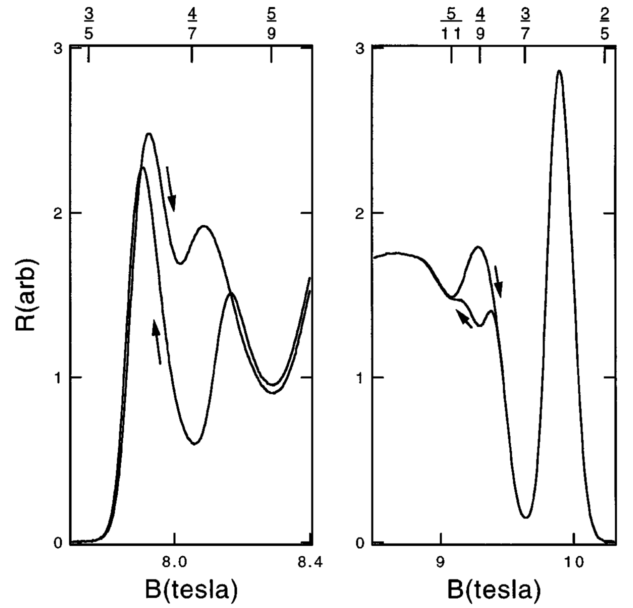

FIG. 4. Magnetoresistance of 250-Å-wide quantum well sample under 12 (left) and 13 (right) kbar of pressure at a temperature of 60 mK.

about the $\nu = 4/7$ FQHE state. Up sweeps data show a magnetoresistance minimum that is weaker than the neighboring $\nu = 5/9$ FQHE. In subsequent down sweeps, a much deeper magnetoresistance minimum is recovered. The overall behavior is qualitatively similar to that observed in the $\nu = 2/5$ FQHE. A spin transition found in the $\nu = 4/9$ FQHE under 13 kbar of pressure results in an even more dramatic discrepancy between up and down sweeps. During up sweeps, a resistance peak, instead of a usual minimum, is obtained at $\nu = 4/9$. In down sweeps the peak seen during up sweeps reverts back to a minimum, creating a distinct bubble loop between up and down sweeps. The spin transitions in odd-numerator FQHE states, though occurring in the similar range of pressure, do not exhibit strong hysteresis as observed in the even-numerator FQHE states.

Observation of hysteresis in our experiment provides a new insight into the nature of the spin transitions in the FQHE [9]. Since hysteresis often accompanies a first order phase transition, it follows that the transitions between FQHE liquids with different spin polarizations may be occurring as a first order phase transition. This is a rather interesting possibility since other phase transitions observed in the 2DES, such as transition between two quantum Hall states or between a quantum Hall state and an insulating phase, are continuous quantum phase transitions that do not exhibit hysteresis [2]. The contrast between these transitions may be reflecting the difference between the orbital and spin degrees of freedom in the 2DES.

In addition, a more interesting scenario is suggested by the absence of hysteresis associated with the spin transitions of odd-numerator FQHE states. In our systematic study of spin transitions under pressure, strong hysteresis has been observed in close proximity of the spin transitions in even-numerator FQHE states at $\nu = 2/5$, $4/7$, and $4/9$. In general, it is relatively easy to detect the hysteretic behaviors due to its presence over a relatively wide range of pressures as shown in Fig. 1. The spin transitions in odd-numerator FQHE states at $\nu = 3/5$, $3/7$, $5/9$, and $5/11$, though found in a similar range of pressure, do not exhibit the pronounced hysteresis seen in the even-numerator states. Consequently the absence of hysteresis in odd numerator states is somewhat puzzling and points toward the symmetry of the FQHE liquids at these fillings playing an important role in the production of the hysteretic behavior.

The pressure and the temperature dependences of hysteresis reveal the interplay of the FQHE state and its proximity to the spin transition. Strong hysteresis is found only in a small range of pressure above and below the critical pressure and disappears at pressures far away from the critical pressure where the FQHE states become strong. The hysteretic behavior is strongest at the lowest temperatures and disappears above 200 mK. Since the FQHE states also disappear at comparable temperatures, the energy scale associated with the hysteresis appears to be comparable to the energy gaps of the FQHE states in the vicinity of the spin transitions.

A puzzling feature of the data is that the hysteresis loop, while centered about those FQHE states undergoing spin transitions, extends well into the adjacent compressible states and even into neighboring FQHE states. This behavior is most prominent in the $\nu = 2/5$ FQHE state where the hysteresis in magnetoresistance extends into the $\nu = 1/3$ and $3/7$ FQHE states. While a detailed analysis of the hysteresis profile is beyond the scope of this paper, modification of the transport features in the nearby compressible states suggests the possible importance of metastability and fluctuations associated with the spin transitions.

The absence of strong hysteresis associated with the spin transitions of odd-numerator FQHE raises a question regarding the difference between the spin transitions of even- and odd-numerator FQHE states. Numerical diagonalization of small systems indicates that only certain FQHE states, such as $\nu = [2/(2n + 1)](\frac{2}{3}, \frac{2}{5}, \frac{2}{7}, \ldots)$, are unpolarized in the limit of vanishing Zeeman energy [4]. Some states such as $\nu = [1/(2n + 1)](\frac{1}{3}, \frac{1}{5}, \ldots)$ always remain spin polarized while other higher order fractions can become partially polarized. Within the composite fermion picture of FQHE [10], the spin polarization of the $\nu = p/(2p \pm 1)$ FQHE state is determined by the configuration of p spin-split Landau levels occupied by composite fermions [11]. Spin transitions occur from coincidence of spin levels as their splitting is varied. The physics of two nearly degenerate Landau levels has been studied recently and may provide an explanation for the origin of the observed hysteresis [12].

Jungwirth *et al.* propose that, for a 2DES system at an even integral filling factor, coincidence of two Landau levels with different spin polarization is analogous to a two-dimensional ferromagnet [12]. Calculation of the anisotropy energy shows that such a system possesses an easy-axis anisotropy. Local fluctuations can result in random pseudospin magnetic field and domains with different spin orientations. Motion of the domain walls results in a history dependence of the magnetization. The hysteresis seen in our experiment may be occurring from the metastability of the domain walls. Interfacial resistance between the domains adds to the overall resistance and a larger magnetoresistance results as seen experimentally. Although the predictions made by Jungwirth *et al.* apply to the coincidence of electronic spin levels in the integer quantum Hall effect, extension to the FQHE regime is possible under the composite fermion picture. While a direct confirmation of the proposed ordering is not possible under the present experiment, the overall qualitative features of the data appear to agree well with the predictions made by Jungwirth *et al.*

In summary, we have observed strong hysteresis associated with the spin transitions of even-numerator FQHE states. The hysteretic behavior occurs in a small range of pressure above and below the critical pressure at which spin-polarized FQHE states become spin unpolarized. Temperature dependence suggests that the relevant energy scale on the order of 100 mK may be associated with the hysteresis. The presence of hysteresis points towards a spin transition being a first order phase transition or a possible ferromagnetlike ordering associated with the correlation of two nearly degenerate Landau levels.

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