Evidence for a Phase Transition in the Fractional Quantum Hall Effect

J. P. Eisenstein, H. L. Stormer, L. Pfeiffer, and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 22 December 1988)

We observe a novel transition between distinct fractional quantum Hall states sharing the *same* filling fraction $\nu=\frac{8}{5}$. The transition is driven by tilting the two-dimensional electron-gas sample relative to the external magnetic field and is manifested by a sharp change in the dependence of the measured activation energy on tilt angle. After an initial decline, the activation energy abruptly begins to increase as the tilt angle exceeds about 30°. A plausible model for these results implies a transition from a spin-unpolarized quantum fluid at small angles to a polarized one at higher angles.

PACS numbers: 73.40.Kp, 73.20.Dx, 73.50.Jt

The earliest ideas concerning the fractional quantum Hall effect (FQHE) in two-dimensional electron systems (2D ES) held the spin Zeeman energy to be so large that all fractional states could be safely assumed to be fully spin polarized. It was also generally thought that only one incompressible quantum liquid existed at any given filling fraction that displayed the FQHE. Halperin[1] was the first to point out that the small g factor ($g\sim0.5$) in GaAs made the usual assumption of full spin polarization worth reexamining. He proposed various candidate ground states containing reversed spins. In particular, the *unpolarized* ground-state wave function he suggested for the $\nu=\frac{2}{5}$ FQHE was later shown[2] to have a lower energy, in the absence of the Zeeman term, than the usual polarized state thought to be a "daughter" of the primitive $\nu=\frac{1}{3}$ fluid. While at high magnetic fields the Zeeman energy will stabilize the polarized state, the possibility remains for a transition to an unpolarized fluid at lower fields. The purpose of this Letter is to present evidence consistent with just such a spin transition in the FQHE ground state at $\nu=\frac{8}{5}$.

It is becoming apparent that the spin degree of freedom may in fact play an important role in forming both the condensed ground state[1-8] and its quasiparticle excitations,[9,10] at least at sufficiently low magnetic field B. The energy gap for creating spin-reversed quasiparticles above the $\nu=\frac{1}{3}$ state has been found[9,10] to be less than that for polarized quasiparticles, at sufficiently low magnetic field. This has been suggested as a way to explain the magnetic field dependence of the observed energy gaps[11] in the FQHE. Recent tilted-field studies[12,13] on the FQHE have also been cited as suggestive of the influence of spin.

The recent discovery[14] of a Hall plateau in the FQHE at the *even-denominator* filling fraction $\nu=\frac{5}{2}$ has generated renewed interest in the possibility of spin-unpolarized ground states. A plausible way to overcome the odd-denominator restriction inherent in Laughlin's many-body wave function[15] describing the primitive FQHE ground states at $\nu=\frac{1}{3}$, $\frac{1}{5}$, etc., is to form pairs of electrons with opposing spins. This was made concrete by Haldane and Rezayi[6] who proposed an unpolarized spin-singlet wave function for the $\nu=\frac{5}{2}$ FQHE. Eisenstein *et al.*[16] have presented experimental evidence that the underlying ground state at $\nu=\frac{5}{2}$ may, in fact, be unpolarized. Their data showed a rapid collapse of the $\frac{5}{2}$ state as the magnetic field was tilted away from the normal to the 2D plane, while nearby odd-denominator states remained largely unaffected. Since the predominant effect of the tilt is the enhancement of the spin-flip energy,[17] the collapse of the $\frac{5}{2}$ state with increasing tilt angle was cited as evidence for a significantly reduced spin polarization.

In the present paper we describe a transition between two distinct FQHE states at the same odd-denominator filling factor $\nu=\frac{8}{5}$. The transition is driven by tilting the magnetic field and the data are consistent with a change from a spin-unpolarized fluid to a polarized one. We have so far found no similar transition in the FQHE states at $\nu=\frac{5}{3}$, $\frac{4}{3}$, $\frac{7}{5}$, or $\frac{11}{7}$.

The sample employed in this study is a GaAs/AlGaAs heterostructure grown by molecular-beam epitaxy. With a 2D carrier concentration $N_s=2.3\times10^{11}$ cm^{-2} and mobility of about 7×10^6 cm^2/Vs, both established by brief low-temperature illumination with a red light-emitting diode, this sample is of extremely high quality. This is evidenced by the substantially enhanced strength of the delicate $\nu=\frac{5}{2}$ FQHE in comparison to earlier observations.[14,16,18] The sample has allowed for a quantitative study of the even-denominator state, the results of which will be published separately.

The sample is mounted upon an *in situ* rotation device attached to the mixing chamber of a dilution refrigerator. Magnetotransport measurements are typically performed using 10-nA, 5-Hz excitation. We have reliably obtained electron temperatures as low as 16 mK with this arrangement. As in our earlier work,[16] the tilt angle is determined by observing the orderly $\cos\theta$ shift of strong features in the diagonal resistivity ρ_{xx}. Details of our techniques have been published earlier.[14,16,18] The use of *in situ* rotation at low temperatures (< 100 mK) is a prerequisite for obtaining reproducibility of delicate

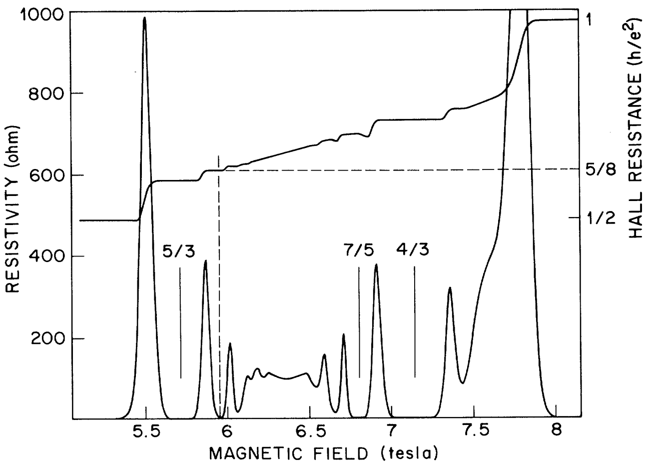

FIG. 1. Overview of diagonal resistivity ρ_{xx} and Hall resistance ρ_{xy} at 25 mK, with the magnetic field perpendicular to the 2D plane. Dashed lines indicate location of the $\frac{8}{5}$ FQHE. Other important FQHE states are indicated.

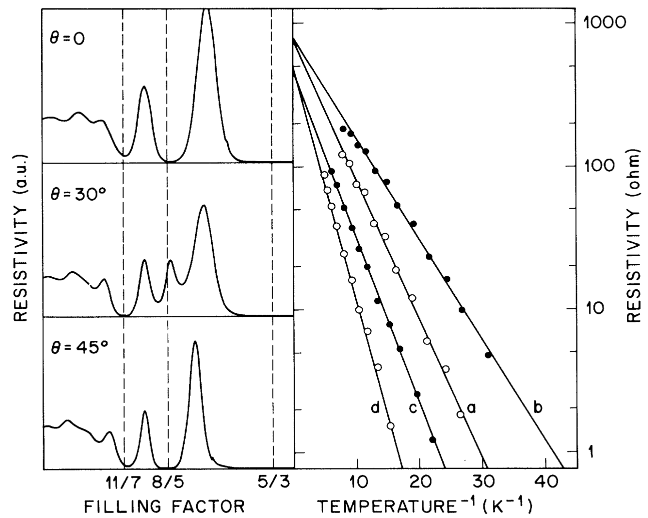

FIG. 2. Left three panels: Expanded views of ρ_{xx} vs *filling factor* in a narrow range around $\nu=\frac{8}{5}$. Note the splitting of $\frac{8}{5}$ minima at $\theta=30°$. Data shown were taken at about 30 mK. Right panel: Arrhenius plots for $\frac{8}{5}$ minimum at various angles. Plot *a*, $\theta=0°$; *b*, $\theta=18.6°$; *c*, $\theta=42.4°$; and *d*, $\theta=49.5°$.

FQHE features. Since the bulk of our data is comprised of activation energy determinations, reliable thermometry in the millikelvin regime is necessary. For this we have employed a ^{3}He melting-curve thermometer similar to that described by Greywall.[19]

Figure 1 shows an overall view of both ρ_{xx} and the Hall resistance ρ_{xy} at 25 mK with the magnetic field perpendicular to the 2D plane, i.e., $\theta=0$. Only the field range corresponding to filling factors $2>\nu>1$ is shown. The filling factor is defined as $\nu=N_s/(eB/h)$, where eB/h is the degeneracy of the individual spin subbands of each Landau level. Thus, Fig. 1 displays electron correlation effects in the upper spin subband of the lowest Landau level. While numerous fractional quantum Hall states are present, as evidenced by minima in ρ_{xx} and plateaus in ρ_{xy}, we will be primarily interested in the $\nu=\frac{8}{5}$ state.

Upon tilting the sample relative to the applied magnetic field an interesting reentrant behavior obtains at $\nu=\frac{8}{5}$. With the field perpendicular to the 2D plane a well-developed FQHE minimum is observed at $\nu=\frac{8}{5}$ (see Fig. 2). Qualitatively, as the angle θ is increased from zero, the $\frac{8}{5}$ FQHE gradually *weakens*. At about 25° a weak satellite minimum appears about 1% higher in field (i.e., lower in filling factor) than the main $\frac{8}{5}$ minimum. Increasing θ further, to about 30°, results in two weak minima of about equal strength whose field positions straddle the location of the $\nu=\frac{8}{5}$ filling factor. The typical splitting of the doublet is only 1% in filling factor. Further tilting reverses all these trends. The high-field component of the doublet becomes dominant and gradually centers on $\nu=\frac{8}{5}$. Beyond about 37° a single, well-developed $\frac{8}{5}$ minima dominates, steadily *strengthening* as θ is increased. For both the low- and high-angle regimes, the Hall resistance exhibits the expected plateau at $\rho_{xy}=5h/8e^2$.

To obtain a quantitative picture of this phenomenon we have carefully measured the activation energy Δ versus tilt angle for the $\frac{8}{5}$ minimum in ρ_{xx}. We define Δ so that $\rho_{xx}=\rho_0\exp(-\Delta/2T)$. Complete temperature dependences are important since we found it easy to be deceived when assigning relative magnitudes to activation energies based solely upon the depth of ρ_{xx} minima at a single temperature. Figure 2 shows typical Arrhenius plots for the $\frac{8}{5}$ state at several tilt angles. For $\theta<25°$ and $\theta>40°$ the ρ_{xx} data display activated behavior over almost two decades in resistivity. On the other hand, around 30°, where the $\frac{8}{5}$ minimum is split, the temperature dependence is complicated. Figure 3 shows the angular dependence of the observed activation energy. As θ increases from zero, Δ smoothly declines. Beyond about 30° Δ begins to rise again, eventually exceeding its value at $\theta=0$. In the range where the doublet is resolved, assignment of an activation energy is somewhat questionable. This is due to the complex interdependence of the two minima, especially at the lowest temperatures. For this narrow range of angles and where it appeared sensible from the Arrhenius plot, we used the high-temperature portion of the data to assign activation energies to one or both members of the doublet. This slight complication is rendered moot since the reentrant behavior of the activation energy is apparent from the data outside the doublet regime.

The data presented in Fig. 3 are all obtained at a fixed filling factor $\nu=\frac{8}{5}$ and hence a fixed perpendicular magnetic field $B_\perp \sim 5.95$ T. They are plotted against *total* magnetic field, $B_{tot}=B_\perp/\cos\theta$. This is the natural choice

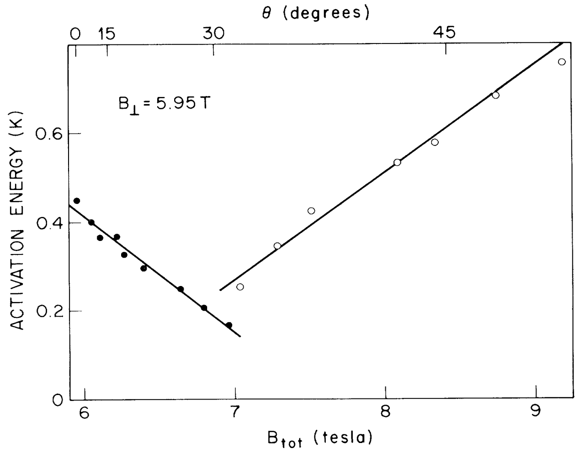

FIG. 3. Activation energy for $\frac{8}{5}$ FQHE vs $B_{\rm tot}$. Difference between symbols is relevant only in doublet regime around 30°. Solid and open symbols refer to low-field and high-field components, respectively.

if the spin Zeeman energy, which is proportional to $B_{\rm tot}$, dominates the tilt dependence of the activation energy. It is clear that a sharp transition occurs in the slope $d\Delta/dB_{\rm tot}$ at around 30°. The transition occurs in coincidence with the splitting of the ρ_{xx} minimum.

This behavior suggests a possible phase transition between two distinct quantum-liquid states $\nu=\frac{8}{5}$. However, the data in Fig. 3 cannot be directly interpreted as a crossover of two separate liquid ground-state energies. The activation energy Δ reflects the energy gap for exciting quasiparticles out of the ground state. Thus, a transition between two species of quasiparticles arising from the same ground state cannot be ruled out. Nevertheless, a plausible model for our results can be proposed by assuming the ground state at small angles (i.e., small Zeeman energy) is an unpolarized state analogous to Halperin's $\frac{2}{5}$ state. The $\frac{8}{5}$ and $\frac{2}{5}$ states are presumably closely related, at least in the absence of inter-Landau-level coupling, since $\nu=2=\frac{2}{5}+\frac{8}{5}$ represents the fully filled lowest Landau level. Halperin's unpolarized state is expected[2] to be lower in energy than the polarized state at sufficiently low magnetic field. As the Zeeman energy at $\nu=\frac{8}{5}$ is increased by tilting, the relative energy advantage of the unpolarized state decreases and eventually the polarized state will become the new ground state. Other contributions to the ground-state energy, such as exchange and correlation effects, depend to first approximation on $B_\perp$ alone and this is constant at fixed ν.

For the unpolarized fluid at small angles, spin-$\frac{1}{2}$ quasielectron and quasihole excited states must each be spin split. Thus, the energy cost for creating an unbound pair of such excitations is smallest when each aligns itself appropriately with the applied field. This implies an activation energy of the form $\Delta=\Delta_0-g\mu_B B_{\rm tot}$, where Δ_0 is the energy gap in the absence of a Zeeman term. We will assume both excitations have the same g factor. In addition, we will ignore any residual angular dependence of Δ_0 due, for example, to wave-function "squashing" effects.[13] From the slope $d\Delta/dB_{\rm tot}$ at small angles in Fig. 3 we find $g\sim0.4$ in remarkable agreement with recent spin-resonance measurements[20] on 2D electrons in GaAs. Interestingly, Furneaux, Syphers, and Swanson[13] obtain a similar result from tilted-field studies of the $\nu=\frac{2}{3}$ FQHE. Whether the g factor for the fractionally charged quasiparticles should be so close to that of uncorrelated electrons is not known.

In the high-angle, polarized state the excitation energies may also depend on the spin of the quasiparticles. At sufficiently low magnetic field, excitation of a spin-reversed quasielectron and spin-polarized quasihole out of the $\nu=\frac{1}{3}$ FQHE ground state has been predicted[9,10] to provide the lowest-energy gap, with the net Zeeman contribution being $+g\mu_B B_{\rm tot}$. Hence, we now write $\Delta=\Delta_0'+g\mu_B B_{\rm tot}$ with Δ_0' the gap in the absence of the Zeeman energy. The high-angle data in Fig. 3 yield a slope $d\Delta/dB_{\rm tot}$ which is nearly the same, but of opposite sign, as that of the low-angle unpolarized state. Hence, the same g factor obtains. At still higher total fields, excitation of polarized quasielectrons should be favored, yielding a roughly angle-independent gap. Such measurements require a larger magnet than is currently fitted on our apparatus.

There are aspects of our data which are not understood at present. In particular, the splitting of the ρ_{xx} minumum around the critical angle is intriguing. It may result from small density variations in the sample that lead to spatial separation of the polarized and unpolarized phases. The splitting is small, requiring a density variation of not more than $\sim2\%$ across the entire 5-mm sample. Such a level of inhomogeneity is not at all unusual. On the other hand, phase separation might occur even in the absence of inhomogeneities, perhaps in analogy with domain formation. A consistent picture describing the nature of the phase separation would be most interesting. A puzzling feature of our data concerns the lack of a discontinuity in the magnitude of Δ at the transition. Although the ground-state energies are becoming degenerate at this point, there is no obvious reason why the excitation gaps should also coincide.

We have also studied the $\nu=\frac{4}{3}$, $\frac{5}{3}$, and $\frac{7}{5}$ FQHE states in tilted fields. All show some variation in activation energy with tilt. They do not, however, display the qualitative reentrant behavior we find at $\nu=\frac{8}{5}$, at least within the same range of angle, field, and temperature. Further measurements on these states are underway.

In summary, we have presented evidence for a phase transition in the FQHE at a filling factor $\nu=\frac{8}{5}$. The transition is driven by tilting the magnetic field away from normal to the 2D plane. We propose a model for our observations in which the FQHE ground state at $\nu=\frac{8}{5}$ undergoes a transition from being spin unpolarized at small angles to spin polarized at larger angles. The angular dependence of the activation energies yields a g factor for quasiparticles of the FQHE that coincides with that found for uncorrelated 2D electrons in GaAs.

It is a pleasure to thank R. Willett, B. I. Halperin, A. H. MacDonald, and P. B. Littlewood for discussions and Kirk Baldwin for his fine technical help. S. M. Girvin also deserves thanks.

[1]B. I. Halperin, Helv. Phys. Acta **56**, 75 (1983).

[2]Tapash Chakraborty and F. C. Zhang, Phys. Rev. B **29**, 7032 (1984); F. C. Zhang and Tapash Chakraborty, Phys. Rev. B **30**, 7320 (1984).

[3]D. Yoshioka, J. Phys. Soc. Jpn. **55**, 3960 (1986).

[4]Mark Rasolt and A. H. MacDonald, Phys. Rev. B **34**, 5530 (1986).

[5]F. D. M. Haldane, in *The Quantum Hall Effect,* edited by R. E. Prange and S. M. Girvin (Springer-Verlag, New York, 1987).

[6]F. D. M. Haldane and E. H. Rezayi, Phys. Rev. Lett. **60**, 956 (1988).

[7]D. Yoshioka, A. H. MacDonald, and S. M. Girvin, Phys. Rev. B **38**, 3636 (1988).

[8]P. A. Maksym, in Proceedings of the International Conference on the Application of High Magnetic Fields to Semiconductor Physics, Würzburg, West Germany, 1988 (Springer-Verlag, Berlin, to be published).

[9]Tapash Chakraborty, Pekka Pietilainen, and F. C. Zhang, Phys. Rev. Lett. **57**, 130 (1986).

[10]E. H. Rezayi, Phys. Rev. B **36**, 5454 (1987).

[11]G. S. Boebinger, A. M. Chang, H. L. Stormer, and D. C. Tsui, Phys. Rev. Lett. **55**, 1606 (1985).

[12]R. G. Clark, J. R. Mallett, S. R. Haynes, P. A. Maksym, J. J. Harris, and C. T. Foxon, in Ref. 8.

[13]J. R. Furneaux, D. A. Syphers, and A. K. Swanson (to be published).

[14]R. L. Willett, J. P. Eisenstein, H. L. Störmer, D. C. Tsui, A. C. Gossard, and J. H. English, Phys. Rev. Lett. **59**, 1776 (1987).

[15]R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).

[16]J. P. Eisenstein, R. L. Willett, H. L. Stormer, D. C. Tsui, A. C. Gossard, and J. H. English, Phys. Rev. Lett. **61**, 997 (1988).

[17]F. F. Fang, and P. J. Stiles, Phys. Rev. **174**, 823 (1968).

[18]P. L. Gammel, D. J. Bishop, J.P. Eisenstein, J. H. English, A. C. Gossard, R. Ruel, and H. L. Störmer, Phys. Rev. B **38**, 10128 (1988).

[19]D. Greywall, Phys. Rev. B **33**, 7520 (1986).

[20]M. Dobers, K. v. Klitzing, and G. Weimann, Phys. Rev. B **38**, 5453 (1988).