

Tunneling into Ferromagnetic Quantum Hall States: Observation of a Spin Bottleneck

H. B. Chan and R. C. Ashoori

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

L. N. Pfeiffer and K. W. West

Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

(Received 26 May 1999)

We explore the characteristics of equilibrium tunneling of electrons from a 3D electrode into a high mobility 2D electron system. For most noninteger filling factors, we find that tunneling can be characterized by a single, well-defined tunneling rate. However, for spin-polarized quantum Hall states ($\nu = 1, 3$, and $1/3$) tunneling occurs at two distinct rates that differ by up to 2 orders of magnitude. The dependence of the two rates on temperature and tunnel barrier thickness suggests that slow in-plane spin relaxation creates a bottleneck for tunneling of electrons.

PACS numbers: 73.20.Dx, 71.45.Gm, 73.40.Gk

The interplay between Zeeman coupling of electronic spins to an applied magnetic field and Coulomb interactions among electrons leads to remarkable spin configurations of quantum Hall systems. For instance, around quantum Hall filling factor $\nu = 1$, powerful exchange interactions align electron spins to form a nearly perfect ferromagnet [1]. Theorists predict that the elementary charge excitations of this $\nu = 1$ quantum Hall state consist of spin textures known as Skyrmions [2]. The small value of the Zeeman energy compared to the Coulomb energy in GaAs gives rise to the appropriate conditions for the formation of Skyrmions. Nuclear spin resonance and magneto-optical absorption experiments [3] have shown that the spin polarization of the 2D electrons attains a maximum at $\nu = 1$ and falls off sharply on either side. This rapid loss of spin polarization away from $\nu = 1$ provides the strongest evidence for the existence of Skyrmions. Transport and heat capacity measurements [4] offer additional support for the Skyrmion picture.

Tunneling experiments have demonstrated a capability to probe electron-electron interactions. For instance, tunneling of electrons into 2D systems in a magnetic field displays characteristics of a pseudogap [5–8] created by Coulomb interactions among electrons. Given the measured and predicted richness of the spin properties of quantum Hall systems, we decided to explore whether tunneling could also prove useful for revealing effects of electronic spins [9]. Such a study should prove most interesting for the ferromagnetic quantum Hall states, but experimental data for tunneling in these regimes have been limited. The major obstacle is that the in-plane conductance of the 2D system drops to near zero around $\nu = 1$. As a result the tunneling charge cannot be collected and measured via conduction in the 2D plane. It is possible to use capacitance techniques to circumvent this problem [5,6]. However, complete characterization involves time-resolved measurements described here or measurements over a broad frequency range that have not been previously performed on high mobility samples.

In this Letter, we describe measurements of tunneling from a 3D electrode into a high mobility 2D electron system in a GaAs/AlGaAs heterostructure at $\nu = 1$. Using a novel capacitance technique reported previously [7], we detect the tunneling current into both localized and delocalized states. Here, we focus on the effects of electronic spins on tunneling by detecting the equilibrium tunneling of electrons in real time, instead of studying the tunneling pseudogap through conventional measurement of nonlinear I - V curves. We observe that the process of electron tunneling into ferromagnetic quantum Hall states differs qualitatively from tunneling into other filling fractions: electrons tunnel into ferromagnetic quantum Hall states at two distinct rates. Some electrons tunnel into the 2D system at a fast rate while the rest tunnel at a rate up to 2 orders of magnitude slower. We observe such a large ratio of tunneling rates only in spin-polarized quantum Hall states ($\nu = 1, 3$, and $\leq 1/3$) in samples of highest mobility. This large ratio of two distinct tunneling rates does not appear at even-integer filling fractions. Our detailed study of the dependence of the two rates on temperature, magnetic field, and tunnel barrier thickness indicates that slow in-plane spin relaxation leads to a bottleneck for tunneling and gives rise to the double tunneling rate phenomenon.

Figure 1a shows a schematic of our samples. The following sequence of layers is grown on $n + \text{GaAs}$ substrate: 6000 Å $n + \text{GaAs}$, 300 Å GaAs spacer layer, AlGaAs/GaAs tunnel barrier, 175 Å GaAs quantum well, 700 Å AlGaAs (undoped) blocking barrier, and 1.3 μm $n + \text{GaAs}$ cap layer. Samples *A* and *C* have AlGaAs/GaAs superlattice tunnel barriers of thickness 193 Å and 147 Å, respectively. For sample *B*, the tunnel barrier is made of 130 Å AlGaAs. A major advantage of our structure is the complete absence of silicon dopants in the AlGaAs layers, eliminating the main source of disorder in the 2D electron system (2DES). Electrons are attracted into the quantum well from the bottom $n + \text{GaAs}$ electrode by application of a positive dc bias to the cap layer. As a result, the mobility of our samples is expected to

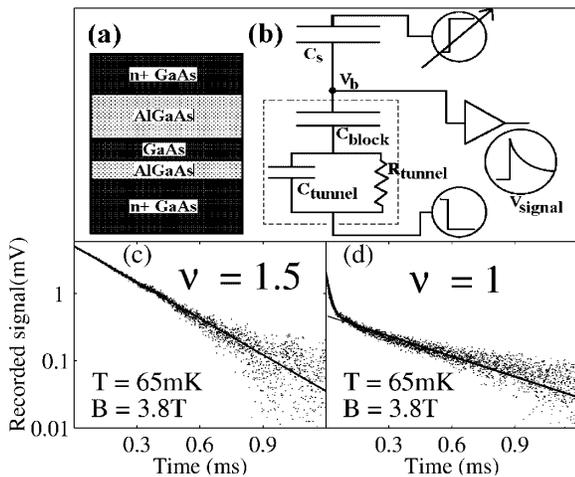


FIG. 1. (a) Structure of our samples. (b) External circuit used to measure R_{tunnel} . The sample can be modeled by linear circuit elements (box) when the excitation voltage is smaller than kT . (c) Recorded signal (amplification of V_b) decays exponentially at $\nu = 1.5$. The line is an exponential fit to the data. (d) Recorded signal is nonexponential at $\nu = 1$. The thin line is an exponential fit to the data. The thick line is a fit to the data using Eq. (1).

be higher than $10^6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, which is consistently achieved in modulation doped GaAs/AlGaAs quantum well heterostructures grown in the same molecular-beam epitaxy (MBE) machine. The dc bias to the cap layer also permits a variation of the 2D electron density from depletion to $3 \times 10^{11} \text{ cm}^{-2}$.

An earlier experiment [7] measured the single particle density of states of a similar structure with lower 2D electron mobility in a magnetic field using “time domain capacitance spectroscopy.” We use the same technique to study the high mobility samples. Here, we focus on “zero-bias” tunneling into the 2DES measured by applying excitation voltages smaller than kT . In this equilibrium tunneling regime [5], we model the tunnel barrier by a capacitor C_{tunnel} shunted by a resistor R_{tunnel} , while a capacitor C_{block} represents the blocking barrier (Fig. 1b). Figure 1b also shows the capacitance bridge used to measure R_{tunnel} . Voltage steps of opposite polarity are applied to the top electrode of the sample and to one plate of a standard capacitor C_s . The other plate of C_s and the bottom electrode of the sample are electrically connected, and the voltage V_b at this balance point is amplified and recorded as a function of time. When the excitation voltage amplitude is smaller than kT , the tunneling resistance R_{tunnel} is independent of excitation voltage across the tunnel barrier. The equivalent circuit of the bridge consists of linear circuit elements and therefore we expect V_b to decay exponentially.

Figure 1c plots on a semilog scale the recorded voltage as a function of time at $\nu = 1.5$. The signal decays exponentially for more than 2 orders of magnitude. In general, we observe such an agreement with an exponential decay when ν is close to half integer. This indicates that for fill-

ing factors at which the 2DES is compressible, electrons tunnel into the 2DES at a single rate and the equivalent circuit model in Fig. 1b adequately describes the sample. Figure 1d shows a drastically different recorded signal at $\nu = 1$. The decay is clearly nonexponential. We can fit it well with a sum of two exponential decays with different time constants and prefactors,

$$V(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2). \quad (1)$$

In other words, at $\nu = 1$ electrons tunnel from the 3D electrode into the 2DES at two distinct rates. Some electrons tunnel at a fast rate while the rest tunnel at a significantly slower rate. We emphasize that the measurement is performed in the linear response limit of R_{tunnel} by applying an excitation voltage across the tunnel barrier ($8.9 \mu\text{V}$) comparable to the temperature (65 mK). This eliminates the possibility that the nonexponential relaxation at $\nu = 1$ is due to a voltage dependent R_{tunnel} caused by the magnetic field induced energy gap in tunneling [5–8].

Figure 2 shows the dependence of the relaxation rates on gate voltage at a fixed magnetic field of 3.8 T. At each gate voltage in Fig. 2, we record a time trace similar to the ones in Figs. 1c and 1d. For gate voltages at which we can fit the time trace by a single exponential decay as in Fig. 1c, we plot the relaxation rate as a hollow square. When it is necessary to use a sum of two exponential decays [Eq. (1)] to fit the signal as in Fig. 1d, filled triangles and circles represent the corresponding fast and slow relaxation rates ($1/\tau_1$ and $1/\tau_2$) obtained, respectively. Figure 2 indicates that tunneling occurs at two distinct rates near integer ν , while electrons tunnel at a single rate when the 2DES is compressible near half integer fillings.

At integer ν , the in-plane conductance vanishes as the electronic states at the chemical potential become localized. Inhomogeneity, such as monolayer fluctuations in the tunnel barrier thickness, gives rise to nonuniform tunneling rates into different lateral positions of the 2D plane. In Fig. 2, the two relaxation rates at $\nu = 2$ differ approximately by a factor of 3 and can be explained well by this argument. In contrast, the fast and slow relaxation

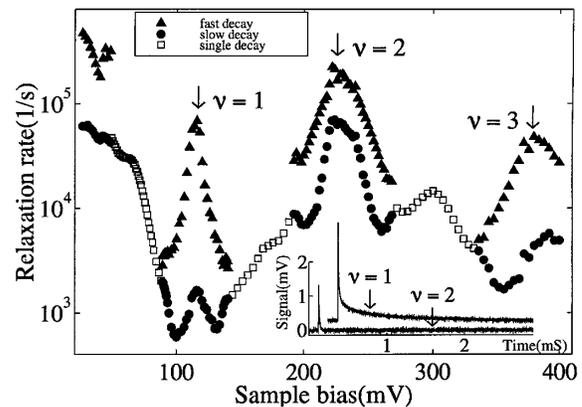


FIG. 2. Dependence of the relaxation rate of the exponential decay on sample bias for sample B at 3.8 T and 65 mK. Inset: Comparison of recorded signal at $\nu = 1$ and $\nu = 2$.

rates at $\nu = 1$ differ by about a factor of 60. Relaxation rate differences of such magnitude cannot be explained by sample inhomogeneity. Moreover, the ratio of the two rates also behaves differently around $\nu = 1$ and $\nu = 2$ as ν deviates from exact integer value. In Fig. 2, the ratio of the two rates remains almost constant around $\nu = 2$. On the other hand, this ratio increases as ν approaches 1, attaining a peak value of 60 at $\nu = 1$. The inset of Fig. 2 illustrates the difference between time traces at $\nu = 1$ and $\nu = 2$. Both traces decay at a comparable rate initially (with time constants $\sim 10 \mu\text{s}$), whereas only the $\nu = 1$ signal contains an additional slower decaying component with a time constant of about $600 \mu\text{s}$.

The $\nu = 1$ and $\nu = 2$ quantum Hall states have the common characteristic that an energy gap exists at the chemical potential, albeit of different origins. At $\nu = 2$, the cyclotron gap is present even when correlation effects are neglected. On the other hand, the existence of an energy gap at $\nu = 1$ is a many body phenomenon. The interactions among electrons lead to ferromagnetic order and the formation of an exchange energy gap. In our experiment, we measure equilibrium tunneling by applying excitation voltages at least 100 times smaller than the Coulomb energy. In an ideal 2DES without disorder at $\nu = 1$, there are no states at the chemical potential into which electrons can tunnel. Any tunneling current detected must arise from the broadening of the Landau levels due to disorder. Consider a 2DES with inhomogeneous density. When the bulk filling factor is 1, regions with local density higher (lower) than the bulk density have filling fraction $\nu > 1$ ($\nu < 1$) into which electrons with minority (majority) spin tunnel. To our knowledge, theories do not presently predict that the tunneling rates of electrons with spin up and down are significantly different. While a difference in the tunneling rates for electrons with opposite spins can lead to the observation of two relaxation rates in our experiment, we show below that this hypothesis is inadequate to explain our data.

Figure 3a plots the relaxation rate vs gate voltage at 5.7 T. Similar to the data at a lower field in Fig. 2, tunneling occurs at two distinct rates around $\nu = 1$. In addition to the relaxation rates, we also show the prefactors of the exponential fits [A_1 and A_2 in Eq. (1) scaled by a constant factor] in Fig. 3b. Around $\nu = 1$, A_1 and A_2 are proportional to the amount of charge tunneling at the fast and slow rates, respectively. For the slow decay, the prefactor (plotted as circles) has a minimum at $\nu = 1$ while the prefactor for the fast decay (plotted as triangles) instead has a maximum. Consider a 2DES with inhomogeneous density at bulk filling factor $\nu = 1$. As the bulk density is increased the fraction of regions with local filling factor $\nu < 1$ decreases monotonically and vice versa for regions with local $\nu > 1$. If electrons with up and down spins tunnel at different rates, we expect the prefactors of the fast (slow) decay to be an increasing (decreasing) function of bulk density around $\nu = 1$, contrary to Fig. 3b. Therefore the observation of

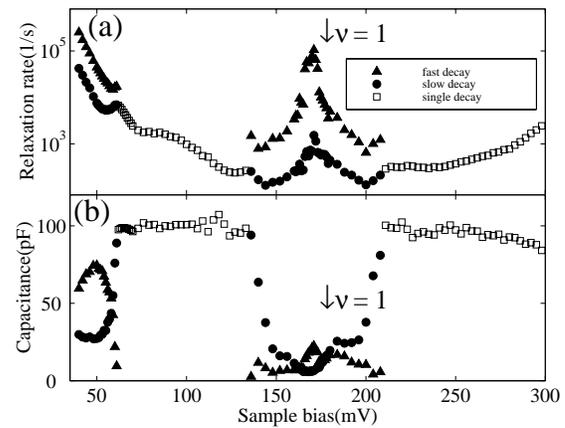


FIG. 3. (a) Relaxation rate vs sample bias for sample *B* at 5.7 T. (b) Sample capacitance charged at the fast and slow rates vs sample bias. The two capacitance contributions refer to the ratio of the charge tunneling at the fast and slow rates [proportional to A_1 and A_2 , respectively, in Eq. (1)] to the constant excitation voltage ($9 \mu\text{V}$).

two relaxation rates at $\nu = 1$ cannot be trivially explained by a difference in the tunneling rates for electrons with up and down spins.

Figure 4 shows the temperature dependence of the two relaxation rates at $\nu = 1$ for three magnetic field strengths. At each field, we adjust the density to maintain the filling factor at $\nu = 1$. Both the slow and fast rates have a rather weak temperature dependence at low temperature for all three magnetic fields. The weak temperature dependence of the slow rate persists up to a temperature beyond which the slow rate speeds up significantly and the double tunneling rate phenomenon recedes. This onset of strong temperature dependence shifts to a higher temperature as the magnetic field is increased. From Fig. 4, we identify the characteristic temperature T_C at which the slow rate rises to a value equal to the geometric mean of the two tunneling rates at the lowest temperature (as indicated by the arrows) and plot it as a function of the magnetic field in the inset of Fig. 4. In this range of magnetic field, T_C ($\sim 450 \text{ mK}$ at

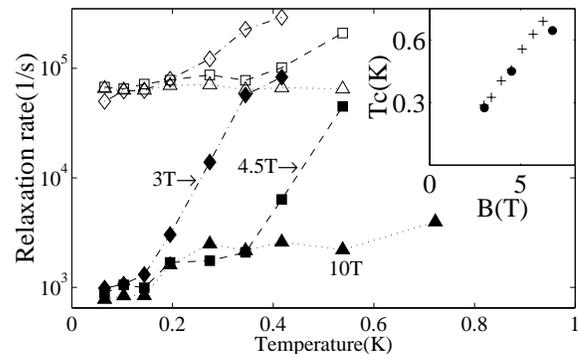


FIG. 4. Temperature dependence of the fast (hollow) and slow (filled) relaxation rates for sample *B* at $\nu = 1$ for 3 T (diamonds), 4.5 T (squares), and 10 T (triangles). Inset: Characteristic temperature T_C (defined in text) vs magnetic field for sample *A* (crosses) and sample *B* (circles).

4.5 T) sets an energy scale that is much smaller than the Coulomb energy and the cyclotron energy (106 and 90 K at 4.5 T, respectively). The only obvious energy scale comparable to T_C is the Zeeman energy (1.3 K at 4.5 T). In other words, the development of the exchange energy gap at $\nu = 1$ is not a sufficient condition for tunneling to occur at two rates. For instance, at a field of 4.5 T and temperature of 1 K, a minimum in the capacitance of the 2DES is clearly observable at $\nu = 1$, indicating the existence of the exchange gap. However, as Fig. 4 shows, electrons no longer tunnel at two rates at this temperature and field. This demonstrates that spin effects are crucial in explaining why tunneling occurs at two rates at $\nu = 1$.

Possible explanations of the double tunneling rate phenomenon at $\nu = 1$ can generally be classified into two approaches. In the first approach, electrons are assumed to tunnel into the 2DES at a fast rate. The system then undergoes a certain form of relaxation, possibly spin related, within the 2D plane at the slow rate. Through the spin relaxation, the 2DES is able to accept more electrons tunneling from the 3D electrode giving rise to a second, slower tunneling rate. Unlike the fast tunneling rate, the slow relaxation is expected to have no dependence on the thickness of the tunnel barrier. A second approach considers the $\nu = 1$ system bifurcating into separate regions into which electrons tunnel at different rates. In contrast to the first scenario, the ratio of the two rates should remain constant as the tunnel barrier thickness is varied.

In order to differentiate between these two possibilities, we measure the relaxation rates for samples grown in the same MBE machine with various tunnel barrier thickness. The results are listed in Table I. At $\nu = 1/2$, we observe a single relaxation rate in all samples. The relaxation rate increases by more than 3 orders of magnitude as the tunnel barrier becomes more transparent. In contrast, the slow rate at $\nu = 1$ is relatively insensitive to the thickness of the tunnel barrier, varying by less than a factor of 10. This provides strong evidence that the slow tunneling rate at $\nu = 1$ is largely due to relaxation within the 2D plane. Since the slow tunneling rate appears only in spin-polarized quantum Hall states at temperatures lower than the Zeeman energy, we describe it as arising from a “spin bottleneck” in which in-plane spin relaxation must proceed before additional electrons can tunnel into the system.

One example of in-plane relaxation that might be relevant is the formation of Skyrmions around $\nu = 1$. For a perfectly uniform system precisely in the $\nu = 1$ ferromagnetic state, tunneling injects a single minority spin because the thickness of the tunnel barrier ensures that electrons tunnel as single entities. Since this is not the lowest energy excitation, over time the 2D system can lower its energy by flipping more spins to create Skyrmions. Because the energy of the 2D system is lowered by Skyrmion formation, more electrons tunnel from the 3D electrode to keep the chemical potentials on the two sides of the tunnel barrier aligned. When the time scale for spin relaxation is long, the intermediate

TABLE I. Relaxation rates at 6.6 T for samples with different tunnel barrier thicknesses at $\nu = 1/2$ and at $\nu = 1$.

Sample	$\nu = 1/2$ (1/s)	$\nu = 1$ Slow rate (1/s)	$\nu = 1$ Fast rate (1/s)
A	3.7	155	4167
B	332	848	75 060
C	6870	1380	Out of range

stage forms a bottleneck and temporarily prevents more electrons from tunneling. The slow relaxation time of ~ 1 ms is comparable to electron spin relaxation times measured in a recent NMR experiment [10]. MacDonald [11] considers spin-up and spin-down electrons tunneling into the $\nu = 1$ state with equivalent tunneling rates. They must, however, be added to the system according to a certain ratio in order to form Skyrmions. For instance, the creation of a Skyrmion consisting of three flipped spins requires the addition of four minority spins together with the removal of three majority spins. This constraint leads to nonequilibrium spin accumulation in the tunneling process, and MacDonald predicts a ratio of fast and slow relaxation rates in good agreement with our data.

Finally, we note that other researchers [6] reported tunneling relaxation measurements on similar structures around $\nu = 1$ and did not observe the bifurcation of rates described here. We believe that this experiment was performed over a range of frequencies too low and narrow to permit detection of the fast rate, and we speculate that their data reflect the behavior of the slow relaxation.

We thank A.H. MacDonald, L.S. Levitov, B.I. Halperin, S.V. Iordanski, P.A. Lee, and X.G. Wen for useful discussions. This work is supported by the ONR, JSEP-DAAH04-95-1-0038, the Packard Foundation, NSF DMR-9357226, and DMR-9311825.

-
- [1] T. Ando and Y. Uemura, *J. Phys. Soc. Jpn.* **37**, 1044 (1974).
 - [2] S.L. Sondhi *et al.*, *Phys. Rev. B* **47**, 16 419 (1993); H. A. Fertig *et al.*, *Phys. Rev. B* **50**, 11 018 (1994).
 - [3] S.E. Barrett *et al.*, *Phys. Rev. Lett.* **74**, 5112 (1995); E. H. Aifer *et al.*, *Phys. Rev. Lett.* **76**, 680 (1996).
 - [4] A. Schmeller *et al.*, *Phys. Rev. Lett.* **75**, 4290 (1995); D. K. Maude *et al.*, *Phys. Rev. Lett.* **77**, 4604 (1996); D. R. Leadley *et al.*, *Phys. Rev. Lett.* **79**, 4246 (1997); V. Bayot *et al.*, *Phys. Rev. Lett.* **79**, 1718 (1997).
 - [5] R. C. Ashoori *et al.*, *Phys. Rev. Lett.* **64**, 681 (1990); R. C. Ashoori *et al.*, *Phys. Rev. B* **48**, 4616 (1993).
 - [6] V. T. Dolgoplov *et al.*, *Phys. Rev. B* **51**, 7958 (1995).
 - [7] H. B. Chan *et al.*, *Phys. Rev. Lett.* **79**, 2867 (1997).
 - [8] J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, *Phys. Rev. Lett.* **69**, 3804 (1992); K. M. Brown *et al.*, *Phys. Rev. B* **50**, 15 465 (1994).
 - [9] J. J. Palacios and H. A. Fertig, *Phys. Rev. Lett.* **79**, 471 (1997).
 - [10] N. N. Kuzma *et al.*, *Science* **281**, 686 (1998).
 - [11] A. H. MacDonald, *Phys. Rev. Lett.* **83**, 3262 (1999).