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LETTER TO THE EDITOR

The Aharonov–Bohm effect in the fractional quantum Hall regime

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Abstract. We have observed Aharonov–Bohm oscillations around an antidot in the fractional quantum Hall regime. The oscillations have the same h/e period as a function of magnetic field as in the integer quantum Hall regime. This directly demonstrates for the first time the existence of fractionally charged quasiparticles.

The fractional quantum Hall effect (FQHE) is a fascinating manifestation of simple behaviour caused by many-body effects [1]. When the ratio of conduction electrons to magnetic flux quanta h/e (the filling factor ν) in a high-mobility two-dimensional electron gas takes certain fractional values $n/(2n+1)$ (where n is an integer), the Hall resistance is quantized. In current theories of the FQHE, the system often becomes much easier to consider intuitively if electrons are replaced with quasiparticles having fractional charge $e^* = e/(2n+1)$ [2–5]. The quasiparticles obey fractional statistics with a phase factor $\exp(i\pi\theta)$ where $\theta = (2n-1)/(2n+1)$ [2,3]. For example, for $n = 1$ the fractional liquid at filling factor $\nu = 1/3$ is associated with a quasiparticle of charge $e^* = e/3$ and $\theta = 1/3$. It has been pointed out by several workers that neither the observation of fractional Hall plateaux, nor the hierarchy of the fractions, can provide evidence for these quasiparticles [6–8]. This is because the current on a plateau is carried by the collective motion of the electron gas, not by individual quasiparticles, and because all fractions can be understood without reference to quasiparticles.

In order to observe the quasiparticles directly, Kivelson and Pokrovsky [6] suggested that quasiparticles can form single-particle (SP) states around a bump in the potential (antidot), just as particles, do, but that successive states would enclose an additional flux h/e^* rather than h/e. Detecting such SP states is possible in the form of Aharonov–Bohm (AB) oscillations [9, 10]. Thus, for $\nu = 1/3$ a $3h/e$ periodicity was expected. Experimental observations of a few fluctuations at first appeared to support this result [11], but then it was pointed out [12] that quasiparticles should show the h/e periodicity due to gauge invariance. Thus, according to the current theories, resonant tunnelling of a fractional state giving rise to h/e AB oscillations in the FQHE regime provides direct evidence for the existence of fractionally charged quasiparticles [12, 7]. The fluctuations that had been observed [11] were, on the other hand, explained to be the result of charging or resonant tunnelling with increased sensitivity to temperature in the FQHE regime. As further confirmation for the fractional charge, it was suggested that localizing a charge e^* on the edge of an antidot would require a Coulomb blockade (CB) charging energy $E_C = e^{*2}/C$, where C is the appropriate capacitance [12]. Since E_C scales as e^{*2}, if CB dominates then the energy scale of the problem should scale as e^{*2}, otherwise the energy level spacing between the SP states scales as $E_r e^*/B$ where B is the magnetic field and E_r is the local electric field. *Either* way, measurement of the energy scale should reveal the fractional charge. Finally, Thouless and Gefen [7] also considered the possible h/e^* periodicity and concluded that on short enough timescales (seemingly unobtainably short), this longer periodicity might prevail, but that it would be replaced by h/e in equilibrium.

In this letter we present measurements of the period of AB oscillations in the integer and the fractional regimes. We show that the period in magnetic field is the same, h/e, in both regimes, for three different devices. This provides the first direct evidence for fractionally charged quasiparticles. We have also studied the period in gate voltage in the two regimes. In one device the period is proportional to $1/B$ as expected, but in the others it is larger than this in the fractional regime. Our device consists of a patterned two-dimensional electron gas formed at the interface of a GaAs–$Al_xGa_{1-x}As$ heterostructure. Narrow channels are defined using the split-gate technique, with widths dependent on the gate biases. The geometry of the gates is shown inset in figure 1. An antidot (potential hump) is formed using a central 0.3 μm diameter gate, and two narrow constrictions on either side are produced with side gates. The centre gate is contacted separately from the others using a special technique [13]. The carrier concentration of the wafers used, after brief illumination with a red LED, was $\sim 1.5 \times 10^{15}$ m^{-2} (devices A and B) and $\sim 1 \times 10^{15}$ m^{-2} (device C) and the mobilities were ~ 150 m^2 V^{-1} s^{-1}. Four-terminal resistance measurements were performed in a dilution refrigerator at temperatures $T < 100$ mK, using standard low-frequency phase-sensitive techniques. A constant current of 0.1 nA was used, low enough to avoid electron heating.

In the integer quantum Hall effect (IQHE), each Landau level has a corresponding edge state near each edge of the sample, including that of the antidot. Closed orbits around the antidot can form quantized SP states if the phase-coherence length is sufficiently long. Each encloses magnetic flux, so as B is varied, the SP states are swept through the Fermi energy E_F at a rate of one per h/e change in flux, due to the AB effect. We have used our devices to study such effects, and find h/e AB oscillations in the resistance measured across the two parallel constrictions [10]. This occurs because electrons travelling along one edge of the sample are brought close enough to the antidot to tunnel into whichever SP state in the same Landau level is at E_F. They must also be able to tunnel out of that state to the opposite edge of the sample, giving rise to backscattering. This process is essentially a single-particle process and is illustrated in the inset to figure 1, where lines around the gates represent edge states.

We have now looked at the fractional quantum Hall effect (FQHE) in such samples. Figure 1(a) shows AB oscillations for device A at low B, in the IQHE regime, with the filling factor in the constrictions $\nu_c = 1$. Figures 1(b) and 1(c) show similar oscillations when the filling factor ν_b in the bulk was 2/3 ($\nu_c = 1/3$). The period ΔB in both cases was approximately 14 mT. Devices B and C also showed AB oscillations that had the same period in both regimes. In the IQHE regime, we calculate the number of spin-split edge states ν_c propagating through each constriction (or whichever is wider), from $\nu_c = (h/e^2)/R$, where R is the two-terminal longitudinal resistance, which is equivalent to the sum of the four-terminal and Hall resistances [14]. Thus plateaux are seen in R as the width of the constrictions is varied by changing a gate voltage, due to reflection of some of the edge states. The same occurs in the FQHE, where plateaux are seen corresponding to the usual strong fractions such as 2/3 and 1/3 [15]. When $\nu_b = 2/3$, we see a very well defined plateau at $\nu_c = 1/3$ ($R = 3h/e^2$; see figure 1). This plateau implies that there is a $\nu = 1/3$ state encircling the antidot. The oscillations that are seen coming off the plateau, and that persist for $\nu_c \leqslant 1/3$ (up to about $\nu_c = 0.2$; see figure 1), are therefore due to the single

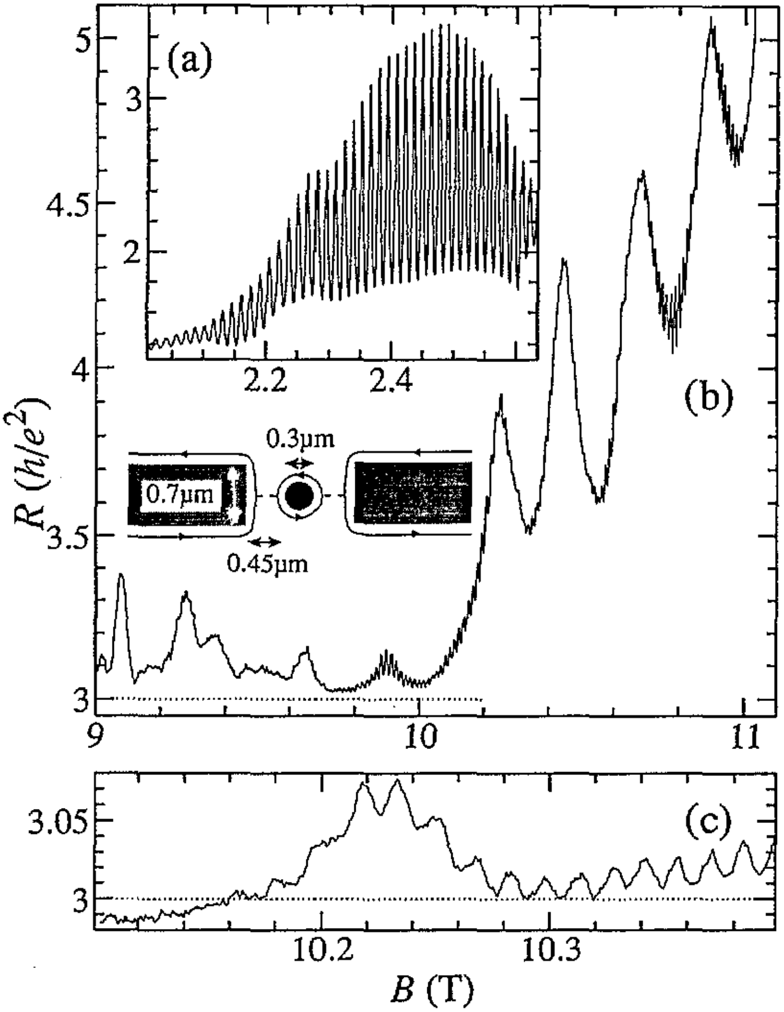

Figure 1. Aharonov–Bohm oscillations in the integer (a) and fractional (b) QHE regimes; (c) *shows an enlargement of the* $3h/e^2$ *plateau region similar to that in (b). Dotted lines indicate* the plateau (sample A).

particles of the FQHE, or quasiparticles, that exhibit the AB effect. As discussed above, in this regime the observed period of h/e is consistent only with AB oscillations resulting from quasiparticles with charge $e/3$, not electrons [7]. Thus we have demonstrated the existence of such quasiparticles, as expected from current theories of the FQHE. One can describe the same phenomena in terms of charge-e particles (such as composite fermions [4, 5]). However, the h/e periodicity corresponds to moving electrons from one state to the next. Since for $\nu = 1/3$ there are three states per electron, this is equivalent to transferring a charge $e/3$ between the inner edge of the sample and the outer, and it is convenient to use the terminology of quasiparticles [4].

We have independent control of the centre gate voltage V_g, and can thus change the size of the potential hump. Figure 2 shows a set of magnetic field sweeps at closely spaced values of V_g. The AB oscillations are seen to shift sideways, yielding a period in gate voltage, $\Delta V_g = 1.15 \pm 0.05$ mV. This has to be compared with the behaviour at low B. Figure 3 shows $1/\Delta V_g$ as a function of $1/\nu_c \propto B$ for three devices. At intermediate values (between

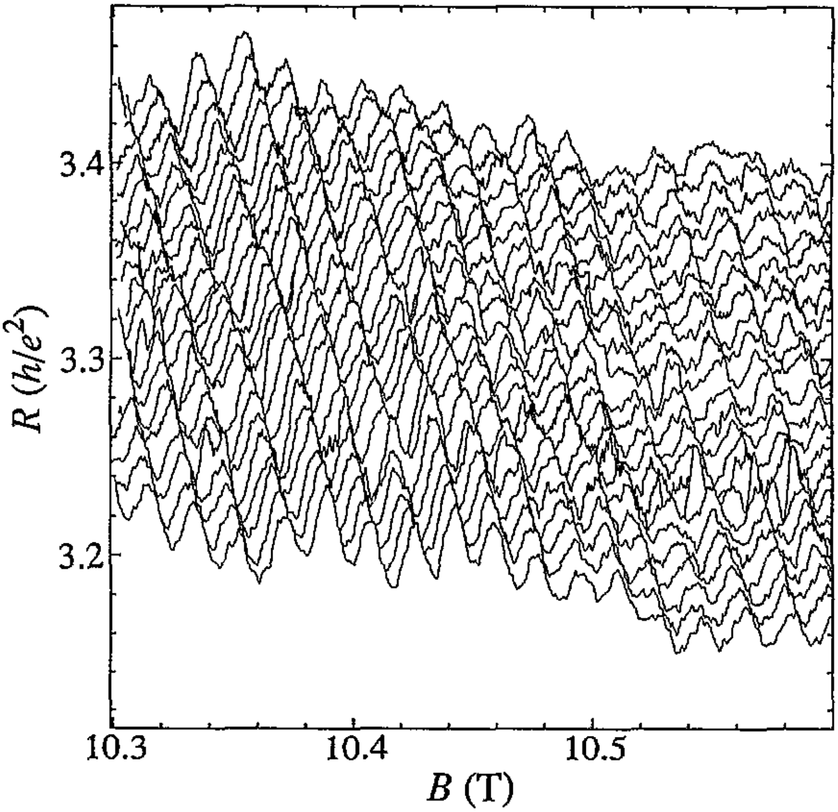

Figure 2. A set of sweeps of B just above the $n_c = 3$ plateau incrementing V_g by 0.2 mV at each step (sample B).

3.5 and 10 T in devices A and B), AB oscillations were not found. We find $\Delta V_g \propto 1/B$ other than for two samples near $\nu_b = 2/3$, where the period is larger than expected from a $1/B$ dependence. The effect of the centre gate voltage V_g is quite complicated. Suppose the central gate has capacitance C_g to the 2DEG. Then a change ΔV_g changes the charge on the 2DEG by $C_g \Delta V_g$. When all Landau levels (LLs) are full (i.e. the filling factor ν_b is an integer), only edge states contribute, and C_g is the sum of the roughly equal capacitances of each edge state to the gate, C_g/N, where $N \approx \nu_b$ is the number of edge states that are affected by the gate.

In a transport measurement of the AB effect, since we see a single-frequency oscillation, we are only detecting tunnelling through one edge state. If ν_b is an integer, all states up to E_F are filled (at zero temperature). Thus a change in V_g sufficient to remove exactly one electron from the edge state also increases the area A (and radius r) just enough to push one SP state above E_F. The correspondence is obvious if one considers that each SP state encloses one flux quantum h/e more than its neighbour closer to the antidot; ν_b is defined as the number of electrons per flux quantum, and there are ν_b edge states. Thus for integer filling factor there are as many electrons as SP states below E_F and so each SP state is occupied. The period (from counting electrons) $\Delta V_g \simeq Ne/C_g \propto 1/B$. Counting states, since $h/e = B\,\Delta A$, we can show that $\Delta V_g = E_r h/(e2\pi r\alpha B) = \nu_b e/C_g \propto 1/B$, where $E_r = \mathrm{d}V/\mathrm{d}r$ is the slope of the potential and $\alpha = \mathrm{d}V/\mathrm{d}V_g$.

These two calculations differ when ν_b is not an integer (due to the simple requirement of charge neutrality). In that case, SP states in the uppermost LL are not all filled, so changing from one to the next (by adding a flux quantum within the antidot) does not necessarily

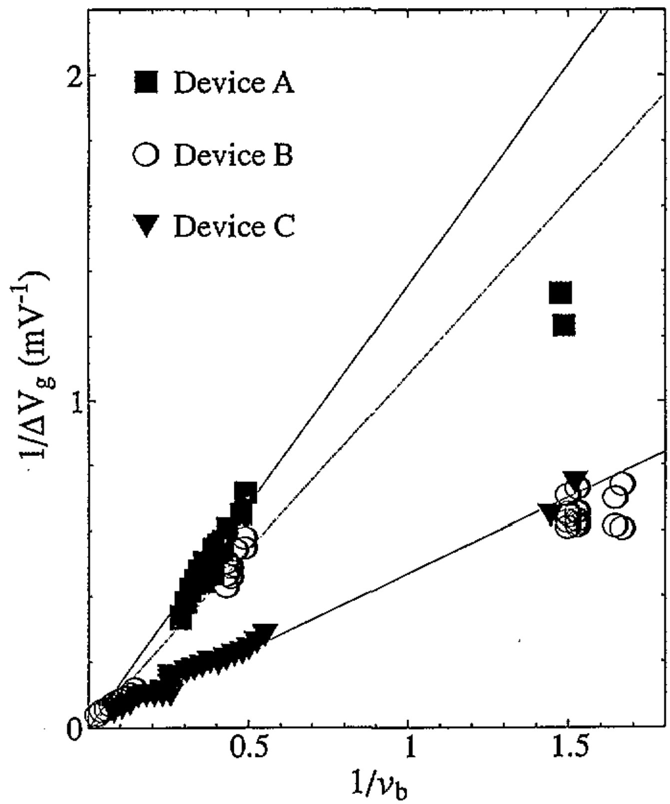

Figure 3. $1/\Delta V_g$ versus $1/n_b$ for three devices. The straight lines are fits through zero to the low-field data.

change the charge by e. One might therefore expect to observe Coulomb blockade (CB), whereby a change in charge is prevented until one whole electron can move. However, there is a significant difference between this system and the cavities in which CB is normally observed. Loosely, one can visualize this as follows: when one flux quantum is added within the antidot, the system has its lowest energy if the pattern of occupation of the states near E_F is shifted by one state from the original arrangement, so that relative to E_F it 'looks' the same as before (assuming that the size of the antidot has not changed by much). If the flux is added slowly, the system will always relax into its lowest energy state (to satisfy gauge invariance), with a relaxation time that is likely to be very short (picoseconds or longer) [7]. Thus the CB will be broken by the system 'readjusting', and oscillations as a function of V_g will have period h/e in the flux added by the increase in size of the centre gate. The same will hold in the FQHE regime, where the readjustment is equivalent to the tunnelling of a quasiparticle of charge e^* between the inner and outer edges [7]. States are still separated in flux by h/e whether they be for electrons or quasiparticles. We can either consider electrons relaxing every h/e or adding a new quasiparticle at the same rate, with as many quasiparticles as h/e states. Thus we should see $\Delta V_g \propto 1/B$ (independent of the charge) over the whole range.

For $\nu_b > 2$, and for device C over the whole range, the $1/B$ relation holds reasonably (figure 3, straight lines). This is not the case for the other two devices at $\nu_b \sim 2/3$ ($\nu_c = 1/3$). Possible explanations for this are that C_g or perhaps the slope of the potential E_r changes with magnetic field, or else that the Coulomb blockade is not in fact broken. The difference between devices was that the distance from the surface to the 2DEG was

~100 nm for devices A and B and 300 nm for device C. This may affect the capacitance and the slope of the potential.

The energy scales should be different in the integer and fractional regimes. From the above discussion, the occupied states' energy spacing scales as e/B or e^*/B, depending on whether electrons or quasiparticles are involved. However, the energy scale for quasiparticles is e^*/e times that for electrons at the same field, whatever the mechanism, since, for each electron, the energy eV from an applied bias V, or the thermal energy $\sim k_BT$, has effectively to be shared among e/e^* quasiparticles. Thus Aharonov–Bohm oscillations die out when e^*/B and k_BTe/e^* are comparable, the *same* condition as for electrons. For device C, at $\nu = 2/3$ ($B = 5.6$ T, $\Delta B = 15.6$ mT) the oscillation amplitude was reduced by a factor of two at 60±10 mK, in comparison with 250±10 mK for the integer regime ($B = 1.8$ T, $\Delta B = 17.1$ mT). Allowing for the slight difference in period due to a change in centre gate voltage, the energy scale has decreased by a factor of 4.6±1, whereas the field changed by a factor of 3.1. From the above discussion these two factors are expected to be the same for quasiparticles or electrons. This is approximately the case, although not within the error estimate. If the factor really is greater than 3.1, then this may be an indication of excitations of quasiparticles of fractional charge rather than electrons. DC bias measurements at the same fields give a ratio of 3.2±0.5, in good agreement with the field change [16].

In conclusion, we have observed Aharonov–Bohm oscillations with flux period h/e in the fractional quantum Hall regime, confirming the expectation that gauge invariance forbids the h/e^* period and demonstrating for the first time the existence of fractionally charged quasiparticles. The period in centre gate voltage has also been measured and for one device the results are as expected. However, two other devices show a saturation that is not at present understood.

We note that just before submission of this manuscript, a preprint was received from V J Goldman and B Su reporting similar observations.

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