Measurement of filling factor 5/2 quasiparticle interference with observation of charge e/4 and e/2 period oscillations

R. L. Willett1, L. N. Pfeiffer, and K. W. West

Physical Sciences Research, Bell Laboratories, Alcatel-Lucent, 600 Mountain Avenue, Murray Hill, NJ 07974

Edited by W. F. Brinkman, Princeton University, Princeton, NJ, and approved March 30, 2009 (received for review December 10, 2008)

A standing problem in low-dimensional electron systems is the nature of the 5/2 fractional quantum Hall (FQH) state: Its elementary excitations are a focus for both elucidating the state’s properties and as candidates in methods to perform topological quantum computation. Interferometric devices may be used to manipulate and measure quantum Hall edge excitations. Here we use a small-area edge state interferometer designed to observe quasiparticle interference effects. Oscillations consistent in detail with the Aharonov–Bohm effect are observed for integer quantum Hall and FQH states (filling factors \( \nu = 2, 5/3, \) and 7/3) with periods corresponding to their respective charges and magnetic field positions. With these factors as charge calibrations, periodic transmission through the device consistent with quasiparticle charge e/4 is observed at \( \nu = 5/2 \) and at lowest temperatures. The principal finding of this work is that, in addition to these e/4 oscillations, periodic structures corresponding to e/2 are also observed at 5/2 \( \nu \) and at lowest temperatures. Properties of the e/4 and e/2 oscillations are examined with the device sensitivity sufficient to observe temperature evolution of the 5/2 quasiparticle interference. In the model of quasiparticle interference, this presence of an effective e/2 period may empirically reflect an e/2 quasiparticle charge or may reflect multiple passes of the e/4 quasiparticle around the interferometer. These results are discussed within a picture of e/4 quasiparticle excitations potentially possessing non-Abelian statistics. These studies demonstrate the capacity to perform interferometry on 5/2 excitations and reveal properties important for understanding this state and its excitations.

5/2 fractional quantum Hall effect | fractional quantum Hall effect | non-Abelian statistics | topological quantum computation

Experimentally, the fractional quantum Hall (FQH) state at \( \nu = 5/2 \) filling factor is anomalous in that it occurs at an even denominator quantum number (1). The state is fragile: It displays a weak quantum Hall effect, requiring temperatures for observation substantially lower than the principal odd denominator states at \( \nu = 1/3 \) and 2/3. It has been proposed as either a spin polarized [Moore–Read Pfaffian (2)] or non-spin polarized [Haldane–Rezayi (3)] paired composite fermion state. The fundamental quasiparticle excitations are expected to be charged e/4, and for the Pfaffian state these quasiparticles are to obey non-Abelian statistics. These non-Abelian states may display utility in topological quantum computational schemes (4).

To the end of determining the charge, and more importantly the statistics of the quasiparticles, interference devices and their function in displaying the Aharonov–Bohm (A–B) effect at 5/2 have been described theoretically (5–9). Interference devices are typically constructed with nominally 2 adjacent quantum point contacts (qpcs), each able to variably transmit current, and a confinement area between the qpcs (see schematic in Fig. 1). By splitting the current at the qpcs, redirection of quantum Hall edge currents around the confined area occurs. Interference of that encircling edge with the other backscattered current is expected to yield oscillatory resistance across the device for changing confinement area, with period dependent on the edge current charge. The encircling quasiparticle statistics may also be assessed by examining the interference pattern if the confinement area holds determinable localized quasiparticles (5–9). This interferometric method is attractive in that for a given device it can be applied to a series of integer quantum Hall (IQH) and FQH states for verification of its operation through measurement of their respective charges, including the charge at 5/2 filling factor.

Edge transport interference in IQH systems has been reported for both accidental and intentional area confinements (10, 11). In

Fig. 1. Interference device and bulk sample transport. (A) Schematic of the interferometer showing ohmic contacts to the 2D electron layer labeled 1–4, the confined area \( A_2 \) delineated by qpcs defined by gates a and c with the central channel controlled by gate b. The side-gate b voltage is referred to in these experiments as \( V_b \). Longitudinal resistance \( (R_L) \) through the device could be measured by the voltage drop from 3 to 4 while driving current from 1 to 2, diagonal resistance \( (R_D) \) measured from 1 to 4 while driving current from 2 to 3. Example propagating edge states are marked by the arrows along the gates and sample edges, with the dashed lines marking where backscattering may occur at the qpcs. (B) Electron micrograph of an interferometer gate structure used in this study. (C) Bulk transport at 30 mK near but not through an interferometer device on a sample used in this study.

Author contributions: R.L.W. and L.N.P. designed research; R.L.W. performed research; L.N.P. and K.W.W. contributed new reagents/analytic tools; R.L.W. analyzed data; and R.L.W. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

1To whom correspondence should be addressed at: Bell Laboratories, Alcatel-Lucent, 600 Mountain Avenue, Room 1d-466, Murray Hill, NJ 07974. E-mail: rlw@alcatel-lucent.com.

This article contains supporting information online at www.pnas.org/cgi/content/full/0812599106/DCSupplemental.
Mach–Zehnder interferometer designs (12, 13), oscillatory transmission is observed for both B-field sweep and enclosed area sweep at IQH states. FOH effect interference measurements have been more elusive. An extensive set of studies by Goldman and colleagues (ref. 14 and references therein) has reported well-defined periodic structures in interferometer transmission near FOH filling factors. Later similar studies by Godfrey et al. (15) over a filling factor range of both IQH and FOH states have shown periodic conduction, with period linearly increasing with magnetic field. These results (ref. 14 and references therein and ref. 15) are qualitatively similar, with both interference devices fabricated as etched and gated structures on the few-micrometer size scale. Such device processing supports the more robust IQH systems but may adversely affect the smaller-gapped FOH states (16). In theoretical analysis of these results and interference devices in general, Rose-now and Halperin (17) point out that periodic transmission results may be attributable to Coulomb blockade effects rather than edge state interference. This concern is of particular significance if the device fabrication adversely affects electron correlations, emphasizing the goal of developing an interferometric device that can accommodate the less robust FOH states.

Here we report interferometry studies using devices particularly designed for accommodating fragile FOH states, specifically the 5/2 state. FOH state confinement in an interferometer geometry is achieved here by using only top gate structures on ultra-high mobility, high-density samples for which the gate structures have minimal negative impact on the 2D electron quality. These top gate structures are designed to allow independent control of the size of the encircled area and the transmission qpcs, thus allowing area modulation to be used to assess quasiparticle interference. With these devices, periodic conduction oscillations are observed for both magnetic field sweeps and lateral confining gate sweeps. The oscillatory transmission observed in these studies occurs over small path lengths (approximately a few micrometers) and demonstrates phase noise. The focus of this study is the finding of periodic conduction features at $\nu = 5/2$ for lateral confining gate sweeps. At lowest temperatures, oscillation periods corresponding to charge e/4 are observed, with calibration periodic conduction at $\nu = 2$ assigned to charge e and with resistive oscillations at $\nu = 5/3$ and 7/3 having period consistent with charge e/3. The principal finding of this study is that, at $5/2$ filling in addition to the e/4 oscillations at lowest temperatures, oscillations of half the e/4 period corresponding to e/2 can also be observed. Properties of these oscillations at 5/2 are shown here, including amplitude, relative prevalence, and preliminary temperature dependence. Among the possible causes, this effective e/2 period may empirically reflect the presence of an e/2 quasiparticle or may be due to a double pass of the e/4 quasiparticle around the interferometer. These results are considered within the important possible picture of non-Abelian e/4 quasiparticle statistics.

Operation of an interferometric device in the quantum Hall regime can follow in 2 modes, examining transmission while either sweeping magnetic field or sweeping device area. Phase accumulation can occur by encircling localized charge or by encircling magnetic flux quanta. In quantum Hall systems, application or retraction of the magnetic field changes both the magnetic flux density and the quasiparticle number (18), therefore influencing the phase accumulation in 2 ways, which suggests that B-field sweeps produce a somewhat complicated interferometric scheme for analysis. However, staying at fixed magnetic field but changing the encircled area size via a side gate provides a simpler method for analysis. By changing the encircled area size via a side gate, the number of encircled magnetic flux quanta is changed inducing A–B oscillations. The period of these A–B oscillations indicates the current carrying charge. Another contribution to phase accumulation will occur in this method if the change in area via the change in side gate voltage also includes a localized quasiparticle in the changed area. However, this density of localized quasiparticles is typically substantially below that of the magnetic flux density (18), with the sweep over magnetic flux lines consequently the dominant source for resistive oscillations. The side gate sweep is therefore the preferred technique given its simpler interpretation. Although a complete theoretical understanding of edge state interference is presently emerging (B I Halperin and A Stern, personal communication), it has been demonstrated experimentally (12, 13) that the area change achieved by using side-gate bias produces A–B oscillations in which the period directly reflects the charge of the edge channels. Attempts to assess the 5/2 quasiparticle charge and statistics through interferometry are therefore best served by employing a device capable of adjusting the area with a side gate while controlling the transmission independently with separately controlled qpcs.

The operation of the interferometer used here is based on generating edge current paths that are schematically shown in Fig. 1A: current from left contact 1 is split at qpc a, with some part of that current traversing the encircled central area $A$, and upon reflection at qpc c returns to qpc a via the right edge, where it interferes with the current backscattered at qpc b. By adjusting the channel voltage $V_c$, the central lithographic area, $A_c$, can be changed to encircled area $A$ using the channel gates b. The resistance across the device ($V_{ac}$) should demonstrate oscillations upon interference with period $\Delta R = \Phi/A = (h/e)^2/4$ for B-field sweeps or period $\Delta A = d\Phi = (h/e^2)/B$, $\Delta A \sim \nu_c$ for side-gate (gate b) sweeps, again neglecting quasiparticle number change for each as described above. The device details are presented in Supporting Information (SI) Text, “Methods and Device Operation.”

Bulk transport and transport through the interferometer are shown in Figs. 1C and 2A, respectively. Details of measurements are provided in SI Text. The bulk transport shows the lowest Landau level series of fractional states at the high B-field side of $\nu = 2$ and a well-developed 5/2 state. The longitudinal resistance through the device, $R_L$, is determined by using current contacts 1 and 2, and voltage drop is measured along 3–4 (19). With complete depletion under the gates at approximately $-2.5$ V, the qpcs and the central channel are biased negatively beyond this value for transmission, which collectively promotes observation of interference effects and adjusts total area $A$, respectively. The $R_L$ data show persistence of the larger gap FOH state zero resistances through the device, and transport at $5/2$ shows a $\nu = 200$ plateau of backscattering or reflection at that filling factor at base temperature.

Oscillations in the longitudinal component $R_L$ are observed in our measurements for both B-field sweeps and side-gate $V_s$ sweeps. First, for B-field sweeps, periodic structures can be observed over a range of FOH and IQH states. Periodic structures can be coarsely observed over most of the B-field range shown in Fig. 2A Inset. Close examination of the resistive oscillations near $\nu = 2$ is provided by Fig. 2A. Here the oscillations are of period $\Delta R = 230 \Omega \pm 20 \Omega$, which corresponds to an effective encircled area $A$ of $\sim 0.2 \mu m^2$, much smaller than the lithographically defined area. This finding is consistent with a small density gradient from depletion to full density, as might be expected with our top gate configuration. This gradual change from depletion to full density would imply that the inner edge state is well removed from the lithographic edge and therefore encloses a substantially smaller area: area $A \ll area_{A_c}$. Using the channel gate b, the encircled area $A$ can be adjusted. For a change in this side-gate $V_s$ of approximately $-3$ V, a 20% smaller area $A$ can be generated (16), which resulted in an oscillation period that commensurately increased by 20%. The observation of oscillations with similar B-field period over a range of filling factors is consistent with past experimental results (ref. 14 and references therein). Given this period change with adjustment of area $A$, it is estimated that a side gate voltage adjustment of $\sim 1$ nV will change the area corresponding to 1 flux quantum at B-fields near $\nu = 2$.

We turn now to the observation of resistance oscillations for variations of the side-gate voltage ($V_s$) for different filling factors. As noted above, a side-gate bias changes the area and so changes
runs of oscillations, with similar period, can be observed under these gating and lower trace shows a similar measurement near Each series or run of coherent oscillations is marked by the charge value. The voltage sweeping the side-gate voltage meter longitudinal resistance delineates the B-field range shown in the larger graph. (C) Quantitative verification of the predominant periods in swept -1.0, -0.8, -0.6, -0.4, -0.2, 0.0, 0.2, 0.4, and 0.6 Ω. The box near 90 kG roughly delineates the B-field range shown in the larger graph. (A) Swept B-field A–B oscillations: R_L features consistent with A–B oscillations through the device with background resistance subtracted to better display the oscillations. Note runs of several oscillations, marked by the vertical lines, each with period at ~230 G. Such runs of oscillations, with similar period, can be observed under these gating and temperature conditions throughout the magnetic field range shown in the R_L vs. B-field plot of Inset. (B) Swept side-gate A–B oscillations: R_L is monitored while sweeping the side-gate voltage V_s at fixed B-field. Near ν = 2, runs or series of oscillations are present, with disruptions of phase between the runs. The period is marked by vertical lines reflecting the charge, period P ~ ΔνS ~ ΔA ~ (\hbar/e*)B. Each series or run of coherent oscillations is marked by the charge value. The lower trace shows a similar measurement near ν = 5/3, with larger period oscillations. The vertical lines marked on that trace are the period calculated from the ν = 2 period assuming e*(ν = 2) = e and e*(ν = 5/3) = e/3, and scaling the different B-field values: P(ν = 5/3) = P(ν = 2)e*(ν = 2)e*(ν = 5/3)/(\hbar/(2me*))B(ν = 2)/(\hbar/(2me*))(ν = 5/3). The principal oscillations in the ν = 5/3 trace agree well with this scaling, consistent with interferometric derivation of the fractional charge e/3 at that filling factor. (C) Quantitative verification of the predominant periods in swept area measurements by FFT. Left and right FFT correspond to transforms applied to the data in B and D, respectively. The principal peak frequency for each filling factor is marked by a vertical line with that frequency matched to the vertical period markers in the data of B and D. (D) From a different sample cool-down, a second example of A–B oscillations near ν = 2 (upper trace) in which the period of those oscillations is used to determine the oscillation period for A–B oscillations at ν = 7/3, matching well those features shown in the lower trace. Temperature is 25 mK, current 2 nA. Again, each run of coherent oscillations is marked by the charge, 3 coherent series for ν = 2 and 3 for ν = 7/3.

Fig. 2. Interferometer A–B oscillations: General comparison of the interferometer longitudinal resistance R_L for two types of measurement in which either the B-field is swept and resistance R_L through the device is measured, or the side-gate voltage V_s is swept while R_L is monitored. (A) Overview of R_L ranging from filling factor ν = 3 to near ν = 2 with qpcs at ~4.5 V bias and central channel bias at ~6.0 V, temperature ~30 mK, and current ~5 nA. The box near 90 kG roughly delineates the B-field range shown in the larger graph. (A) Swept B-field A–B oscillations: R_L features consistent with A–B oscillations through the device with background resistance subtracted to better display the oscillations. Note runs of several oscillations, marked by the vertical lines, each with period at ~230 G. Such runs of oscillations, with similar period, can be observed under these gating and temperature conditions throughout the magnetic field range shown in the R_L vs. B-field plot of Inset. (B) Swept side-gate A–B oscillations: R_L is monitored while sweeping the side-gate voltage V_s at fixed B-field. Near ν = 2, runs or series of oscillations are present, with disruptions of phase between the runs. The period is marked by vertical lines reflecting the charge, period P ~ ΔνS ~ ΔA ~ (\hbar/e*)B. Each series or run of coherent oscillations is marked by the charge value. The lower trace shows a similar measurement near ν = 5/3, with larger period oscillations. The vertical lines marked on that trace are the period calculated from the ν = 2 period assuming e*(ν = 2) = e and e*(ν = 5/3) = e/3, and scaling the different B-field values: P(ν = 5/3) = P(ν = 2)e*(ν = 2)e*(ν = 5/3)/(\hbar/(2me*))B(ν = 2)/(\hbar/(2me*))(ν = 5/3). The principal oscillations in the ν = 5/3 trace agree well with this scaling, consistent with interferometric derivation of the fractional charge e/3 at that filling factor. (C) Quantitative verification of the predominant periods in swept area measurements by FFT. Left and right FFT correspond to transforms applied to the data in B and D, respectively. The principal peak frequency for each filling factor is marked by a vertical line with that frequency matched to the vertical period markers in the data of B and D. (D) From a different sample cool-down, a second example of A–B oscillations near ν = 2 (upper trace) in which the period of those oscillations is used to determine the oscillation period for A–B oscillations at ν = 7/3, matching well those features shown in the lower trace. Temperature is 25 mK, current 2 nA. Again, each run of coherent oscillations is marked by the charge, 3 coherent series for ν = 2 and 3 for ν = 7/3.
Figure 3 shows oscillations near filling factor 2, where the predominant period is e/4, with respective periods marked by arrows. The frequency peaks are consistent with quasiparticles of charge e/4 as derived from the period of the e/2 traces; the marked vertical lines are e/4 period derived from e/2 and consistent with peaks of the FFT spectra in both e/2 traces. Additional oscillation features of shorter period are apparent traces of each graph are taken near 5/2, with evidence for e/4 charge present in both sample preparations. In each graph, at 5/2, small-period oscillations are observed at these low temperatures (~25 mK). These expected periods are marked in Fig. 2, showing frequency peaks that verify the marked period lines in the swept gate data. The bottom traces of each graph are taken near 5/2 filling factor displaying oscillations with periods corresponding to e/4 and e/2. Fig. 3 shows that the period derived for e/4 quasiparticles from the swept gate data is 2π ~ 1.5 μm.

With this validation of the interferometer operation for determining quasiparticle charge, measurements are then made near ν = 5/3, with important results. Fig. 3 shows device resistance vs Vg is swept at multiple filling factors, including ν = 5/2 for a sample following 2 different cool-downs from room temperature to base temperature. From each cool-down, the high-mobility 2D system displays slightly different properties in standard bulk transport measurements and, likewise, displays different properties in standard transport through the interference device. For this reason we display two typical Rl vs. Vg trace sets to provide a demonstration of both the persistence of the A-B effects and the variability in the details of the traces for samples prepared differently. Additional trace sets are provided in Fig. S1, and SI Text includes a discussion of the high reproducibility of oscillatory features in Vg sweep data. Fig. 3 shows oscillations near ν = 2, where the predominant period there is then translated to the expected period for oscillations at either ν = 5/3 or ν = 7/3. These expected periods are marked in each ν = 5/3 or 7/3 trace with good correspondence to oscillatory features. These are the controls for 5/2. FFT of the side-gate sweep measurements of Rl near ν = 2 and ν = 5/3 or ν = 7/3 are shown in the insets of the bottom graphs. The peaks in the frequency spectra demonstrate quantitative agreement of the respective filling factors for expected AB oscillations.

Fig. 3 show data taken near 5/2, with evidence for e/4 charge present in both sample preparations. In each graph, at 5/2, large-period oscillations are observed at these low temperatures (~25 mK). These prominent features are runs of oscillations with period consistent with quasiparticles of charge e/4 as derived from the period of the ν = 2 traces; the marked vertical lines are the e/4 period derived from ν = 2 and consistent with peaks of the FFT spectra in both e/4 traces. Additional oscillation features of shorter period are present that correspond to a period as expected from charge e/2, again marked by corresponding vertical lines. The amplitudes of the e/2 oscillations are generally smaller than those of the e/4, thirds, and integral filling factors. The bottom graphs show FFT spectra of the 5/2 traces, each demonstrating both e/4 and e/2 frequency peaks. Again, the arrows show the frequency/period marked in the swept gate data.
consistent with the limited-range oscillation sets for $\nu = 2$ and $\nu = 5/3$ or 7/3. FFT data shown in the bottom graphs demonstrate peaks in the spectra at the frequency expected for e/4 given the FFT spectral peaks at filling factors 2, 5/3, and 7/3. The narrow FFT peaks corresponding to the respective orbits' filling factor data provide specific determination of the expected 5/2 FFT peak position and are used in their calculation. Further examples of 5/2 data are shown in Fig. S2a and b.

These large-period oscillations are consistent with interference of charge e/4 quasiparticles, given the correspondence in detail of charge scaling (e to e/4) and magnetic field scaling (from near $\nu = 2$ to near $\nu = 5/2$) as expected for A–B oscillations. Note that the observed oscillation periods near filling factors 5/2, 7/3, 2, and 5/3 do not respectively progress monotonically in B-field. Previous interferometer results (13) potentially attributable to Coulomb blockade possessed monotonic B-field dependence of the oscillation period, distinctly different from the results shown here. This result of e/4 charge at 5/2 is consistent with the conclusions of previous measurements of both shot noise (20) and qpc tunneling (21). These prominent oscillatory features with a period corresponding to e/4 provide substantial support for the model that the elementary excitation at 5/2 has charge e/4.

Beyond these properties of the e/2 and e/4 oscillations, preliminary temperature dependence is displayed in Fig. 4. The top 2 graphs show typical prevalence of the e/4 and e/2 periods at the base temperature near 5/2 filling factor. The data include FFT spectra demonstrating the presence of peaks corresponding to both e/4 and e/2. The influence of temperature on the presence of this shorter period e/2 oscillation is tested in Fig. 4c, in which the sample temperature is changed during a side-gate sweep. The sample is first held at $\sim$30 mK, where large-period oscillations are observed corresponding to e/4 as marked. The sample temperature is then abruptly increased to near 150 mK, and the shorter period consistent with e/2 is exposed. These results indicate that at higher temperatures the predominant A–B period may become e/2 with diminishing occurrence of e/4 oscillations. This possibility is further examined by the data in Fig. 4d. Here, 3 different side-gate sweeps are performed at progressively higher temperatures. These sweeps are measured with a low drive current of 2 nA; other data collected at higher drive current is shown in Fig. S3. At lowest temperature, periods consistent with e/4 and e/2 are present. At the higher temperature of 130 mK, a greater prevalence of e/2 oscillations is observed: At this temperature the 5/2 state in bulk still demon-
strates a distinct minimum in $R_{xx}$. In these samples, the activation energy in bulk measurement is $\sim 150$ mK. At the next higher temperature ($610$ mK) shown in Fig. 4D, the overall amplitude of the $R_{xx}$ measurement is substantially diminished, with only a background noise apparent. These $5/2$ data suggest that, as temperature is increased, the $e/2$ period may become the prevailing feature before elimination of the quantum Hall state above the temperature corresponding to the activation energy. The data of Fig. 4 and Fig S3 provide only a preliminary indication of the $e/4$ and $e/2$ temperature dependence.

The principal findings of this study of a small-area interferometer in which the area is changed with a side gate are as follows. (i) Results consistent with interference of FQH edge currents are observed and supported by data of transmission oscillations, with periods corresponding to both charge and magnetic field positions at filling factors 2, 5/3, and 7/3. (ii) In the model of interference of edge currents, transmission oscillations of a period appropriate to charge $e/4$ are demonstrated at filling factor 5/2. (iii) Near 5/2, an additional oscillation period corresponding to $e/2$ is prominent in the side-gate sweep data.

The finding of $e/4$ period oscillations at 5/2 is consistent with the present theoretical understanding of the 5/2 state excitations (2, 3) and their common predicted charge of $e/4$. This result provides a consistency with the paired state pictures of the Moore–Read state and the Haldane–Rezayi state, yet cannot discriminate between these models. Additionally, this charge assessment does not determine the underlying statistics of the excitation.

The origin of the $e/2$ oscillations at lowest temperatures can include empirically 2 fundamental possibilities: (i) the oscillations represent the presence of a quasiparticle of $e/2$ charge, or (ii) the oscillations are the result of an $e/4$ quasiparticle completing 2 full passes or laps around the interferometer before the interference occurs; the enclosed area is doubled (the number of encircled magnetic flux are doubled) and therefore the period is halved. The first possibility, that the smaller $e/2$ period directly reflects the presence of $e/2$ quasiparticles, is not supported by early theory, which describes the elementary excitations as $e/4$ (2, 3, 5, 6). However, the possibility of $e/2$ excitations has been broached in more recent work (22). A viable picture of the presence of an $e/4$ quasiparticle must also include a rational for coexistence with $e/4$ quasiparticles and how either $e/2$ or $e/4$ period is expressed in the data sequentially, as observed in the data.

The second possibility in which $e/4$ quasiparticles produce both $e/2$ and $e/4$ periods, the $e/2$ period being caused by $e/4$ accomplishing 2 laps around the interferometer, has the fundamental constraint that the coherence length of the $e/4$ quasiparticle must be sufficient to allow completion of the longer double pass. This may be the case given the small perimeter of the interferometer and the apparent preservation of the 2D electron system high quality in the device. In addition, the generally lower amplitude of the $e/2$ oscillations supports this possibility. An argument against this multiple pass picture is that at higher temperatures the $e/2$ oscillations appear to become more prevalent, not less. Heuristically it might be expected that the larger path length of the double traversal would leave the $e/2$ vulnerable to thermal dephasing. The origin of the presence of the $e/2$ oscillations remains an open question.

Despite these difficulties, the possibility that $e/4$ quasiparticles double traverse the interferometer offers a model (5, 6) that has importance for its implications as to the statistics of the $5/2$ excitations. Here the $e/2$ oscillations may represent a direct manifestation of the non-Abelian statistics of $e/4$ quasiparticles. From the theory for non-Abelian $e/4$ quasiparticles, if the interferometer area $A$ encircled by the $e/4$ quasiparticle encloses an even number of localized quasiparticles or quasiholes, an $e/4$ period results: If an odd number of quasiparticles is enclosed, interference and so transmission oscillations are suppressed. Given that enclosure of an odd number of localized quasiparticles suppresses $e/4$ oscillations due to the non-Abelian statistics, the $e/4$ quasiparticles can still traverse the perimeter of the interferometer and have the potential to add two laps to the area $A$. In this case, the odd number of localized particles in $A$ has now been encircled twice, so that an even number has been encircled in sum, and interference oscillations are now not suppressed. Also, the total area encircled is now twice $A$, twice the enclosed number of magnetic flux quanta, which would produce an effective period of $e/2$. Because the $e/4$ period from the single lap is suppressed, the $e/2$ period from the double lap can be expressed, but at period $e/2$. This picture is consistent with the sequential observation of $e/2$ or $e/4$ periods; as the side gate is swept, an odd or even number of localized quasiparticles may be enclosed. This picture also is consistent with the observation that the $e/2$ period oscillations are generally of smaller amplitude. Because of the longer path length that must be traversed by the quasiparticles over 2 laps, any decoherence mechanisms present will result in a concomitant amplitude reduction.

The data of this study do not provide sufficient evidence to conclude this as the proper model. However, this picture is important in considering interferometric determination of potential non-Abelian $e/4$ excitation statistics.

In conclusion, the principal findings of this work are that interferometric measurements can be accomplished on the $5/2$ FQH state: Apparent A–B oscillations are observed demonstrating periods consistent with $e/4$ charge for lowest temperatures but also demonstrating oscillation periods consistent with $e/2$. The origin of the $e/2$ oscillations is an open question. These findings of $e/2$ and $e/4$ periods may be considered in the model of non-Abelian properties of the $e/4$ quasiparticle.

ACKNOWLEDGMENTS. We thank B. I. Halperin, A. Stern, and H. L. Stormer for useful discussions and M. Peabody for technical assistance.

6. Stern A, Halperin BI (2006) Proposed experiments to probe the non-Abelian $e/4$ and $e/2$ periods, the $e/2$ period being caused by $e/4$ accomplishing 2 laps around the interferometer, has the fundamental constraint that the coherence length of the $e/4$ quasiparticle must be sufficient to allow completion of the longer double pass. This may be the case given the small perimeter of the interferometer and the apparent preservation of the 2D electron system high quality in the fraction $e/4$ quasiparticle encloses an even number of magnetic flux quanta, which would produce an effective period of $e/2$. Because the $e/4$ period from the single lap is suppressed, the $e/2$ period from the double lap can be expressed, but at period $e/2$. This picture is consistent with the sequential observation of $e/2$ or $e/4$ periods; as the side gate is swept, an odd or even number of localized quasiparticles may be enclosed. This picture also is consistent with the observation that the $e/2$ period oscillations are generally of smaller amplitude. Because of the longer path length that must be traversed by the quasiparticles over 2 laps, any decoherence mechanisms present will result in a concomitant amplitude reduction.

The data of this study do not provide sufficient evidence to conclude this as the proper model. However, this picture is important in considering interferometric determination of potential non-Abelian $e/4$ excitation statistics.

In conclusion, the principal findings of this work are that interferometric measurements can be accomplished on the $5/2$ FQH state: Apparent A–B oscillations are observed demonstrating periods consistent with $e/4$ charge for lowest temperatures tested but also demonstrating oscillation periods consistent with $e/2$. The origin of the $e/2$ oscillations is an open question. These findings of $e/2$ and $e/4$ periods may be considered in the model of non-Abelian properties of the $e/4$ quasiparticle.
Methods and Device Operation. Experiments were performed on high mobility ($>25 \times 10^{3}$ cm$^2$/V-sec), high density ($\sim 4 \times 10^{11}$/cm$^2$) AlGaAs/GaAs heterostructures. These samples were designed to optimize the 2/5 filling factor state in top gate devices. The 2D electron systems reside roughly 200 nm below the sample surface in all samples tested. Sample illumination with a red LED is used to maximize mobility. At the sample surface a large scale (0.6 mm $\times$ 0.3 mm) mesa is etched in the sample to provide a Hall bar, with contacting on the perimeter and gates placed internally and extending to the edge of the Hall bar. Before gate definition a thin ($<40$ nm) amorphous SiN layer is deposited on the entire surface. The high mobility of the device is preserved as demonstrated by the transport in Fig. 1C. The confinement device surface gates, comprised of $\sim 60$ nm Al, are arranged in the form of two quantum point contacts enclosing a channel (Fig. 1A). Each pair of quantum point contacts can be biased independently, as is true for the channel referred to as voltage $V_s$, allowing independent transmission and size control of the confinement area delineated by the surface gates. The total area as defined by the surface gates is greater than 2 $\mu$m$^2$ (see electron micrograph, Fig. 1C). Some of the channel properties and gating results have been described elsewhere (1). Configurations for resistance measurements (2) corresponding to longitudinal ($R_L$) and diagonal ($R_{xy}$) resistances are described in the text according to Fig. 1A schematic. Standard lock-in techniques are used for these measurements. Low temperatures are achieved using a dilution refrigerator. Gate performance is monitored using both the resistance measurements and gate leakage measurements. $R_L$ values shown in this study are taken for nondiscernable gate leakage ($<4$ pA) which is viable to over a $-6$ V bias. Extensive gate testing is used, with these samples demonstrating full depletion at bias of near $-2.5$ V. The 3 components of the confinement device are first tested for integrity; each qpc and the depletion at bias of near $25$ mK. In addition to e/4 oscillations, the data show runs of oscillations in each scan that are not specifically reproducible in detail in the number of oscillations in each run, but with sufficiently long gate equilibration the general features of the oscillatory sets or runs can be reproduced.

When examining 5/2 filling factor, as shown above, oscillations with periods consistent with e/2 and/or e/4 charge were observed in each of the scans at lowest temperatures, again under the optimized conditions. While the data shown above and collected to date demonstrate a high prevalence of e/4 consistent oscillations, often coexistent in side-gate sweeps with e/2 oscillations, a precise determination of that relative prevalence is presently under study.

Comparisons of A–B Data from Side-Gate Sweeps at $\nu = 2$, 5/3, and 5/2. Fig. S1 contains 2 graphs, each demonstrating $R_L$ for side-gate sweeps comparing filling factors 2, 5/3, and 5/2. The predominant oscillation period at $\nu = 2$ is used to calculate the A–B period that should be observed at 5/3 and 5/2. The marked vertical lines in the $\nu = 2$ trace are measured, the vertical lines in the 5/3 and 5/2 traces are the calculated lines. Good correspondence is seen in the 5/3 and 5/2 traces to the periods derived from $\nu = 2$. The data cover relatively small side gate sweeps, with excitation current of 5 nA in these traces, and refrigerator temperature in these traces $<30$ mK. In addition to e/4 oscillations, the data display evidence for e/2 period oscillations.

These data represent that taken in the early cool-downs of these experiments. The sample preparation here included cooling to base temperatures and illumination at that temperature, followed by charging of the gates. In these procedures measurements immediately followed charging of the gates. In the interim it has been observed that allowing the gate charged device to equilibrate over a several day period exposes a lower noise signal that promotes observation of the interference features, such as the e/2 oscillations. It has also been noted that excitation current of 2 nA rather than 5 nA, as used in the early experimental trials, promotes observation of the interference effects.

The nature of the findings for the side gate sweeps at the various filling factors, that of short runs of oscillations at the respective periods, raises the question of how reproducible are the findings, or what is the success rate at observing the oscillations? Using a scan of the side gate of $\sim 40$ mV or more, in each of the four cool downs sets of the target filling factors (2, 5/3, 7/3, and 5/2) were tested. Oscillations of the appropriate period were observed in each of the scans performed for all sets tested specifically for optimized qpc voltages and for magnetic field position within a range around the target filling factor. It was found that for qpcs voltages set at only marginally more than depletion or at high values nearing pinch-off, the oscillations were not consistent or were absent. At the optimized qpc voltages and magnetic field values repeated side gate scans showed runs of oscillations in each scan that are not specifically reproducible in detail in the number of oscillations in each run, but with sufficiently long gate equilibration the general features of the oscillatory sets or runs can be reproduced.

A–B oscillations at 5/2 with periods e/4 and e/2. Figs. S2a and b demonstrate data sets of $R_L$ versus side gate voltage near filling factor 5/2 and at base temperature near 25 mK for 2 different sample preparations using 2 nA current. A–B oscillations features representing e/4 and e/2 periods are apparent in both traces. The vertical lines delineating those periods are derived from oscillations measured at filling factor 2 for each and are consistent with FFT spectra of the traces. As noted in the text, the e/2 oscillations are generally of smaller amplitude than the e/4 oscillations.

The marking of e/4 and e/2 periods are supported by fast Fourier transforms of the spectra, each showing peak frequencies consistent with the marked periods in the side gate voltage sweep data. Separation of the data into sections of e/2 and e/4 periods is shown in the lower graphs, where FFT spectra of those separated data are also displayed. The peaks in the FFT spectra of the separated data further demonstrate the independent occurrence of the 2 periods e/4 and e/2.

Temperature Dependence at 5/2 with 5 nA Drive Current. Fig. S3 shows $R_L$ versus side gate sweep data near 5/2 filling factor at three different temperatures. At the lowest temperature of 25 mK structures are present at period consistent with charge e/4, with the period marked and V$s$ scaling accomplished as described previously with respect to filling factor 2. At the higher temperature of 76 mK periodic features corresponding to e/2 are apparent and fill the V$s$ scan window. At 145 mK little $R_L$ structure is present, with only a hint of e/2 properties.

This data set resulted from measurements undertaken early in the execution of the experiments using a relatively high drive current of 5 nA. As noise reduction within the experiment was accomplished, and sample preparation became more refined as described above, lower drive current of 2 nA could be used. As
used in the data of Fig. 4D and many of the prior figures, this lower current may have reduced heating within the interference device compared to using 5 nA. Given this point, the data in Fig. S1 and Fig. S3 may represent a functionally higher temperature in the device than the temperature posted, and possibly higher than that using 2 nA current. The higher resolution of the interference features in the more recent experimental results, those using the lower current of 2 nA, can be attributed to this noise reduction and may also reflect the expression of the interference at a lower temperature within the device.

Fig. S1. Interferometer longitudinal resistance versus side-gate voltage change measured at multiple filling factors for 2 sample cool-downs. Excitation current is 5 nA, temperature is 25 mK.
Fig. S2a. Interferometer longitudinal resistance versus side gate voltage change operated near filling factor 5/2 for 2 different sample illuminations (Fig. S2a and b). Excitation current is 2 nA, temperature is 25 mK. FFT of the entire side gate sweep spectra are shown within the upper graphs as insets, both demonstrating peaks at frequencies corresponding to e/4 and e/2 periods. The lower graphs show the sections of e/4 and e/2 oscillations that are each taken from the upper plot. FFT are then performed on those sections, showing their respective peak frequencies. In both cases of the isolated e/2 oscillations the marked period in $R_L$ versus gate voltage change matches well the peak of the FFT spectrum.
Fig. S2b.
Fig. S3. Interferometer longitudinal resistance versus side gate voltage change measured near filling factor 5/2 at 3 different temperatures. Excitation current is 5 nA.