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Resonant Tunneling in the Quantum Hall Regime: Measurement of Fractional Charge

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In experiments on resonant tunneling through a “quantum antidot” (a potential hill) in the quantum Hall (QH) regime, periodic conductance peaks were observed as a function of both magnetic field and back gate voltage. A combination of the two periods constitutes a measurement of the charge of the tunneling particles and implies that charge deficiency on the antidot is quantized in units of the charge of quasi-particles of the surrounding QH condensate. The experimentally determined value of the electron charge e is 1.57×10^{-19} coulomb = $(0.98 \pm 0.03)e$ for the states $\nu = 1$ and $\nu = 2$ of the integer QH effect, and the quasi-particle charge is 5.20×10^{-20} coulomb = $(0.325 \pm 0.01)e$ for the state $\nu = 1/3$ of the fractional QH effect.

Laughlin (1) has explained the exactness of the Hall conductance quantization in the integer quantum Hall effect (QHE) (2) as a consequence of a combination of the gauge invariance of the electromagnetic field and the quantization of the charge of the current carriers, the electrons. He considered a gedanken experiment in which a two-dimensional electron system (2DES) forms a finite length cylinder with magnetic field B normal to the surface of the cylinder and additional magnetic flux Φ threaded through the cylinder parallel to its axis. Laughlin showed that if (i) disorder is sufficiently small so that it does not destroy the Landau quantization of the electronic states, (ii) the chemical potential μ lies in the mobility gap between two Landau levels, and (iii) temperature T is small as compared to cyclotron energy, then adiabatic change of Φ by Φ_0 , the flux quantum, is strictly equivalent to the transfer of one electron per Landau level from one edge of the cylinder to the other. This implies that the Hall conductance of such a 2DES sample is quantized exactly to ie^2/h , where i is the number of Landau levels below μ and h is Planck’s constant. This gedanken experiment was adapted to Corbino geometry and elaborated by Halperin (3).

In a seminal work (4), Laughlin related

the fractional QHE (5) at Landau level filling $\nu = 1/(2k + 1)$ (k is an integer) to the fractional quantization of the charge of elementary charged excitations (quasi-particles) of that state in units of $e^* = e/(2k + 1)$. Halperin (6) recognized that Laughlin’s quasi-particles could be described by fractional statistics, and Kivelson and Rocek (7) have shown that fractionally charged quasi-particles must obey fractional statistics.

It has been argued (8) that fractional quantization of Hall conductance implies that the quasi-particles have a charge that is a rational fraction of the electron charge. However, it was subsequently recognized that quantization of Hall conductance is a property of the condensate; for example, the fractional QHE states can be understood within the composite fermion theory (9), without explicit consideration of quasi-particles at all. Several experiments have been attempted to determine the charge of quasi-particles (10). However, either their interpretations were ambiguous or the measurement can be related to the quantization of Hall conductance. Several theoretical works (11, 12) have considered resonant tunneling (RT) in the QHE regime, which is, in some sense, a microscopic implementation of Laughlin’s gedanken experiment. Experimental work was reported on RT in confined quantum dots (13) and antidots (14), all in the integer QHE and without back

gates. However, we are not aware of experimental or theoretical works explicitly predicting quantization of charge deficiency on an antidot.

Here we report experiments on RT through states magnetically bound on a lithographically defined potential hill (“quantum antidot”) in the integer and fractional QHE regimes. We see quasi-periodic RT conductance peaks as a function of both the magnetic field B and back gate voltage V_{BG} . We find that a combination of these two measurements for a given ν QHE state constitutes a direct measurement of the charge of the tunneling particles. Our results imply that the charge deficiency on the antidot is quantized in units of the charge of the quasi-particles of the surrounding QHE condensate q . Using this technique, we have measured the electron charge as $q = 1.57 \times 10^{-19}$ C = $(0.98 \pm 0.03)e$ at $\nu = 1$ and $\nu = 2$ and the quasi-particle charge as $q = 5.20 \times 10^{-20}$ C = $(0.325 \pm 0.01)e$ at $\nu = 1/3$.

Samples were fabricated from very low disorder GaAs heterostructure material described in (15). The antidot-in-a-constriction geometry was defined by standard electron-beam lithography on a pre-etched mesa with ohmic contacts (Fig. 1). The sample was then chemically etched, and Ag front gates were deposited in the etched trenches; samples were mounted on sapphire substrates with In, which serves as the back gate. The two front gates were contacted independently and were used to vary ν between the gates (in a given B) and to balance the two barriers in the RT regime. We prepared the 2DES with a density $n \approx 1 \times 10^{11}$ cm $^{-2}$ and $\mu \approx 2 \times 10^6$ cm 2 V $^{-1}$ s $^{-1}$ by exposing the sample to red light. Experiments were performed in a dilution refrigerator with sample probe wires filtered at millikelvin temperatures, so that the total electromagnetic background at the sample’s contacts is believed to be < 2 μ V (root mean square). The four-terminal magnetoresistance of the samples $R_{(2-3;1-4)}$ (see Fig. 1) was measured with a lock-in amplifier with an excitation of ~ 2 μ V.

The etched front gates and antidot cre-

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ate depletion potential hills in the sample, and in quantizing B , the QHE edge channels (3) are formed along the equipotentials where the self-consistent electron density corresponds to integer or fractional ν near the periphery of the undepleted 2DES (Fig. 1A). In these low-density, thick spacer samples, it is necessary to apply considerable negative front gate voltage (~ 1 V) to bring the edges between the front gates and the antidot close enough so that RT conductance is measurable. As a result, ν between the front gates is different (smaller) from ν_B in the bulk of the sample, far from the front gates (the two front gates are biased to give the same ν on either side of the antidot). Thus Fig. 1A illustrates $\nu = 1$, $\nu_B = 2$ for the integer QHE, or $\nu = 1/3$, $\nu_B = 2/5$ for the fractional QHE. This situation (if no RT occurs) is identical to a single front gate biased to give ν under it, when the rest of

the sample has ν_B (16); the four-terminal resistance is then given by $R_{(2-3;1-4)} = (h/e^2)(1/\nu - 1/\nu_B)$. Indeed, we do obtain these values of $R_{(2-3;1-4)}$ and use them to ascertain ν (ν_B is known from measurements with no gate bias); we checked ν by also measuring the Hall resistance $R_{(2-4;1-3)}$ directly.

Figures 2 through 4 give the tunneling conductance G_{TUN} versus B and V_{BG} for $\nu = 1$ and $\nu = 1/3$. The quantity G_{TUN} was calculated from the directly measured $R_{(2-3;1-4)}$ with the quantized $(1/\nu - 1/\nu_B)$ contribution subtracted; the low B side of the $\nu_B = 3/5$ plateau is seen in Fig. 3A for $B < 7.6$ T. Both G_{TUN} versus B and G_{TUN} versus V_{BG} data display intervals of periodic RT peaks conjoined by a "phase slip." For example, phase slips are seen at 2.267 and 2.33 T in Fig. 2A, at $V_{\text{BG}} \approx 0$ V in Fig. 2B, at 7.62 and 7.735 T in Fig. 3A, at -3.5 V in Fig. 3B, at 10.697 and 10.778 T in Fig. 4A, and at 0.8 V in the upper curve of Fig.

4B. Most of these phase slips are reproducible; their origin will be discussed later. Most RT peaks in the G_{TUN} versus B data correspond to peaks in the G_{TUN} versus V_{BG} data, as illustrated in Figs. 2C and 3C. The RT peaks nearly wash out at 150 mK (50 mK) and when excitation is raised to 30 μV (root mean square) (10 μV) for $\nu = 1$ ($\nu = 1/3$); these values yield the energy quantization of quasi-particle states bound on the antidot at ~ 30 μeV for $\nu = 1$ and at ~ 10 μeV for $\nu = 1/3$ (17).

Figure 1B shows the detail of the edge states near the antidot. There are two edge channels corresponding to ν going around each of the front gates; their energy spectrum is continuous where they intercept the

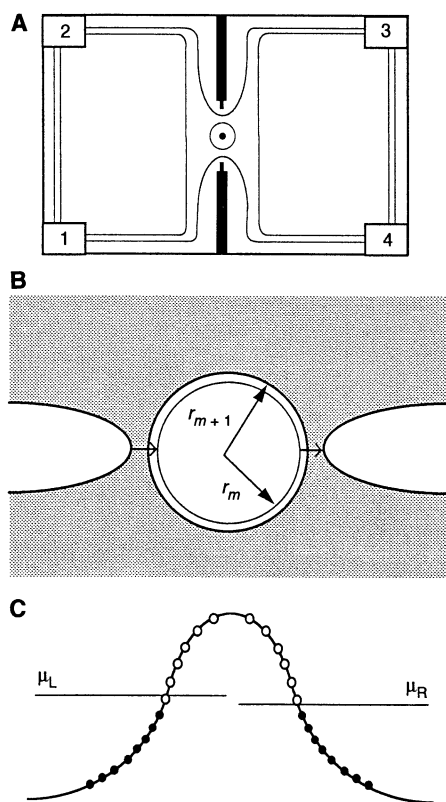


Fig. 1. (A) Illustration of the sample; numbered rectangles are ohmic contacts, black areas are front gates in etch trenches, and lines are edge channels. The back gate extends over the entire sample area on the opposite side of the substrate. (B) Near the antidot (potential hill), quasi-particle states are quantized; only two are shown: the highest occupied ($m + 1$)st and the lowest unoccupied m th. The gray area represents QH condensate at ν ; the two solid lines are the edge channels around the front gates. (C) Potential profile near the antidot. Open circles are unoccupied states, and closed circles are occupied states; subscripts L and R signify left and right.

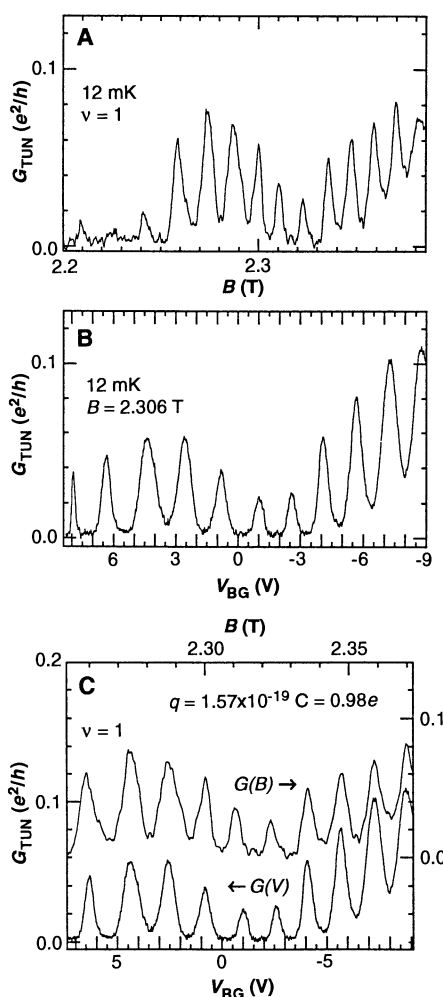


Fig. 2. The RT conductance of electrons at $\nu = 1$ (in the bulk, $\nu_B = 2$). By combining the periods from the two data sets (A and B) we obtain electron charge as discussed in the text. Panel (C) illustrates the correspondence between RT peaks versus B and V_{BG} ; $V_{\text{BG}} = 0$ in (A).

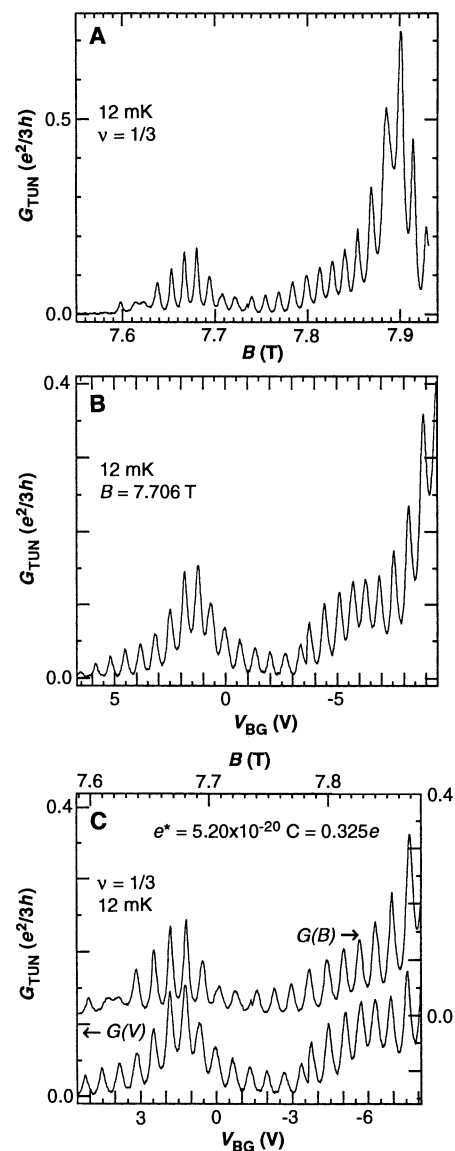


Fig. 3. The RT conductance of quasi-electrons at $\nu = 1/3$ (in the bulk, $\nu_B = 3/5$). By combining the periods from the two data sets (A and B) we obtain quasi-electron charge as discussed in the text. Panel (C) illustrates the correspondence between RT peaks versus B and V_{BG} ; $V_{\text{BG}} = 0$ in (A).

chemical potential μ so that there is no gap for charged excitations at these edges. The states of the ν edge channel around the antidot are quantized by the condition that the Aharonov-Bohm and statistical phase of the particle taken around the antidot be an integer multiple of 2π : $BS_m = m\phi_0 + \sum n_j \phi_j$ (11, 12), where S_m is the area enclosed by the m th state and the term $(\sum n_j \phi_j)/\phi_0$ represents (schematically) the statistical phase due to n_j quasi-particles of species j within S_m (neglecting change in the Coulomb interaction). In Fig. 1C we illustrate that the RT conductance measured with sufficiently small Hall voltage $\mu_L - \mu_R$ reflects tunneling of a particle from within $k_B T$ (k_B is the Boltzmann constant) of μ_L of the left edge to the lowest unoccupied quantized state on the antidot, and then to the right edge.

Suppose at some conditions (B^m , V_{BG}^m , front gate voltage) the lowest unoccupied quasi-particle state is aligned with μ ; then RT is possible, and we observe a peak in G_{TUN} . At a fixed V_{BG} , as B is increased gradually, S_m decreases so that the product BS_m remains constant to satisfy the quantization condition, and the m th state moves higher in energy and out of resonance. When B is raised by $\Delta B = B^{m+1} - B^m$ enough to satisfy $\Delta BS_m = \phi_0$, the $(m+1)$ st state moves just above μ and becomes the lowest unoccupied state; now RT

through this state becomes possible and we observe the next G_{TUN} peak. Thus, ΔB corresponds to the addition of one flux quantum to within the area of the lowest unoccupied quasi-particle state S_m as the number of quasi-holes within this state increases by one, similar to the results of Laughlin's gedanken experiment.

The area S_m is largely determined by self-consistent electrostatics at B and a front gate voltage corresponding to ν ; for a small variation of B , the area oscillates with an amplitude of $(\Delta B/B)S_m$. However, once every several periods, in order to minimize the self-consistent Coulomb potential, a charged particle is added to within S_m so that the charge within S_m changes without a corresponding change in flux; this results in a change in self-consistent potential and a phase slip of the RT period. Because $\sum n_j \phi_j$ can change only by a multiple of ϕ_0 (12), change in the statistical interaction does not result in a phase slip. Thus, the exact periodicity of RT peaks is modified by the gradually changing self-consistent Coulomb potential.

Similarly, when V_{BG} is decreased at a fixed B , peaks in G_{TUN} occur periodically when a quasi-electron is removed (a quasi-hole is added) from the m th state, that is, every $\Delta V_{BG} = q/CS_m$, where q is the charge of the quasi-particle and $C = \epsilon\epsilon_0/d_{BG}$ is the capacitance per unit area between the "compressible 2DES" and the back gate separated by the distance $d_{BG} = 428 \pm 5 \mu\text{m}$ of GaAs ($\epsilon = 13.1$) (18). Here we say compressible 2DES (as at $B = 0$) because the quasi-particle is removed from an edge, where there is no gap for charged excitations and the action of the back gate on the bulk 2DES is very accurately described by a parallel plate capacitor model, even in the QHE regime. This is so because the QHE gap in the bulk is a mobility gap, so that the density of localized states is nonzero, and the charge state of these localized states can change, as required by electrostatics, under adiabatic change of the back gate voltage (19).

We can combine the above expressions for ΔB and ΔV_{BG} to obtain the unit of quantization of charge in the QHE state at ν

$$q = \epsilon\epsilon_0\phi_0\Delta V_{BG}/p_\nu d_{BG}\Delta B \quad (1)$$

where p_ν is an integer that gives the number of quasi-particles transferred from the antidot per added flux quantum at ν , that is, the number of branches of charged excitations in corresponding edge channels; for example, $p_\nu = 1$ for $\nu = 1, 1/3$, and $1/5$, $p_\nu = 2$ for $\nu = 2, 2/5$, and $2/9$, and so on (20). Using Eq. 1, we obtain the quasi-particle charges for several integer and fractional QHE states: $1.55 \times 10^{-19} \text{ C} = (0.97 \pm 0.04)e$ at $\nu = 2$, 1.57×10^{-19}

$\text{C} = (0.98 \pm 0.03)e$ at $\nu = 1$, $5.20 \times 10^{-20} \text{ C} = (0.325 \pm 0.01)e$ at $\nu = 1/3$ (Fig. 3), and $5.3 \times 10^{-20} \text{ C} = (0.33 \pm 0.02)e$ at $\nu = 1/3$ (Fig. 4). All values are reasonably close to the expected values. However, there appears to be a systematic error: Experimental values are smaller than expected by $\sim 2\%$.

In conclusion, we would like to point out that, even without reference to a precise value of the capacitive coupling to the back gate, these experiments still measure the quasiparticle charge at $\nu = 1/3$ in units of electron charge at $\nu = 1$: $e^*/e = [\Delta B^{(1)} \Delta V_{BG}^{(1/3)}]/[\Delta B^{(1/3)} \Delta V_{BG}^{(1)}] = 0.331 \pm 0.006$ from the data of Figs. 3 and 4. Moreover, the data of Figs. 2 and 3 yield the same (within experimental uncertainty) quasiparticle charge for significantly different $B \sim 8 \text{ T}$ and $B \sim 11 \text{ T}$.

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17. The energy spacing of states bound on the antidot depends sensitively on the self-consistent confining potential. Therefore, the fact that the ratio of energy spacing is about 3:1 appears to be fortuitous. For our device, $m \approx 500$, radius $r_m \approx 300 \text{ nm}$, $r_{m+1} - r_m \approx 0.3 \text{ nm}$, and electric field $E_m \approx 10^5 \text{ V m}^{-1}$.
18. This result for charge deficiency is exact in classical electrostatics model problems of either a circular hole or a narrow slit in a conducting plane in a uniform external field. See, for example, L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon, Oxford, ed. 2, 1984), chap. 1, section 4.
19. $V_{BG} = 1 \text{ V}$ is a small perturbation; it takes $V_{BG} \sim 500 \text{ V}$ to deplete the 2DES.
20. For the hierarchy of QHE states, see J. K. Jain and V. J. Goldman, *Phys. Rev. B* **45**, 1255 (1992).
21. We acknowledge use of MBE material grown by M. Shayegan and interesting discussions with A. S. Goldhaber, J. K. Jain, S. A. Kivelson, and K. K. Likharev. This work was supported in part by the National Science Foundation under grant DMR-9318749 and by the Office of Naval Research under grant N0014-93-1-1090.

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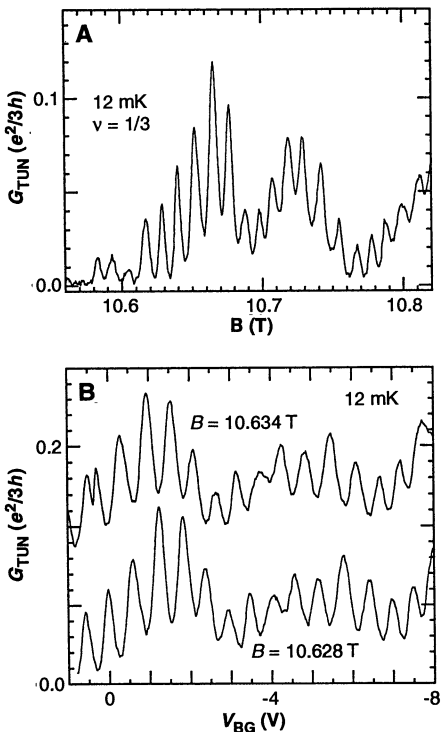


Fig. 4. The RT conductance of quasi-electrons at $\nu = 1/3$ (in the bulk, $\nu_B = 3/7$). **(A)** $V_{BG} = 0$. **(B)** The upper trace has a conductance minimum at $V_{BG} = 0$ (offset vertically by $0.08 e^2/3h$); the lower trace has a conductance maximum at $V_{BG} = 0$.