Unexpected Behavior in a Two-Path Electron Interferometer

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We report the observation of an unpredictable behavior of a simple, *two-path*, electron interferometer. Utilizing an electronic analog of the well-known optical Mach-Zehnder interferometer, with current carrying edge channels in the quantum Hall effect regime, we measured high contrast Aharonov-Bohm (AB) oscillations. Surprisingly, the amplitude of the oscillations varied with energy in a lobe fashion, namely, with distinct maxima and zeros (namely, no AB oscillations) in between. Moreover, the phase of the AB oscillations was constant throughout each lobe period but slipped abruptly by π at each zero. The periodicity of the lobes defines a new energy scale, which may be a general characteristic of quantum coherence of interfering electrons.

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Electrons in two dimensions and under a strong magnetic field perform forward moving *skipping orbits* along the edges of the sample—hence propagating in a beamlike motion. Quantizing this motion leads to *chiral edge states* in effective one-dimensional *edge channels,* which are the most basic ingredient of the quantum Hall effect (QHE) [1]. Based on the fact that backscattering from one edge of the sample (from the forward moving channels) to the opposite far away edge (to the backward moving channels) is highly suppressed, we constructed a *single channel* electronic Mach-Zehnder interferometer (MZI) [2,3], with extremely large contrast interference oscillations. This novel MZI attracted already considerable attention, and proposals were published to utilize it for the study of dephasing and decoherence [4], for the observation of fractional statistics of quasiparticles [5,6], for the demonstration of interference of fractional charges [7], and to demonstrate interference between two identical particles [8].

Here we report a bizarre behavior of the interference oscillations in a MZI operating in the integer QHE (IQHE) regime, which might significantly impact the above-mentioned proposals. As we changed the injection energy of the electrons, the contrast of the interference oscillations (the *visibility*) changed periodically, with maxima and zero minima (namely, no oscillations) in between, with the phase of the oscillations slipping abruptly by π at each zero. We cannot explain this behavior by the ubiquitous Landauer-Buttiker formalism [9], suggesting that the single particle model, which is expected to hold in the IQHE regime, is invalid. As we show later, it is likely that interactions might have to be invoked in order to explain this unexpected effect.

A rather simple realization of such an interferometer, based on a high mobility 2D electron gas (embedded some 85 nm below the surface of a GaAs-Al_xGa_{1-x}As heterostructure), is described in Fig. 1. Edge channels propagate along the edges of the sample that are defined by etching. Instead of the beam splitters in the optical MZI we employed partly transmitting potential barriers, formed by quantum point contacts (QPCs). QPC1 splits the incoming beam from source S2 to two paths and QPC2 recombined the paths back together with resultant outgoing currents collected by drains D1 and D2. A modulation gate MG controls the phase difference φ between the two paths by changing the contour of one path and consequently the enclosed area between the two paths via the Aharonov-Bohm (AB) effect [10]. Note that the current in D1 is out of phase with respect to the current in D2, because of charge conservation.

In the linear regime (without dc bias applied) the conductance from source S2 to drains D1 and D2 corresponds to the transmission probabilities T_{S2D1} and T_{S2D2} via the Landauer-Buttiker formalism [9]. The transmission probability, in turn, depends on the interference between the transmission amplitudes of the two paths. When the system is tuned to the IQHE regime, say filling factor $\nu = 1$, a single edge current is injected from S2, split by QPC1 to transmitted and reflected edge channels, propagating along the inner and outer boundaries of the "ring." For transmission and reflection amplitudes t_i, r_i of the ith QPC (with $|r_i|^2 + |t_i|^2 = 1$); the collected currents at D1 and D2 can be expressed as $I_{D1} \propto T_{S2D1} = |t_1 r_2 + r_1 t_2 e^{i\varphi}|^2 = |t_1 r_2|^2 + |r_1 t_2|^2 - 2|t_1 t_2 r_1 r_2| \cos\varphi$ and $I_{D2} \propto T_{S2D2} = |t_1 t_2 + r_1 r_2 e^{i\varphi}|^2 = |t_1 t_2|^2 + |r_1 r_2|^2 + 2|t_1 t_2 r_1 r_2| \cos\varphi$ with $I_{D1} + I_{D2} = I_{S2}$. We define the visibility of the oscillating current in each drain as $\nu = (I_{max} - I_{min})/(I_{max} + I_{min})$.

Previous conductance measurements on a simpler version of the MZI resulted with a monotonic decay of the visibility with increased dc voltage and temperature [2]. Additional shot noise measurements excluded decoherence as an explanation for this decay. A recent theoretical paper suggested that some low frequency fluctuations, such as $1/f$ noise, may be present, hence changing randomly the area of the interferometer and quenching the visibility [4]. We show here a much richer and quite different set of experimental results that puts the above model in doubt.

The present MZI is similar to its predecessor [2] except for an additional quantum dot (QD)—from it only QPC0 was operated—inserted in the current path from S2 to QPC1 (see Fig. 1), allowing selective transmission of edge channels toward the MZI. Differential measurements were performed at the electron temperature of ~20 mK by superimposing a small ac voltage (~1 μV at ~1 MHz) on a dc bias at S2 and measuring the ac voltage at D2. The ac voltage at D2 was then amplified by an *in situ*, homemade, preamplifier cooled to 4.2 K, followed by a room temperature amplifier and a spectrum analyzer that measured the ~1 MHz amplified signal.

The ac measurements were conducted at filling factor $\nu = 1$ and 2, however, at $\nu = 2$, unlike reported in Ref. [2], the inner edge was now totally reflected by QPC0, leaving only the outer edge channel to arrive at the MZI with finite bias. Strong AB oscillations were observed as a function of the voltage applied to the MG (with visibility as high as 45%) when no dc bias was applied at S2 and $T_{QPC1} = T_{QPC2} = 1/2$.

Applying a dc bias at S2 the interference signal evolved in a most unexpected way [see Fig. 2(a)]. Surprising beating appeared in the contrast of the oscillations as the dc

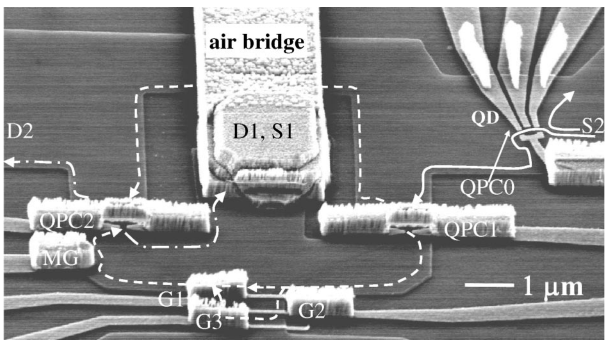

FIG. 1. A top scanning electron microscope micrograph of the Mach-Zehnder interferometer (MZI). The edges of the sample were defined by plasma etching of the GaAs-$Al_xGa_{1-x}As$ heterostructure, which embeds a high mobility 2D electron gas, some 85 nm below the surface. Edge channels were formed by applying a perpendicular magnetic field (2–5 T), with filling factors $\nu = 1$ or 2 in the bulk. The quantum dot that follows the source S2 (not seen in the picture) was not used, but one of its quantum point contacts (QPC0) served to reflect back the desired edge channel. The incoming edge channel (solid white line) was split by QPC1 to two paths (dotted white lines), of which one moved along the outer edge of the device and the other around the inner drain D1 (under the metallic air bridge). The two paths met again at QPC2, interfered, and resulted in two complementary currents: one in D1 and the other in D2. The modulation gate (MG) changed the contour of one path, thus changing the enclosed area between the two paths and the phase difference between them (via the Aharonov-Bohm effect). Significant changes in path length could also be done by opening gates G1 and G2. The signal at D2 was filtered around a center frequency of ~1 MHz with a cold LC resonant circuit and then was amplified by a low noise, preamplifier, cooled to 4.2 K. Note that the centrally located small Ohmic contact (3 × 3 μm^2) served both as D1 and S1. Being grounded, via a long metallic air bridge, it collected the interfering current while injecting edge states at zero chemical potential. Two smaller metallic air bridges applied voltage to the inner gates of QPC1 and QPC2.

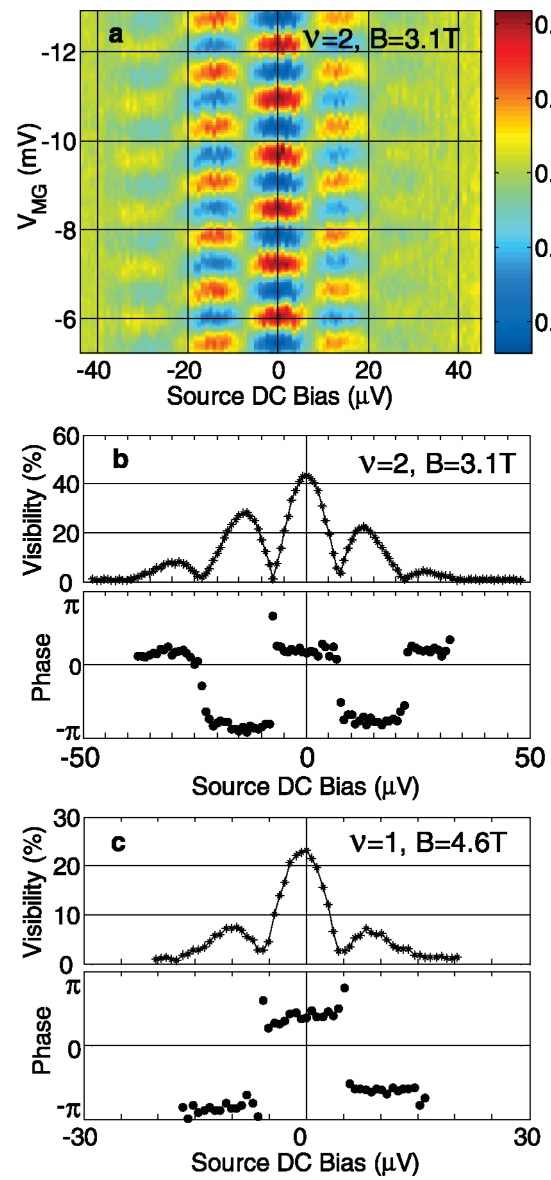

FIG. 2 (color). Interference oscillations and the visibility. (a) Two-dimensional color plot of the ~1 MHz ac signal amplitude measured at D2 as a function of the applied dc bias at the source S2 (that was biased by both 1 MHz ac signal of ~1 μV and dc) and the modulation gate voltage, at filling factor $\nu = 2$ and QPC1 and QPC2 with transmission $T \sim 0.5$. (b) The visibility (defined as $[V_{D2}(\max) - V_{D2}(\min)]/[V_{D2}(\max) + V_{D2}(\min)]$, with V_{D2} the measured ac signal at D2) and the phase of the interference pattern at $\nu = 2$ as a function of the applied dc bias to S2 [deduced from Fig. 2(a)]. Five major lobes are visible, each ~14 μV wide. The phase at each lobe is constant but it slips abruptly by π at each node. (c) A similar graph to that of Fig. 2(b), but at $\nu = 1$, exhibiting only 3 major lobes with similar "stick-slip" phase behavior.

bias increased. It is clearly seen in Figs. 2(b) ($\nu = 2$) and 2(c) ($\nu = 1$), where we plot the visibility and the phase of the AB oscillations as a function of dc voltage. Two striking features are common to Figs. 2(b) and 2(c): (a) The visibility evolves in a periodic lobe pattern as a function of energy—dipping to zero at specific dc voltages; and (b) the phase of the AB oscillations stays constant throughout each lobe (*stick*) but jumps abruptly (*slip*) by π at each zero. This surprising beating pattern presents a new energy scale of the order $\sim$10–20 μeV, much smaller than the cyclotron or the Zeeman energies. When the magnetic field was lowered, moving along the $\nu = 2$ plateau, both the amplitude and the period of the lobe pattern shrank (Fig. 3). The interference disappeared altogether for magnetic fields in the lower half of the $\nu = 2$ plateau.

Figures 2 and 3 summarize the surprising results of this work. What is the source of the lobe pattern with period 10–20 μV? What forces the phase rigidity throughout each lobe? In order to get a better insight we discuss first the simpler independent particle 1D problem, which electrons in the IQHE regime are expected to obey. The probed chemical potential in D2 can be expressed as a mixture of the chemical potentials of the two edge channels emanating from S1 and S2: $\mu_{D2} = \mu_{S1} + \bar{T}\Delta\mu$, where μ_{S1} and μ_{S2} are the chemical potentials of the two sources, $\bar{T}$ is the average transmission from S2 to D2, and $\Delta\mu \equiv \mu_{S2} - \mu_{S1} = \mu_{S2}$ since S1 was grounded. The transmission $\bar{T}$ depends, in the linear regime, on the individual transmissions through QPC1 and QPC2 and on the AB phase. In the nonlinear regime it might depend also on $\Delta\mu$. For a finite bias and zero temperature, the Landauer-Buttiker formalism [9] is usually being extended as follows:

$$\mu_{D2} = \mu_{S1} + \int_{\mu_{S1}}^{\mu_{S2}} T_{S2D2}(\varepsilon, B, V_{MG})d\varepsilon. \qquad (1)$$

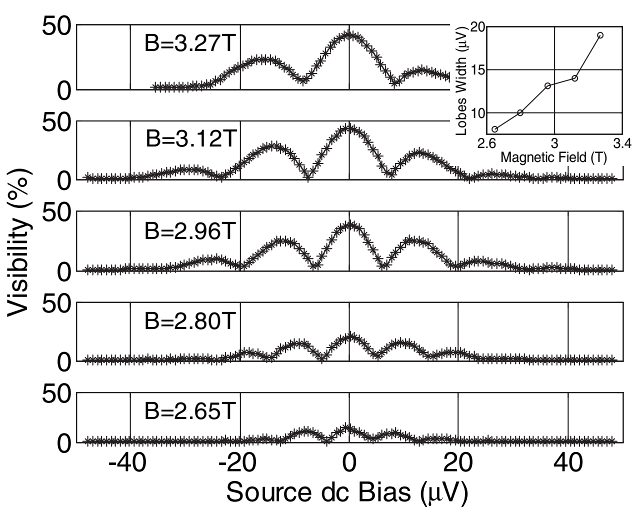

FIG. 3. Magnetic field dependence of the visibility plotted as function of the applied V_{dc}. The magnetic field is chosen to be on the conductance plateau of filling factor $\nu = 2$. As the magnetic field weakened the periodicity of the lobe structure got smaller and the strength of the oscillations diminished.

Since the transmission of each QPC is fairly constant with energy ε, the dependence of T_{S2D2} on energy is mostly through the dependence of each single particle state on the phase. This phase is given by

$$\varphi = \varphi_0(B) + \beta V_{MG} + \frac{\Delta L}{\hbar \nu_g}(\varepsilon - \varepsilon_f), \qquad (2)$$

with $\varphi_0(B)$ the AB phase at the Fermi energy ε_f, βV_{MG} the added phase due to the modulation gate voltage, ΔL the length difference between the two paths, and ν_g the single particle group velocity at ε_f (assumed to be constant for small enough dc bias). Performing ac measurements with a dc bias applied is equivalent to taking a derivative of μ_{D2} with respect to μ_{S2} at the applied dc bias,

$$\delta V_{D2}^{AC} = \left(\frac{d\mu_{D2}}{d\mu_{S2}}\right)_{eV_{DC}} \delta V_{S2}^{AC}, \qquad (3)$$

leading to an *energy independent* visibility $v = \frac{2\sqrt{t_1 r_1 t_2 r_2}}{t_1^2 t_2^2 + r_1^2 r_2^2}$ and a linear dependence of phase on energy $\Delta\varphi = \frac{\Delta L \Delta\mu}{\hbar \nu_g}$. This is expected since in the single particle model the differential measurement is equivalent to the injection of a quasimonoenergetic beam of electrons at V_{DC}, leading to energy independent AB oscillation with a monotonic phase increase with energy. Clearly, the independent electron model contradicts the experimental results.

We point now at a basic inconsistency of the single particle model. The average transmission $\bar{T} = \frac{1}{\Delta\mu} \times \int_{\mu_{S1}}^{\mu_{S2}} T_{SD}(\varepsilon)d\varepsilon$ must be invariant to a simultaneous addition of a potential V to S1 and S2. However, $\int_{\mu_{S1+V}}^{\mu_{S2+V}} T_{SD}(\varepsilon)d\varepsilon = \int_{\mu_{S1}}^{\mu_{S2}} T_{SD}(\varepsilon + V)d\varepsilon$ depends on V and therefore cannot describe properly the real system. We can try and correct this by a mean field approximation where charging of each edge, proportionally to its current, takes place. Charging, because of the finite capacitance of the edge, will raise the bottom of the conductance band at the edge by eV. As a result, each single particle state (with wave number k) has now energy $\varepsilon(k) + eV$ instead of $\varepsilon(k)$. Applying this model to our MZI, the mean chemical potential in one edge will change to $\varepsilon_f + T_{QPC1}\Delta\mu$ and in the other edge to $\varepsilon_f + R_{QPC1}\Delta\mu$ (neglecting the potential fluctuations due to the partitioning at QPC1). This implicitly assumes an edge channel capacitance $C = Le^2/h\nu_g$. The expression for the phase in Eq. (2) is now modified:

$$\varphi = \varphi_0(B) + \beta V_{MG} + \frac{L_1}{\hbar \nu_g}[\varepsilon - (\varepsilon_f + T_{QPC1}\Delta\mu)] - \frac{L_2}{\hbar \nu_g}[\varepsilon - (\varepsilon_f + R_{QPC1}\Delta\mu)]. \qquad (4)$$

The differential response depends now on the whole energy range (determined by the applied voltage). For the special condition $T_{QPC1} = R_{QPC1} = 0.5$ we find

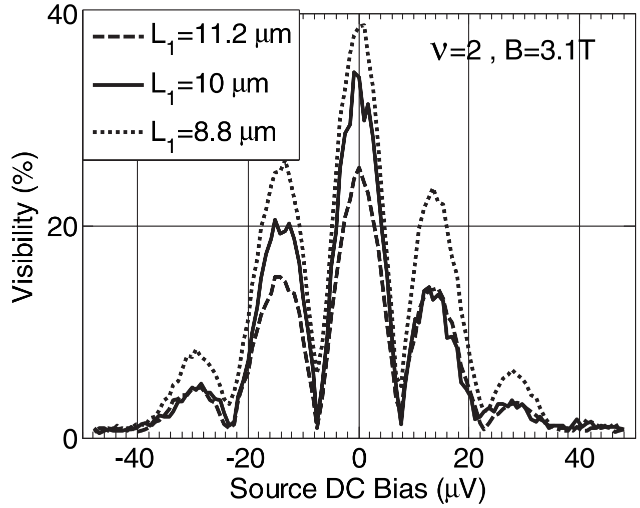

FIG. 4. The effect of changing the length of one path on the visibility. The length of the path (L_1) was increased in two steps by removing the bias from gates G1 and G2 that confine the outer edge of the interferometer. As L_1 changed from 8.8 to 11.2 μm the lobe periodicity and the phase behavior (not shown) did not change, but the visibility got smaller.

$$\left(\frac{d\mu_{D2}}{d\mu_{S2}}\right)_{\Delta\mu} = 0.5 + \sqrt{T_2 R_2}\cos[\Phi_0(B) + \beta V_{MG}] \times \cos\left(\frac{\Delta L \Delta\mu}{\hbar \nu_g}\right). \tag{5}$$

Equation (5) describes AB oscillations with constant phase and amplitude multiplied by a cosine term that depends on the applied bias. The zeros of the visibility, where π phase lapses take place, are $\frac{\Delta L \Delta\mu}{\hbar\nu_g} = \frac{\pi}{2} + n\pi$. Even though from first sight Eq. (5) seems to explain our results, it is highly sensitive to the condition $T_{QPC1} = R_{QPC1} = 0.5$ and to the paths' length difference ΔL. Deforming the interferometer, either by changing the transmission T_{QPC1} or by changing ΔL, provides a simple test of the validity of the above model. Varying T_{QPC1} from 0.1 to 0.9 (hence, R_{QPC1} from 0.9 to 0.1) did not affect the lobe pattern and the phase behavior except for a trivial change in the visibility according to $\sqrt{T_{QPC1}(1 - T_{QPC1})}$ (not shown here). We then increased the length of one path in two equal steps (via removing the negative voltage on gates G1 and G2), changing thus ΔL considerably. As seen in Fig. 4, while the amplitude of the visibility decreased with the path lengthening the overall beating pattern and phase retained the same periodicity.

We summarize now the main results: (a) The visibility beats with varying the injection energy and the phase of the oscillations stick slips. (b) The periodicity of the beating pattern, being 10–20 μV, represents a new "energy scale" that depends strongly on magnetic field but is not affected by the details of the interferometer. In additional experiments [11] we employed two active edge channels. There we demonstrated the presence of strong interchannel, and thus intrachannel, interactions—justifying our assertion of the presence of electron correlation and charging of the edges.

The unexpected behavior of interfering electrons, possibly related to interactions, raises an important question: Is this behavior common to all the systems with an energy dependent transmission? Or, is it specific only to an interferometer in the IQHE regime? In the first and more general case it presents a clear demonstration of breakdown of Landauer's conductance picture away from the linear regime. Note that a similar behavior was also observed before in two-terminal, multiple-path interferometers, at "zero" magnetic field [12,13]. The similarity in the behavior of these two totally different setups might suggest a more fundamental principle governing the behavior of interfering electrons.

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