

tions at the following epochs: 21 November 1997, 14 December 1997, 15 January 1998, 12 February 1998, 7 March 1998, 8 April 1998, 9 June 1998, 11 July 1998, 14 August 1998, 19 September 1998, 29 October 1998, 28 November 1998, 17 February 1999, and 17 March 1999. The calibrator sources 0420-014, OJ287, BL Lac, and 3C454.3 were used to compare the VLA and VLBA integrated polarization position angles. Estimated errors in the orien-

tation of the magnetic vectors vary from epoch to epoch, but usually lie in the range of 5° to 10° . Simultaneous observations at 43 GHz were also obtained for all observing epochs, with an estimated error in the orientation of the magnetic vectors between 7° and 15° .

28. Supported in part by the Spanish Dirección General de Investigación Científica y Técnica under grant PB97-1164, by the U.S. NSF through grant AST-

9802941, and by the Fulbright commission for collaboration between Spain and the United States. We thank J. M. Martí for comments on our manuscript. The VLBA is an instrument of the National Radio Astronomy Observatory, a facility of the U.S. NSF operated under cooperative agreement by Associated Universities Inc.

30 May 2000; accepted 3 August 2000

Quantum Hall Ferromagnetism in a Two-Dimensional Electron System

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Experiments on a nearly spin degenerate two-dimensional electron system reveals unusual hysteretic and relaxational transport in the fractional quantum Hall effect regime. The transition between the spin-polarized (with fill fraction $\nu = 1/3$) and spin-unpolarized ($\nu = 2/5$) states is accompanied by a complicated series of hysteresis loops reminiscent of a classical ferromagnet. In correlation with the hysteresis, magnetoresistance can either grow or decay logarithmically in time with remarkable persistence and does not saturate. In contrast to the established models of relaxation, the relaxation rate exhibits an anomalous divergence as temperature is reduced. These results indicate the presence of novel two-dimensional ferromagnetism with a complicated magnetic domain dynamic.

The two-dimensional electron system (2DES) under low temperatures and high magnetic fields has become a test bed for studying quantum phase transitions in low dimensions (1–3). Unlike classical phase transitions that are driven largely by thermal fluctuations, the phase transitions found in the quantum Hall effect (QHE) regime represent a class of zero-temperature phase transitions that are driven by strong electron-electron interaction. Under intense magnetic fields, quantization of the electronic motion into Landau levels quenches the kinetic energy and the interaction energy determines the thermodynamic properties of the underlying 2DES. At integral and certain fractional commensuration of the electron density and the applied magnetic flux, called filling fraction ν , gain in the interaction energy produces transitions to the quantum Hall states with Hall conductance $\sigma_{xy} = \nu e^2/h$ (1, 2). The collective, many-body nature of the QHE states is evident from the dissipationless longitudinal transport and the existence of energy gap in the excitation spectrum. The magnetotransport in the vicinity

of a transition between two QHE phases is well described in terms of critical behavior normally associated with a second-order phase transition. The universal scaling exhibited by the QHE transitions and the existence of well-defined critical exponents provide compelling evidence indicative of a zero-temperature quantum phase transition (3–5).

In addition to the transitions between two different QHE states, the translationally invariant quantum Hall phases can exhibit novel forms of two-dimensional ferromagnetism (6). Driven by gain in the anisotropy energy over the Coulomb exchange energy, the ferromagnetic transitions in the multicomponent QHE systems are accompanied by spatial ordering of pseudospin degrees of freedom represented by discrete quantum numbers such as electronic spin, Landau level index, and electron layer quantum number. Analogous to the ferromagnetically ordered electronic spins in magnetic systems, resulting quantum Hall ferromagnets represent a new class of low-dimensional ferromagnets with remarkable properties (7, 8). The distinguishing features of quantum Hall ferromagnets include broken symmetry arising from spontaneous magnetic ordering, existence of Goldstone mode in the ordered state, and topological objects as its low-energy excitations (6).

The underlying symmetry of the quantum Hall ferromagnet is determined by the associated pseudospin of the QHE phase. In case of even integral QHE states in single-layer

electron systems, the spin configuration of the associated Hall states becomes the pseudospin quantum number of the transformed state. Because the possible spin geometries are limited to a fully polarized state with all electron spins aligned parallel to the applied magnetic field and an unpolarized state with equal numbers of up and down spins, the resulting pseudospin degree of freedom possesses a bimodal, Ising symmetry. In double-layer 2DESs found in double quantum wells or a wide quantum well, the in-plane degree of freedom leads to a transition to a two-dimensional XY ferromagnet (9–11). In some QHE states, interplay of spin and the layer quantum numbers can produce a transition to an Ising ferromagnet in wide-well system (8, 12).

Our experiment was performed on a high-quality GaAs/AlGaAs heterostructure. Data was taken at pressures above 10 kbar where a large reduction in the magnitude of the electronic g factor favors formation of spin-unpolarized fractional quantum Hall effect (FQHE) states. The evolution of the $\nu = 2/5$ FQHE state with pressure indicates enhancement of spin fluctuations against their tendency to align parallel to the applied magnetic field. Under increasing pressure, the spin-unpolarized ground state competes against the spin-polarized state, leading to coexistence over a broad region of pressure. The transition to the pseudospin ferromagnetic state is distinguished by emergence of hysteretic transport and anomalous temporal relaxation of magnetoresistance. The observed correlation between hysteretic and relaxational evolution of magnetotransport points toward existence of intriguing domain dynamics in the pseudospin ferromagnet.

The density of the GaAs/AlGaAs heterostructure used in the experiment was $n = 3.5 \times 10^{11} \text{ cm}^{-2}$ with mobility of $\mu = 2.4 \times 10^6 \text{ cm}^2/\text{V s}$. A miniature beryllium-copper pressure cell was used to achieve high pressure. Samples were immersed inside a homogeneous hydrostatic medium that transmits uniform pressure to the sample. A small light-emitting diode was placed inside the pressure cell to illuminate the sample at low temperatures. A gradual reduction in the electronic density was found with increasing pressure.

The magnetoresistivity of a high-quality 2DES sample is shown (Fig. 1) in the hysteretic region found between 11 to 14 kbar of

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pressure. Although the FQHE states at $\nu = 2/3$, $3/5$, $1/2$, and $1/3$ are unchanged in this region of pressure, the $\nu = 2/5$ FQHE state demonstrates an intriguing evolution with increasing pressure. Between 11.2 and 13.5 kbar of pressure, the $\nu = 2/5$ FQHE state becomes progressively weaker at higher pressures and exhibits strong hysteresis between up and down magnetic field sweeps. A slight increase in the pressure to 13.8 kbar restores the $\nu = 2/5$ FQHE state. This type of reentrant behavior is also found in other FQHE states and provides a compelling evidence of spin transitions that alter the spin polarization of the associated FQHE states (13–17). Tilted field experiments show that the electronic spins are aligned completely parallel to the applied magnetic field for pressure below 13.5 kbar, whereas there are equal numbers of up and down electronic spins in the state for pressure above 13.5 kbar (18).

In the temperature dependence of the normalized hysteretic resistance obtained around $\nu = 2/5$ for a 2DES under 13 kbar of pressure (Fig. 2), the series of hysteretic resistance was obtained by subtracting the up and down magnetoresistance sweeps and dividing it by the average magnetoresistance. The hysteresis profile was found to be weakly dependent on the sweep rate. The hysteresis is most pronounced at the lowest temperatures, and several crossings between up and down traces reveal a complicated hysteresis curve. The fine features in the hysteresis resistance disappear at temperatures above 200 mK, and no hysteresis is detected above 300 mK. The observed hysteretic behavior under pressure points toward presence of unusual ground state in the vicinity of the $\nu = 2/5$ FQHE state. This is further reinforced

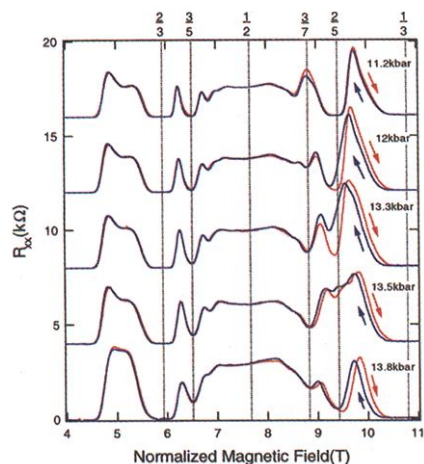


Fig. 1. Magnetoresistance of a high-quality GaAs/AlGaAs heterostructure at 40 mK of temperature under pressure near filling fraction $\nu = 2/5$. Arrows indicate the sweep direction. Magnetic field scale has been normalized to the highest pressure shown here for the sake of comparison. Each pressure data point represents individual cool-down after adjustments in the pressure.

by presence of logarithmic time dependence of magnetoresistance.

An extended logarithmic time dependence is found over a range of fillings and temperatures for $\nu = 2/5$ (Fig. 3). The time scans were initiated after sweeping from zero field and holding the magnetic field at $\nu = 2/5$. Typical time scans were performed over a 12- to 24-hour period, though scans lasting several days have been performed on some occasions. The logarithmic time dependence is robust and reproducible under repeated thermal and magnetic field cyclings. In all cases, the resistance at $\nu = 2/5$ increases logarithmically in time and no saturation was ever detected. As the temperature is lowered, magnetoresistance relaxation becomes enhanced and a larger change in the overall magnetoresistance was obtained. Similarly pronounced relaxation behavior was found at different levels of excitation currents. To quantify the magnetoresistance relaxation, we defined an effective relaxation rate in terms of the derivative of magnetoresistance (R_{xx}) with respect to logarithm of time, $dR_{xx}/d[\log(t)]$. The inset of Fig. 3 shows the effective relaxation rate $dR_{xx}/d[\log(t)]$ as a function of temperature T at $\nu = 2/5$. As the temperature is reduced, the relaxation rate is found to increase dramatically. Least square analysis shows that the relaxation rate diverges as $1/T^\alpha$ with $\alpha = 1.3$.

The temporal evolution of magnetoresistance at fillings around $\nu = 2/5$ at a temperature of 69 mK (Fig. 4) reveals a strong magnetic field dependence of the relaxation behavior. In particular, the logarithmic relaxation of magnetoresistance is limited to fillings between $\nu = 3/7$ and $1/3$, and no time dependence is found outside these filling factors. For fillings between $\nu = 3/7$ and $2/5$, magnetoresistance relaxes toward a larger resistance, whereas for fillings between $\nu = 2/5$ and $1/3$, magnetoresistance decreases as a

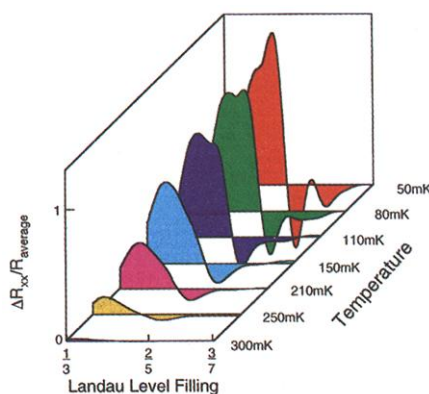


Fig. 2. Temperature dependence of normalized hysteretic resistance around $\nu = 2/5$ for a heterostructure sample under 13 kbar of pressure. The hysteretic magnetoresistance was obtained by subtracting the up and down magnetoresistance sweeps and dividing it by the average magnetoresistance.

function of time. For both behaviors, no saturation in magnetoresistance was found.

Summarizing the magnetic field dependence of the relaxation rate $dR_{xx}/d[\log(t)]$ at 69 mK (Fig. 5A), a sign change in the relaxation rate occurs at a magnetic field slightly above that corresponds to $\nu = 2/5$. Most remarkably, the magnetic field dependence of the relaxation rate reveals a striking similarity to the hysteretic loop derived from magnetic field sweeps. Figure 5B illustrates the hysteresis in magnetoresistance obtained by subtraction of up-sweep from the down-sweep data. The correlation between the hysteresis and the logarithmic relaxation is highly suggestive of common origin for both hysteresis and the magnetoresistance relaxation. In particular, the temporal evolution of magnetoresistance is suggestive of an intriguing dynamics in the vicinity of the $\nu = 2/5$ FQHE state.

The theoretical studies of quantum Hall ferromagnetism have shown that certain quantum Hall states with two nearly degenerate pseudospin Landau levels are susceptible to ferromagnetic ordering (7, 8). In case of the $\nu = 2/5$ FQHE state, the coexistence region of the two degenerate—polarized and unpolarized—spin configurations under pressure can be mapped to an equivalent pseudospin ground state. Gain in the anisotropy energy leads to spontaneous symmetry breaking and a transition to a two-dimensional easy axis (Ising) ferromagnet ensues. Local potential fluctuations lead to nucleation of domains that are pinned by defects, leading to

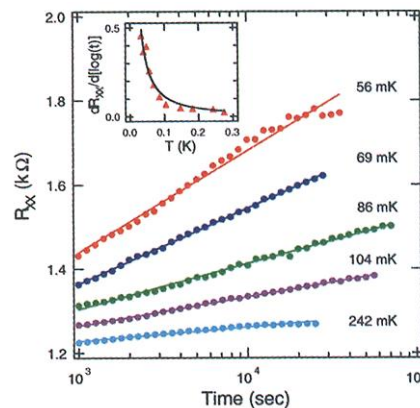


Fig. 3. Time evolution of the magnetoresistance at $\nu = 2/5$ from a GaAs/AlGaAs heterostructure sample under 13 kbar of pressure for various temperatures. Time scans are initiated immediately after the magnetic field sweep is finished. Because of slight eddy current heating that occurs from magnetic field sweeps, a small temperature drift (~ 2 to 3 mK) is detected during the initial ~ 20 min necessary to equilibrate the temperature. Consequently, only the stable temperature data after initial 1000 s is shown. Magnetoresistance has been offset for the sake of clarity. (Inset) Plot of relaxation rate $dR_{xx}/d[\log(t)]$. The solid line represents a curve fit by $1/T^\alpha$, where $\alpha = 1.3$.

complicated domain geometry. The anomalous magnetotransport observed in the vicinity of the spin transition of the $\nu = 2/5$ FQHE state provides a compelling evidence of such a magnetic ordering in the FQHE regime.

Near $\nu = 2/5$, the magnetic field sweeps alter the energetics of the pseudospin interaction in the quantum Hall ferromagnet, causing modification of the Zeeman splitting between competing spin configurations. Consequently, it becomes necessary for individual pseudospin domains to grow, shrink, or coalesce in response to the changes in the local energetics. Irreversible changes in the local spin configurations occur as a result of complex domain dynamics. As the distribution of up and down pseudospin domains is altered, history-dependent hysteresis accompanies the magnetic field sweeps, in close analogy with conventional ferromagnets.

The temperature dependence of hysteresis (Fig. 2) largely illustrates the strength of the magnetic ordering at low temperatures. Due to the coupling between the electrical current and the pseudospin degree of freedom through enhanced scattering at the domain boundaries, the hysteretic loops largely mirror the temperature dependence of the order parameter in the quantum Hall ferromagnet. Coupled to the pseudospin magnetization, the hysteresis gradually weakens and disappears at high temperatures. The ground state below 300 mK may be best described as an ordered ferromagnet and at high temperatures, a pseudospin paramagnet. Measurement of thermodynamic quantities such as specific heat (19, 20) and magnetization (21) is ex-

pected to yield a similar behavior.

The logarithmic time dependence exhibited by magnetoresistance in the vicinity of $\nu = 2/5$ is indicative of relaxation of magnetic domains in the quantum Hall ferromagnet. The correlation between the relaxation rate and the hysteresis likely arises from existence of energy-dependent interaction between the domains within the sample. Depending on the nature of interaction and magnitude of the potential barrier, relaxation between neighboring domains can occur at vastly different time scales (22, 23). The motion between two domains with identical magnetization involves crossing a region of opposite magnetization that acts as a potential energy barrier. The domain wall energy of such a barrier is proportional to $\sqrt{t\kappa}$, where t represents the anisotropy energy and κ is the exchange stiffness. Magnetic pressure exerted on the domain walls produces slippage and propagation of domains through the sample. Such a relaxation process may be generically described in terms of hopping between neighboring minima of potential wells that are driven via thermal activation at finite temperatures (24) and quantum tunneling near zero temperature (25–28).

In a large specimen possessing a distribution of various domain sizes and shapes, the collective response of the magnetic domains can span an extended time range due to availability of response at all time scales. In the vicinity of hard potentials in which two domains are separated by a large barrier, low probability of tunneling and thermal activation produce slow relaxation. In contrast, the tendency for relaxation is enhanced near soft

potentials where domains can readily move and slide against each other. As a result, presence of a broad distribution of domain energies manifests in a logarithmic time dependence instead of exponential or power-law time dependence (22). Although disorder can modify the relaxation behavior, systems with strong residual interaction between neighboring domains exhibit slow, logarithmic relaxation (23).

Relaxation processes with time scale comparable to our system are found in spin glasses (29) and low-dimensional ferromagnets (30–32). Aspects of relaxation such as randomness of local spin configurations and broad distribution of relevant energy scales are common between these systems. However, a salient feature of our experiment is the relaxation of magnetoresistance instead of magnetization. This is accountable in terms of domain growth or shrinking (33). As the scattering at domain walls enhances the resistance, the fractional change in the overall magnetoresistance is proportional to the total length of the domain wall in the system. The relaxation toward a larger resistance between $\nu = 3/7$ and $2/5$ (Fig. 4) may be attributed to the overall growth of domain walls in the quantum Hall ferromagnet. On the other hand, the relaxation toward a smaller resistance between $\nu = 2/5$ and $1/3$ indicates overall reduction in the total length of domain walls. The domain growth or shrinking in quantum Hall ferromagnets is presumably governed by the Zeeman energy difference between neighboring pseudospin domains. Existence of domains in the sample is also supported by strong nonlinearity in the current-voltage characteristics of the $\nu = 2/5$ FQHE (34).

One intriguing feature of the data is the temperature dependence of relaxation rate. The divergence of the observed relaxation rate with temperature cannot be easily reconciled within a simple model of thermally activated relaxation. In classical models of relaxations, thermally activated systems exhibit a relaxation rate proportional to temperature (24). In systems in which relaxations are driven by quantum tunneling, the relaxation rate becomes independent of temperature at low temperatures (25–28). Consequently, the divergence in the temperature dependence of the relaxation rate points to some unconventional relaxation process in the quantum Hall ferromagnet. Similar divergence in the relaxation rate at low temperature has been observed in some low-dimensional ferromagnets (30–32). Because there is no theoretical description of relaxation in a quantum Hall systems at this time, it remains unclear what type of relaxation processes dominate in a quantum Hall ferromagnet. Because disorder and Coulomb interaction play a nontrivial role in the QHE, the possi-

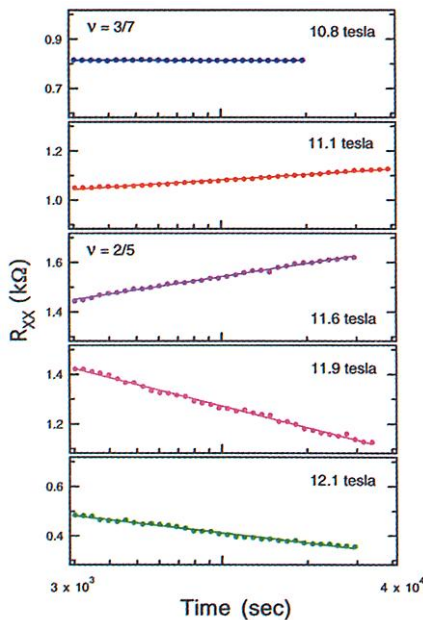


Fig. 4. Time evolution of magnetoresistance for different magnetic fields around $\nu = 2/5$. For the sake of comparison, the same scale is used for different magnetic fields. The time traces are taken at a temperature of 69 mK.

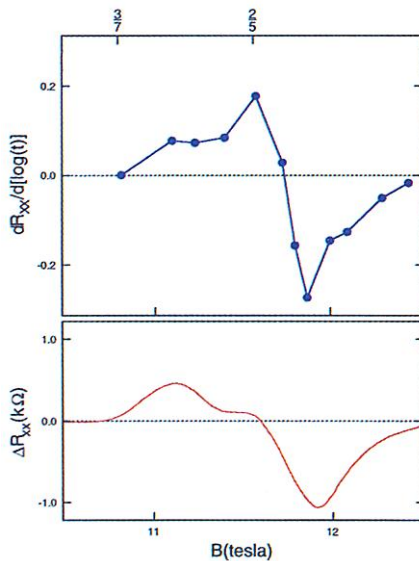


Fig. 5. (A) Magnetic field dependence of the relaxation rate at temperature of 69 mK. (B) Hysteresis in magnetoresistance, ΔR_{xx} , obtained by subtracting the up- from down-sweep magnetoresistance around the $\nu = 2/5$ fractional quantum Hall effect.

bility of some relaxation process unique to quantum Hall ferromagnets cannot be ruled out at this time.

In particular, coupling to nuclear spins may be responsible for the origin of the slow relaxation in the vicinity of the $\nu = 2/5$ FQHE. In GaAs, the lattice nuclei consist of $S = 3/2$ nuclear isotopes of ^{69}Ga and ^{71}Ga and ^{75}As with which conduction electrons interact through hyperfine coupling. In general, the coupling between electronic and nuclear spins is extremely weak and the relaxations of nuclear spins occur at a negligibly slow rate. However, presence of low-energy spin excitations has been shown to enhance the coupling between the spins of electrons and nuclei in the quantum Hall regime. At $\nu = 1$, presence of electron spin texture excitation known as Skyrmions (1, 6) leads to an enhanced nuclear spin diffusion and gives rise to a large heat capacity at low temperatures (19, 20). An earlier experiment also has shown that nuclear spin polarization can produce hysteresis and memory effects in the magnetotransport (35). Consequently, enhanced coupling to nuclear spins cannot be ruled out in our experiment. A possible route of coupling between nuclear and electronic spins is through existence of a Skyrmion-like excitation associated with the $\nu = 1/3$ FQHE state. Because the $\nu = 2/5$ FQHE state can be considered to be a daughter state of the $\nu = 1/3$ state, Skyrmionic excitations from the $\nu = 1/3$ FQHE state may be responsible for the coupling to the nuclear spin in the $\nu = 2/5$. Alternatively, the quasiparticles from the $\nu = 1/3$ FQHE that nucleate the $\nu = 2/5$ FQHE couple to the nuclear spins may be giving rise to the observed slow dynamics. Further experiments will be necessary to elucidate the coupling to nuclear spin in the FQHE regime.

In conclusion, we have observed transport and relaxational behavior associated with the ferromagnetic ordering in the FQHE regime of a 2DES. Our experiment demonstrates a previously unknown type of magnetic ordering of FQHE states and a slow, aging effect associated with multidomain structure. Further experiments should reveal additional properties of this many-body magnetism. In particular, we speculate on the nature of quantum Hall magnetism at micrometer or sub-micrometer lengthscales. Study of single domain dynamics in the quantum Hall ferromagnets should reveal time-dependent phenomena such as macroscopic quantum tunneling, switching, and telegraphic behaviors. Detection of such effects should lead to greater understanding of many-body magnetism and quantum mechanics at small lengthscales.

References and Notes

1. S. Das Sarma and A. Pinczuk, Eds., *Perspectives on Quantum Hall Effects* (Wiley, New York, 1997).
2. R. E. Prange and S. M. Girvin, Eds., *The Quantum Hall Effect* (Springer-Verlag, New York, 1990).

3. S. L. Sondhi, S. M. Girvin, J. P. Carini, D. Shahar, *Rev. Mod. Phys.* **69**, 315 (1997).
4. H. P. Wei, D. C. Tsui, A. M. M. Pruisken, *Phys. Rev. B* **33**, 1488 (1986).
5. H. P. Wei, D. C. Tsui, M. A. Paalanen, A. M. M. Pruisken, *Phys. Rev. Lett.* **61**, 1294 (1988).
6. S. M. Girvin and A. H. MacDonald, in (1), pp. 161–224.
7. T. Jungwirth, S. Shukla, L. Smrcka, M. Shayegan, A. H. MacDonald, *Phys. Rev. Lett.* **81**, 2328 (1998).
8. A. H. MacDonald, R. Rajaraman, T. Jungwirth, *Phys. Rev. B* **60**, 8817 (1999).
9. S. Q. Murphy, J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer, K. W. West, *Phys. Rev. Lett.* **72**, 728 (1994).
10. K. Yang et al., *Phys. Rev. Lett.* **72**, 732 (1994).
11. A. Sawada et al., *Phys. Rev. Lett.* **80**, 4534 (1998).
12. V. Piazza et al., *Nature* **402**, 638 (1999).
13. J. P. Eisenstein, H. L. Stormer, L. N. Pfeiffer, K. W. West, *Phys. Rev. Lett.* **62**, 1540 (1989).
14. R. G. Clark et al., *Phys. Rev. Lett.* **62**, 1536 (1989).
15. J. P. Eisenstein, H. L. Stormer, L. N. Pfeiffer, K. W. West, *Phys. Rev. B* **41**, 7910 (1990).
16. L. W. Engel, S. W. Hwang, T. Sajoto, D. C. Tsui, M. Shayegan, *Phys. Rev. B* **45**, 3418 (1992).
17. R. R. Du et al., *Phys. Rev. Lett.* **75**, 3926 (1995).
18. H. Cho et al., *Phys. Rev. Lett.* **81**, 2522 (1998).
19. V. Bayot, E. Grivei, J. M. Beuken, S. Melinte, M. Shayegan, *Phys. Rev. Lett.* **79**, 1718 (1997).
20. S. Melinte, E. Grivei, V. Bayot, M. Shayegan, *Phys. Rev. Lett.* **82**, 2764 (1999).
21. S. A. J. Wieggers et al., *Phys. Rev. Lett.* **79**, 3228 (1997).
22. J. J. Prejean and J. Souletie, *J. Phys. (Paris)* **41**, 1335 (1980).
23. D. K. Lottis, R. M. White, E. D. Dahlberg, *Phys. Rev. Lett.* **67**, 362 (1991).
24. W. F. Brown, *Phys. Rev.* **130**, 1677 (1963).
25. E. M. Chudnovsky and L. Gunther, *Phys. Rev. Lett.* **60**, 661 (1988).
26. M. Enz and R. Schilling, *J. Phys. C* **19**, 1765 (1986).
27. J. L. van Hemmen and A. Suto, *Europhys. Lett.* **1**, 481 (1986).
28. L. Gunther and B. Barbara, Eds., *Quantum Tunneling of the Magnetization* (North American Treaty Organization Advanced Study Institute, Kluwer, Dordrecht, Netherlands, 1995), series E, vol. 301.
29. E. Vincent, J. Hammann, M. Ocio, J. P. Bouchaud, L. F. Cugliandolo, in *Complex Behaviour of Glassy Systems: Proceedings of the XIV Sitges Conference*, Sitges, Spain, M. Rubi and C. Perez-Vicente, Eds. (Springer-Verlag, Berlin, 1997), pp. 184–219 and references therein.
30. H. Yamazaki, G. Tatara, K. Katsumata, K. Ishibashi, Y. Aoyagi, *J. Magn. Magn. Mater.* **156**, 135 (1996).
31. J. E. Wegrowe et al., *Phys. Rev. B* **52**, 3466 (1995).
32. J. E. Wegrowe et al., *Europhys. Lett.* **38**, 329 (1997).
33. F. Alberici-Kious, J. P. Bouchaud, L. F. Cugliandolo, P. Doussineau, A. Levelut, *Phys. Rev. Lett.* **81**, 4987 (1998).
34. J. Eom et al., unpublished data.
35. M. Döbers, K. v. Klitzing, J. Schneider, G. Weimann, K. Ploog, *Phys. Rev. Lett.* **61**, 1650 (1988).
36. We thank A. MacDonald and G. Mazenko for useful discussions. The work at the University of Chicago was supported in part by the Material Research Science and Engineering Center Program of the National Science Foundation (grant no. DMR-9808595) and the David and Lucille Packard Foundation.

28 April 2000; accepted 23 August 2000

Imaging Coherent Electron Flow from a Quantum Point Contact

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Scanning a charged tip above the two-dimensional electron gas inside a gallium arsenide/aluminum gallium arsenide nanostructure allows the coherent electron flow from the lowest quantized modes of a quantum point contact at liquid helium temperatures to be imaged. As the width of the quantum point contact is increased, its electrical conductance increases in quantized steps of $2e^2/h$, where e is the electron charge and h is Planck's constant. The angular dependence of the electron flow on each step agrees with theory, and fringes separated by half the electron wavelength are observed. Placing the tip so that it interrupts the flow from particular modes of the quantum point contact causes a reduction in the conductance of those particular conduction channels below $2e^2/h$ without affecting other channels.

The use of scanned probe microscopes (SPMs) in the study of mesoscopic physics has grown rapidly and has allowed direct imaging of a wide range of phenomena, including quantum corrals (1–3), electron flow through nanostructures (4, 5), charge distribution and photoactivity of dopant atoms (6), quantum Hall–effect edge states and liquids

(7–9), and spectra of metallic nanoclusters (10). Quantum point contacts (QPCs) formed in two-dimensional electron gases (2DEGs) have attracted strong attention. After the initial discovery that they show conductance quantization (11, 12), QPCs have been used in a wide variety of investigations, including transport through quantum dots, the quantum Hall effect, magnetic focusing, and the Aharonov-Bohm effect (13). Electron flow from QPCs has been studied both theoretically and experimentally (14–15). Although the basic concepts are understood, many interesting issues remain. Because they play such an important role in the operation of mesoscopic devices, QPCs make an

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