

Fabry-Perot Interferometry with Fractional Charges

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Resistance oscillations in electronic Fabry-Perot interferometers near fractional quantum Hall (FQH) filling factors $1/3$, $2/3$, $4/3$, and $5/3$ in the constrictions are compared to those near integer quantum Hall (IQH) filling factors in the same devices and at the same gate voltages. Two-dimensional plots of resistance versus gate voltage and magnetic field indicate that all oscillations are Coulomb dominated. A charging-model analysis of gate-voltage periods yields an effective tunneling charge $e^* \approx e/3$ for all FQH states and $e^* \approx e$ for IQH states. Temperature decay of the oscillations appears exponential, qualitatively consistent with a recent prediction, and the surprising filling-factor dependence of the associated energy scale may shed light on edge structure.

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Like their optical analogs, electronic Fabry-Perot interferometers allow quantum interference to be probed via tunable parameters that induce periodic transmission oscillations. Moreover, working with charged excitations in quantum Hall edge states, these devices feature an interplay of coherence, interaction, and magnetic effects; notably, such devices could demonstrate anyonic [1] and non-Abelian [2–5] statistics and potentially comprise topologically protected qubits [6]. In the integer quantum Hall (IQH) regime, recent experimental [7–10] and theoretical [11,12] work has extended the results of initial experiments [13–17] and clarified the role of Coulomb interactions. Behavior consistent with Aharonov-Bohm interference of noninteracting electrons was recently observed [9,10] and can be qualitatively distinguished from the Coulomb-dominated (CD) type using a 2D plot of resistance versus magnetic field and gate voltage.

In the fractional quantum Hall (FQH) regime, signatures of fractional charge [11] and both Abelian [1,12] and non-Abelian [2,5] statistics have been predicted in both the CD [2,5,11,12] and Aharonov-Bohm [1,2,5,12] regimes, but few experimental results have been published. Resistance oscillations generally occur when the interferometer resistance deviates slightly from a plateau, indicating weak tunneling through an IQH or FQH state in the constrictions; we will classify oscillations according to f_c , this state's rational filling factor. Camino *et al.* [18] first observed oscillations at $f_c = 1/3$ consistent with CD-regime tunneling of charge- $e/3$ quasiparticles, though other explanations may be possible [9,18]; Ofek *et al.* [10] later reported a similar result that included a 2D plot justifying a CD-regime explanation. Weaker oscillations have been reported [19] near $f_c = 7/3$ and $5/2$, though apparent device instability hampers their interpretation. This experiment [19], shot-noise measurements near FQH states in the first [20,21] and second [22] Landau levels, and related theoretical work [23,24] suggest the possibility of

tunneling mediated by quasiparticles with a larger charge than expected. Analysis of CD oscillations can reveal the charge of tunneling quasiparticles, but such measurements have not been reported for f_c other than $1/3$, where experiments have consistently found the expected charge.

In this Letter, we report measurements of CD oscillations near the low-magnetic-field edges of quantized plateaus associated with several IQH and FQH states: $f_c = r = 1, 2, 3, 4$ and $f_c = r/3 = 1/3, 2/3, 4/3, 5/3$. The dependence of gate-voltage periods on f_c is well described by a charging model [11,12], allowing extraction of effective charges consistent with $e^* \approx e/3$ for fractional f_c and $e^* \approx e$ for integer f_c . Magnetic-field periods are roughly proportional to $1/r$ in both the integer and fractional regimes, also consistent with the model. The oscillation amplitudes decay exponentially with temperature, as anticipated theoretically [12], but with a surprising pattern: the associated temperature scale is different for the IQH and FQH regimes, but otherwise independent of f_c and device area.

Interferometers were fabricated using e -beam lithography on GaAs/AlGaAs heterostructures with a two-dimensional electron gas (2DEG) of density $n_b = 1.7 \times 10^{11} \text{ cm}^{-2}$ and mobility $\mu = 2 \times 10^7 \text{ cm}^2/\text{Vs}$ in a 40 nm quantum well centered 290 nm below the surface. A BCl_3 reactive ion etch formed 150 nm deep trenches [25] into which Ti/Au gates were deposited in the same lithographic step [Fig. 1(a)]. Measurements on two devices are reported, one with lithographic area $A_{\text{lith}} = 4 \mu\text{m}^2$ and 750 nm constrictions [identical to the device in Fig. 1(a), and shown schematically in Fig. 1(b)] and the other with $A_{\text{lith}} = 2 \mu\text{m}^2$, 600 nm constrictions, and a single gate V_B in place of gates V_{LB}, V_B, V_{RB} . Devices were cooled in a dilution refrigerator with base temperature $\lesssim 10 \text{ mK}$ [26]. The interferometer's diagonal resistance R_D [27] and the bulk Hall resistance R_{xy} were measured simultaneously using LI-75A preamplifiers from NF Corporation followed

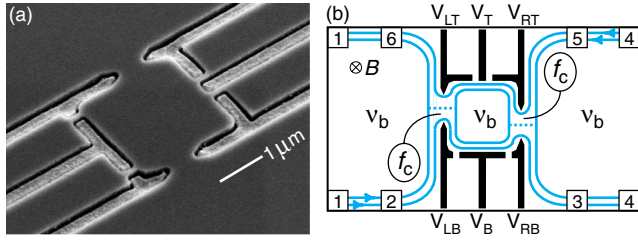


FIG. 1 (color online). (a) Scanning electron micrograph of a typical interferometer. (b) Gate layout of the $4 \mu\text{m}^2$ device with schematic diagram of edge state paths, filling factors, and ohmic contacts. A current bias applied between contacts 1 and 4 allows measurement of diagonal resistance R_D (contacts 2–5) and Hall resistance R_{xy} (contacts 3–5). This picture assumes that only one edge is partially transmitted by the interferometer, while others are fully transmitted or reflected. For clarity, only one fully transmitted edge and no fully reflected edges are shown.

by a lock-in with ac current bias $I = 0.25 \text{ nA}$ [Fig. 1(b)] and time constant $\sim 0.5 \text{ s}$.

Figure 2(a) shows R_{xy} and R_D of the $4 \mu\text{m}^2$ device as a function of perpendicular magnetic field B , covering filling factors from $2/3$ to 3 in both constrictions and bulk. Voltages of $\sim -200 \text{ mV}$ on gates V_{LT} , V_{RT} , V_{LB} , and V_{RB} reduced electron density in both constrictions by $\sim 10\%$ compared to the bulk, while preserving several FQH plateaus. Oscillations in R_D (Fig. 2 insets) were

observed at the low-field edges of several IQH and FQH plateaus, where presumably the only forward transmission of the interfering edge occurs via weak forward tunneling through the f_c quantum Hall state [Fig. 1(b)]. Gate-voltage adjustments allowed variation of the magnetic field (and thereby the bulk filling factor $\nu_b = n_b h/eB$) where each plateau and its associated oscillations appeared, as in the lower panel of the $f_c = 2/3$ inset. Even as ν_b was thus tuned through a range of compressible and incompressible states, the magnetic-field and gate-voltage periods at each f_c remained nearly constant. The slight period difference between the two $f_c = 2/3$ inset panels [more apparent as a frequency difference in Fig. 3(d)] is consistent with reduced device area at more negative gate voltages. Two-dimensional sweeps of magnetic field and gate voltage [Figs. 2(b)–2(e)] show positively sloped constant-phase lines, indicating CD oscillations [9].

Field and gate periods were extracted from fast Fourier transforms (FFT's; Fig. 3), which all show a sharp peak at a single frequency. A Gaussian fit to the peak gives the center frequency f_0 and full width at half-maximum δf , with periods ΔB or ΔV_g given by $1/f_0$. For FFT's over N_{osc} oscillations, we find $\delta f \sim 1/N_{\text{osc}}$, indicating that the uncertainty results from the finite data range.

Similar oscillations appeared in the $2 \mu\text{m}^2$ device, and at $f_c = 1/3, 5/3, 3$ and 4 . The remaining figures present three data sets, with the same gate voltages used at all

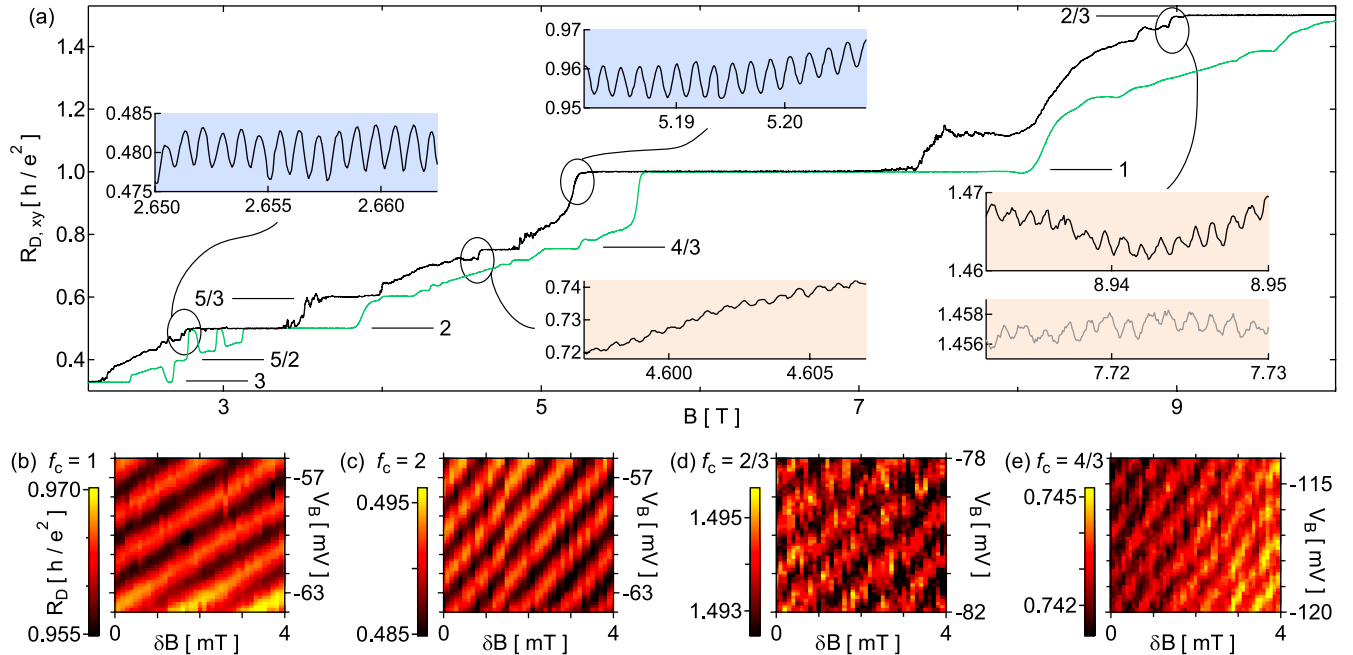


FIG. 2 (color online). (a) Resistances R_D (black) and R_{xy} (green) as a function of perpendicular magnetic field B , with V_T and V_B near -100 mV and all other gate voltages near -200 mV . Numbered horizontal lines indicate filling factors of notable quantum Hall plateaus. Insets: detail views of R_D , revealing oscillations at $f_c = 1$ (top), 2 (left), $2/3$ (right), and $4/3$ (bottom). For the lower panel in the $f_c = 2/3$ inset, constriction gate voltages are near -500 mV . All features are independent of the field sweep rate (typically $\sim 20 \text{ mT/min}$) and direction. Here and throughout, blue (orange) indicates integer (fractional) f_c . (b)–(e) Plots of R_D in the $B - V_B$ plane, with gate voltages comparable to those in (a); $B = B_0 + \delta B$, with $B_0 = 5.200 \text{ T}$, 2.670 T , 8.831 T , and 4.684 T , respectively.

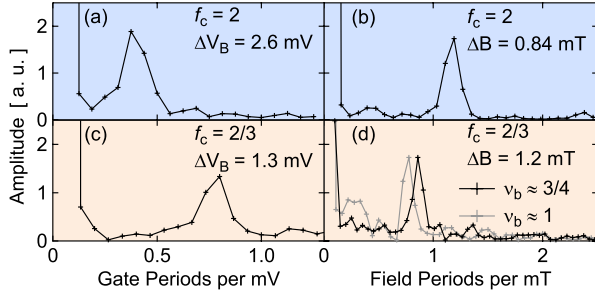


FIG. 3 (color online). Sample FFT's of oscillations with respect to V_B and B , for $f_c = 2$ and $2/3$. Raw data for (b) and (d) are shown in the corresponding Fig. 2(a) insets, while raw data for (a) and (c) are vertical cuts from 2D plots as in Figs. 2(c) and 2(d) but with a larger gate-voltage range for greater frequency resolution.

integer and fractional f_c within each. Gate periods [Fig. 4(a)] are normalized by their values at $f_c = 1$, allowing comparison of periods from all four gates common to both devices. A steady increase in ΔV_g with f_c appears in the FQH regime, with a similar but weaker trend in the IQH regime. Field periods [Fig. 4(b)] appear proportional to $1/r$, where $f_c = r$ in the IQH regime and $f_c = r/3$ in the FQH regime. Separate fit lines of the form $\Delta B \propto 1/r$ agree with data from each regime in each data set, with slightly larger slopes in the FQH regime than in the IQH regime.

We next summarize the theoretical charging model [11,12] used to analyze the data [28]. In this model, oscillations can arise from charge balancing in a nearly isolated island of charge, coupled to the leads via weak forward tunneling, with charging events occurring in units of the quasiparticle charge e^* in the constrictions. This charge is expected to depend not on the identity of the partitioned edge, but instead on the state f_c : for integer f_c , $e^* = e$, and for $f_c = r/s$, the composite fermion model [29] predicts $e^* = e/s$. The charge on the island is $N_L e^*$, with N_L quantized to an integer value. The 2DEG in this area also contains continuous negative charge $N_\phi f_c e$ from the lower-energy electrons, where $N_\phi = BA/\phi_0$ is the (non-quantized) number of quanta of flux, $\phi_0 = h/e$, in the area A enclosed by the interfering edge. To minimize energy, the total negative charge must balance the background positive charge $N_{BG}|e|$ from ionized donors (positive) and gate voltages (negative), yielding the charge neutrality equation $N_\phi f_c e + N_L e^* \approx N_{BG} e$, where quantization of N_L prevents exact equality. Expressing N_ϕ and N_{BG} in terms of gate voltage and magnetic field, and finding the change in these parameters needed to induce a unit change in N_L , allows calculation of oscillation periods.

Gate voltages affect the charge balance in three ways: through the enclosed flux via area, with $\beta_g \equiv dN_\phi/dV_g = (B/\phi_0)(dA/dV_g)$, and through the background charge via both density n_{BG} and area. Summing the two background

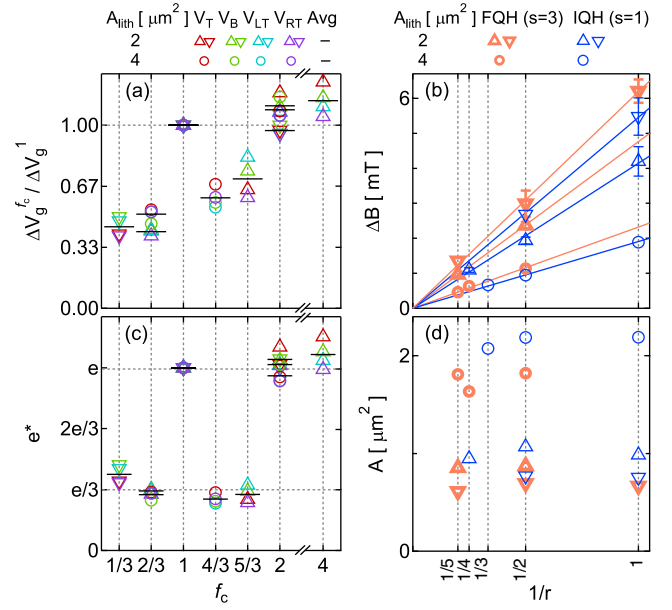


FIG. 4 (color online). (a) Gate periods ΔV_T (red), ΔV_B (green), ΔV_{LT} (aqua), and ΔV_{RT} (purple), and their average (horizontal black lines), as a function of f_c , normalized by their values at $f_c = 1$. Throughout Figs. 4 and 5, two data sets are taken from the $2 \mu\text{m}^2$ device (triangles) and one from the $4 \mu\text{m}^2$ device (circles). (b) Field periods of IQH ($f_c = r$; thin, blue line) and FQH ($f_c = r/3$; thick, orange line) oscillations versus $1/r$. Error bars, corresponding to FFT peak widths, are omitted when smaller than markers. Fit lines have slopes 1.9, 2.3, 4.1, 4.8, 5.4, and 6.2 mT from bottom to top. (c) Effective charges e^* extracted from the gate periods shown in (a) using Eq. (1), assuming $e^* = e$ at $f_c = 1$. (d) Effective areas calculated using Eq. (2) from the values of ΔB shown in (b).

charge effects gives $\gamma_g \equiv dN_{BG}/dV_g = n_{BG}(dA/dV_g) + A(dn_{BG}/dV_g)$, which is assumed B independent [12]. For fixed magnetic field, the charge neutrality equation then yields the gate-voltage period

$$\Delta V_g = \frac{e^*/e}{\gamma_g - \beta_g f_c}. \quad (1)$$

This result reflects the Coulomb-blockade intuition that $\Delta V_g \propto e^*$, but here the gating effect of the lower-energy electrons, represented by $\beta_g f_c$, may cause the lever arm to depend on f_c : although $\beta_g \propto B$ and $f_c \sim 1/B$, the second relationship is inexact since plateau widths are nonzero and f_c is discrete. Considering oscillations at the low-field edges of plateaus, those near weaker plateaus will have larger $\beta_g f_c$, hence larger ΔV_g , consistent with the data in Fig. 4(a). An f_c -independent lever arm would be obtained for $dA/dV_g = 0$, i.e., for an ideal back gate, but both the geometry of our device and the observed f_c dependence of ΔV_g suggest that the gates mainly affect the area.

Assuming ideal side gates (i.e. $dn_{BG}/dV_g = 0$) and an infinitely steep confining potential allows consolidation of

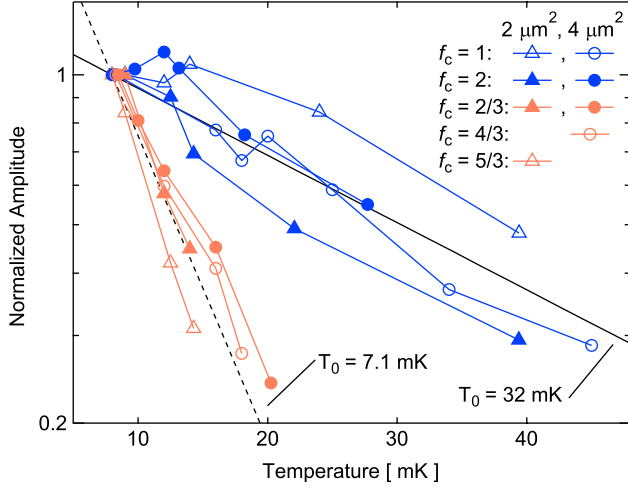


FIG. 5 (color online). Temperature dependence of oscillation amplitude at several filling factors in the IQH (blue) and FQH (orange) regimes. Lines are given by De^{-T/T_0} , with T_0 representing the average value obtained from fits to the individual data sets in each regime. Integer f_c have an average $T_0 = 32$ mK and standard deviation 7.0 mK, while fractional f_c have average $T_0 = 7.1$ mK with standard deviation 1.8 mK; in both cases, any dependence on filling factor or device size is smaller than the measurement uncertainty. Data at $f_c = 4$ were similar to those at $f_c = 1, 2$ and therefore omitted for clarity; data at $f_c = 1/3$ were unobtainable because of device drift. Above 20 mK, FQH-regime oscillations were immeasurably small.

γ_g and β_g : $\gamma_g - \beta_g f_c = \eta_g(B_1 - Bf_c)$, where $\eta_g = \beta_g/B$ is the only free parameter and $B_1 = n_b \phi_0$ is the field at which $\nu_b = 1$. Then η_g may be extracted from ΔV_g measured at a single f_c with known e^* (we choose $f_c = 1$), and finally used at all other f_c to calculate e^* from each ΔV_g . Performing this calculation for each gate and each data set yields the values shown in Fig. 4(c), approximately e/s for all f_c .

A similar analysis of the charge neutrality equation, assuming fixed gate voltages instead of fixed B , predicts

$$\Delta B = \frac{\phi_0}{rA}, \quad (2)$$

where dependence on e^* has been absorbed by taking $e^* = e/s$ (justified by the gate-voltage analysis), leaving A as the only fit parameter. As apparent from Fig. 4(d), where Eq. (2) has been used to extract A from each period in Fig. 4(b), fractional f_c consistently have slightly smaller areas than integer f_c within the same data set, similar to a previous result [18]. The area difference between the two data sets in the $2 \mu\text{m}^2$ device reflects the use of less-negative gate voltages for the data set with larger areas.

To study factors that may limit oscillation amplitudes, oscillations as a function of B were measured at a series of mixing chamber temperatures T , and the average frequencies and amplitudes of the oscillations at each f_c were extracted at each temperature. The frequencies are T

independent, but the amplitudes depend strongly on T , as shown in Fig. 5, where each data set is normalized by its value at the lowest temperature. Each data set can be characterized by an exponential decay of the form De^{-T/T_0} , where T_0 represents a characteristic temperature scale. The continuation of this behavior down to the lowest temperatures confirms that the 2DEG was well thermalized to the mixing chamber even for $T \lesssim 10$ mK; furthermore, IQH regime data up to 100 mK (not shown) remain consistent with an exponential dependence, different from the power-law behavior observed in the IQH regime at higher temperatures [30]. The T_0 values differ significantly between the IQH and FQH regimes but otherwise appear insensitive to both f_c and area.

Reference [12] hints at a physical interpretation of the exponential dependence and the difference in T_0 between the two regimes: T_0 is related to an effective charging energy $E_m = (e^*)^2/C_{\text{eff}}$, where C_{eff} is determined by both the capacitance of the island and edge-structure details [31]. Using this expression with $e^* = e/s$, the measured T_0 yield C_{eff} twice as large in the IQH regime as in the FQH regime. Since T_0 appears insensitive to area, this difference cannot be attributed directly to the area difference between the two regimes; instead, both likely result from a more general structural difference between the IQH and FQH regimes.

In summary, analysis of gate-voltage periods reveals a quasiparticle charge close to $e/3$ at all FQH states studied, a result that agrees with previous work at $f_c = 1/3$, adds to a complicated story at $f_c = 2/3$, and constitutes the first published value at $f_c = 4/3$ and $5/3$. Magnetic-field periods imply slightly different effective areas for fractional and integer f_c . The temperature scales on which the oscillations decay suggest the existence of further structural differences between the two regimes.

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