ARTICLES

Observation of neutral modes in the fractional quantum Hall regime

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The quantum Hall effect takes place in a two-dimensional electron gas under a strong magnetic field and involves current flow along the edges of the sample. For some particle–hole conjugate states of the fractional regime (for example, with fillings between 1/2 and 1 of the lowest Landau level), early predictions suggested the presence of counter-propagating edge currents in addition to the expected ones. When this did not agree with the measured conductance, it was suggested that disorder and interactions will lead to counter-propagating modes that carry only energy—the so called neutral modes. In addition, a neutral upstream mode (the Majorana mode) was expected for selected wavefunctions proposed for the even-denominator filling 5/2. Here we report the direct observation of counter-propagating neutral modes for fillings of 2/3, 3/5 and 5/2. The basis of our approach is that, if such modes impinge on a narrow constriction, the neutral quasiparticles will be partly reflected and fragmented into charge carriers, which can be detected through shot noise measurements. We find that the resultant shot noise is proportional to the injected current. Moreover, when we simultaneously inject a charge mode, the presence of the neutral mode was found to significantly affect the Fano factor and the temperature of the backscattered charge mode. In particular, such observations for filling 5/2 may single out the non-Abelian wavefunctions for the state.

When the fractional quantum Hall effect[1] is operative, current propagates along the edges of a two-dimensional electron gas (2DEG) by way of edge modes with a chirality dictated by the applied magnetic field[2]. For some particle–hole conjugate states (when, for example, the filling of Landau levels in the bulk, ν_b, is given by $p-1/2<\nu_b<p$, with p an integer), counter-propagating current modes were predicted[3,4], but experiments did not find such edge modes[5]. It was suggested that in the presence of disorder and interactions, edge reconstruction would lead to counter-propagating neutral modes, which would carry only energy[6,7]. Such modes would be difficult to detect, as they would not carry charge. Because (to the best of our knowledge) these neutral modes have not been observed thus far[8]—and are sometimes termed 'elusive'—it is not surprising that very little is known about them. For example, the following are unknown: the energy they carry; their interactions with potential barriers; their decay length; their temperature dependence; their velocity; and their interaction with charge modes.

Proposals for detecting the neutral modes include measuring tunnelling exponents in constrictions[7], observing thermal transport[9–11], searching for resonances in a long constriction[12], or looking for heating effects on the properties of charge modes[13,14]. In contrast, our approach is to allow an upstream neutral mode, if it were to exist, to impinge on a quantum point contact (QPC) constriction, in the hope that the neutral quasiparticles would be fragmented into charge carriers. As the neutral mode is not expected to carry average current, fragmentation was tested by measuring shot noise. By injecting a charge mode simultaneously, we could also measure the effect of the neutral mode on the transmission probability (t) of the QPC constriction and on the shot noise of the partitioned charge mode. Whereas we found t to depend very weakly on the presence of the neutral mode, the shot noise due to the charge mode was found to be highly sensitive to the presence of the neutral mode. We report in some detail the behaviour of this 'model' for the fractional state $\nu_b=2/3$; we also present data, albeit more briefly, for $\nu_b=3/5$, 5/3 and 5/2. For comparison, we also performed similar experiments for 'regular' states, namely $\nu_b=1$, 2/5 and 1/3, proving the absence of such striking effects. We stress that we concentrate here mainly on the observation of neutral modes and not on many of their unique properties, which are now under investigation.

Neutral edge in the $\nu_b = 2/3$ state

At $\nu_b=2/3$ in an ideal 2DEG, with a rather fast charge density drop towards the edge of the sample, it was predicted that two spatially separated edge modes coexist: an electron channel moving downstream close to the sample's edge, and an inward $e^2/3h$ upstream channel[3,4] (here e is the electron charge and h Planck's constant). This picture can also be explained with the composite fermion model[15], which is applicable to fractional states in the lowest Landau level. This two channel model predicts a two-terminal conductance of $(4/3)e^2/h$, which has not been observed. When electron interactions and disorder are taken into account, mixing of the two oppositely propagating charge modes is expected to result in a downstream mode of conductance $(2/3)e^2/h$ and an upstream neutral mode[6,7,9], agreeing with the measured two-terminal conductance $(2/3)e^2/h$. One can view the neutral mode as a fluctuating 'dipole' that propagates at a lower velocity than the charge mode velocity[7,12] (or even at zero velocity[16,17]), decaying with distance and with temperature T as T^{-2} (ref. 7).

Sample and set-up

The configuration of our sample (used for all filling factors except for $\nu_b=5/2$), fabricated in a GaAs–AlGaAs heterostructure with an embedded 2DEG, is shown in Fig. 1. The 2DEG, with a carrier density of $10^{11}\,\mathrm{cm^{-2}}$ and a dark mobility of $>10^7\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ at $T<1$ K, was buried 116 nm below the surface of the heterostructure. An ~100-nm-long negatively biased split-gate (15 nm Ti/30 nm Au)

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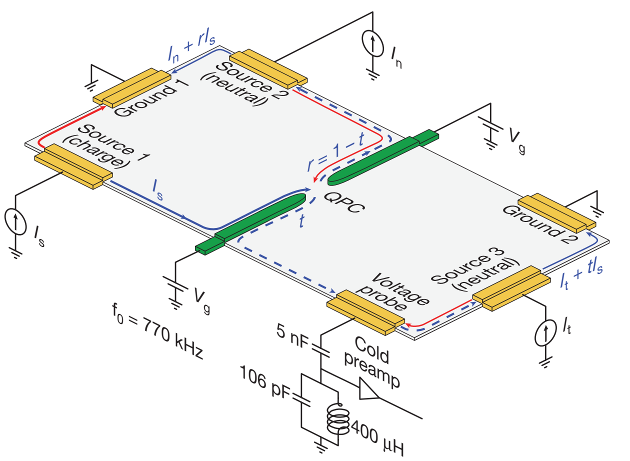

Figure 1 | The experimental set-up for measuring the neutral mode. The orange pads are ohmic contacts. The green pads form the split-gate of the QPC constriction, with V_g controlling the transmission probability t (or the reflection $r = 1 - t$). The grounded contacts are directly connected to the cold finger of the dilution refrigerator. Excitation current is driven to the sources via a d.c. voltage V and a large resistor in series. The a.c. signal, tuned to the LC resonance frequency ($f_0 = 770$ kHz), is used to measure the two-terminal differential conductance. Blue lines describe the downstream charge edge modes, while red lines stand for the upstream neutral edge modes. Note that owing to the multi-terminal configuration the 'current noise' of the preamplifier (injected backwards from the preamplifier's input into the sample) and the measured thermal noise (measured with 10-kHz resolution bandwidth around f_0) were both independent of t (ref. 18). The cryogenic preamplifier's 'current noise' was ~13.6 fA Hz$^{-1/2}$ and its 'voltage noise' was 680 pV Hz$^{-1/2}$, both referred to its input.

with an opening ~600 nm wide formed the QPC constriction. The grounded contacts (made of AuGeNi) were tied directly to the cold finger of the dilution refrigerator at ~10 mK, thus effectively cooling the electrons to ~10 mK (verified by noise measurements). The magnetic field was raised to $B = 6.4$ T, leading to $\nu_b = 2/3$—as identified by a longitudinal resistance, $R_{xx} \approx 0$ (in the bulk and also through the QPC), and a Hall plateau identified by Hall resistance, $R_{xy} \approx 39$ kΩ. Current was injected from source 1 (I_s) with an anticlockwise chirality, directing the current towards the QPC constriction (transmission probability t). Generated shot noise was collected by the voltage probe (with an LC resonant circuit tuned to 770 kHz with bandwidth ~40 kHz). The signal was first amplified by a cooled, home-made preamplifier (voltage gain ~7), which was followed by a room temperature amplifier (NF-220F5) with voltage gain ~200 and a spectrum analyser. From the opposite side of the mesa, current was injected from source 2 (I_n), propagating downstream away from the QPC constriction and collected by ground 1. A neutral mode, if it were to exist, was expected to emanate from source 2 and move upstream towards the QPC constriction, which was ~40 μm (or ~120 μm) away. Similarly, source 3 could be charged too.

What is the expected noise at the voltage probe? The total noise is composed of shot noise that exists only when current is driven (termed 'excess noise'); thermal (Johnson-Nyquist) noise; background noise, mainly due to instrumentation noise. For stochastic backscattering events by the QPC constriction, injecting a noiseless current from a source at zero temperature is expected to lead to a binomial charge distribution in the partitioned current[18–22]. For single edge channel transport, partitioning of e^* charges at finite temperature was found to be also stochastic under certain conditions, with the current low-frequency spectral density (S^i) of the excess noise and thermal noise, $S^i(V_s, f \approx 0)_T$ (f is the frequency), being given by[18]:

$$S^i(V_s, f=0)_T = 2e^* V_s g_b\, t(1-t)\left[\coth\left(\frac{e^* V_s}{2k_B T}\right) - \frac{2k_B T}{e^* V_s}\right] + 4k_B T g_b \quad (1)$$

where V_s is the applied source d.c. voltage, $g_b = \nu_b e^2/h$ is the Hall conductance, and k_B is Boltzmann's constant. Empirically, all the noise measurements here complied with this form. The dependence of the excess shot noise is captured by the inferred quasiparticles' temperature (T) and effective charge (e^*). We will describe the effect of I_n on the noise throughout these two parameters. It should be clear that what we actually measure is the Fano factor (the ratio between the noise and the average current). We interpret it as an effective charge in the sense that a stochastically partitioned beam of particles with this charge would reproduce the same measured results. Note that lower lying channels, which traverse the constriction with unity transmission probability, do not carry excess noise[22].

Measurements of the $\nu_b = 2/3$ state

Sources 1, 2 and 3 in Fig. 1 were charged separately. (1) Charging source 3, hence injecting I_t anticlockwise and a neutral mode clockwise towards the voltage probe, did not add any measurable noise at the voltage probe (our temperature resolution was <2 mK Hz$^{-1/2}$). (2) Reversing the polarity of the magnetic field and then charging source 1, thus injecting I_s clockwise and a neutral mode towards the QPC constriction, led again to a null added noise independent of t. (3) Back in the original orientation of the magnetic field, charging source 2, thus injecting I_n anticlockwise and a neutral mode clockwise, led to a significant excess noise in the voltage probe for $t < 1$ (see Fig. 2). The excess noise, which increased initially almost linearly with I_n, tended to saturate for $I_n > 2$ nA. Moreover, it was seemingly proportional to $t(1 - t)$ (with zero excess noise when $t = 1$ or $t = 0$ and with a maximum at $t \approx 1/2$).

These results can be understood qualitatively if indeed an upstream neutral mode exists. When source 2 is charged, some of the power dissipated at source 2 can excite the upstream neutral mode there. When incident on the QPC, the excited neutral mode leads to enhanced fluctuations in the charge crossing the QPC. This can be modelled as if neutral quasiparticles ('dipoles') were fragmented into partitioned quasiparticles and quasiholes, or in a manner similar to Johnson noise, which occurs when thermal energy is present in all the incident channels. The current noise generated at the QPC then follows the chirality of the charge mode and is detected in the voltage probe (note that the chirality of electrons and holes in the conduction band is similar). Thus, the QPC effectively converts the

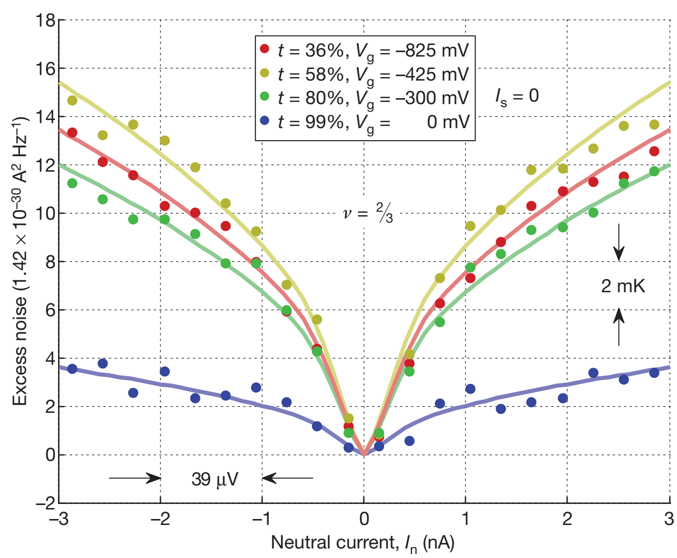

Figure 2 | Detection of the neutral mode at $\nu_b = 2/3$. Shown is excess noise measured at the voltage probe as a function of driven current I_n via source 2, for different transmission probabilities t of the QPC constriction. The noise is proportional to I_n and approximately to $t(1 - t)$, vanishing for $t = 1$ or $t = 0$. Horizontal arrows indicate $\Delta V_n = 39$ μV for $\Delta I_n = 1$ nA; vertical arrows indicate $\Delta T = 2$ mK, calculated via $\Delta S^i = 4k_B g_{2/3} \Delta T$.

upstream neutral current into a measurable charge noise signal. To get an order of magnitude, the excess noise for $I_n = 2$ nA is equivalent to shot noise generated by ~250 pA.

We test now the interaction of the neutral mode with a charge mode at the QPC constriction. Excess noise of partitioned charge modes had been already measured at $\nu_b = 2/3$ (ref. 22). The backscattered quasiparticle charge was found to be strongly temperature dependent, with $e^* = (2/3)e$ at $T \approx 10$ mK over a wide range of t, dropping to $e^* \approx e/3$ around $T \approx 120$ mK (the charge evolution is shown again for convenience in Fig. 3d). Injecting I_s (from source 1 while $I_n = 0$) led, again, to an excess noise and $e^* \approx (2/3)e$ for $t = 0.3$–0.8. Measurements of the nonlinear transmission and shot noise were repeated when source 2 was also charged, thus injecting a neutral mode towards the QPC constriction (Fig. 3a). Whereas the transmission changed merely by a fraction of a percent, the noise was affected dramatically by I_n. These results can be understood in the following way. First, charging source 2 added a constant noise at the voltage probe (seen for $I_s = 0$ in Fig. 3a, and being symmetric with respect to $\pm I_n$); second, the partitioned quasiparticle charge dropped down to $e^* \approx 0.4e$ at $I_n = 3$ nA ($V_n \approx 120\,\mu$V; Fig. 3b). Third, the apparent temperature of the partitioned quasiparticles increased by $\Delta T_{qp} \approx 15$ mK at $I_n = -2$ nA—with temperature reaching ~25–30 mK (Fig. 3c)—as determined from the 'increased rounding' in the spectral density near $I_s = 0$ (see equation (1)). This relatively small temperature increase cannot account for the charge evolution shown in Fig. 3b (see temperature dependence in Fig. 3d). Similar measurements were performed at different electron temperatures and are detailed in Supplementary Information.

Before presenting results for three more fractional states that were theorized to posses an upstream neutral mode, $\nu_b = 3/5$, 5/3 and 5/2, we show evidence that 'simpler' fractional states, such as $\nu_b = 1/3$, 2/5 and 1, do not support upstream neutral modes (in general, the states are with $p \le \nu < p + 1/2$, with p zero or an integer). We start with $\nu_b = 2/5$, because its partitioned fractional charge was found also to evolve with temperature in a fashion similar to that of $\nu_b = 2/3$, namely, the weakly backscattered quasiparticle charge was $e^* = (2/5)e$ at 10 mK, dropping to $e^* = e/5$ at approximately 50 mK (ref. 23; hence, no change in the noise will exclude a simple 'heating' effect caused by I_n). Increasing the field to $B = 10.5$ T (corresponding to $\nu = 2/5$), we first charged source 2 with $I_s = 0$; we observed no increase in the excess noise for two different transmissions (Fig. 4a). Performing conductance and noise measurements as function of I_s, at different values of I_n ($I_n = 0$–3 nA) did not show, again, any effect of I_n (Fig. 4b). These results are in overwhelming contrast with those at $\nu_b = 2/3$, excluding the presence of an upstream neutral mode. Similar measurements were performed at $\nu_b = 1/3$ and $\nu_b = 1$, and again, no measurable effects were observed when the neutral contact (source 2) was charged (results not shown).

Measurements of the $\nu_b = 3/5$ state

We continue with the fractional state $\nu_b = 3/5$. Being the particle–hole conjugate of $\nu_b = 2/5$, it is expected to support two upstream neutral modes and one downstream charge mode[7,9]. Tuning the field to $B = 7$ T with a clear fractional state $\nu_b = 3/5$, charging source 3 did not lead to any increase in the noise at the voltage probe. However, as for $\nu_b = 2/3$, injecting the neutral mode by charging source 2 with $t < 1$ of the QPC constriction led to excess noise nearly linear with $I_n < 1$nA, and tending to saturate for higher values of I_n (Fig. 5a). The excess noise (or, the equivalent temperature) was more than 50% higher than in $\nu_b = 2/3$, possibly accounting for the two upstream neutral modes in the $\nu_b = 3/5$ state. Charging source 1 in the presence of charged source 2, the presence of I_n affected only slightly the nonlinear conductance (by a fraction of a percent, Fig. 5b); however, again, the excess noise altered significantly (Fig. 5c). As before, the determined charge of the backscattered quasiparticles dropped with I_n from $e^* \approx (2/5)e$ at $I_n = 0$ to $e^* = 0.25e$ at $I_n \approx 5$ nA (Fig. 5c and d). As evident in Fig. 5c, the temperature of the partitioned quasiparticles increased as I_n increased.

We also tested the $\nu_b = 5/3$ $(= 1 + 2/3)$ fractional state. Unlike the $\nu_b = 2/3$ state, this state is expected to support two downstream modes and only one upstream mode. Unfortunately, we are not aware of a theoretical treatment of this complex edge mode with

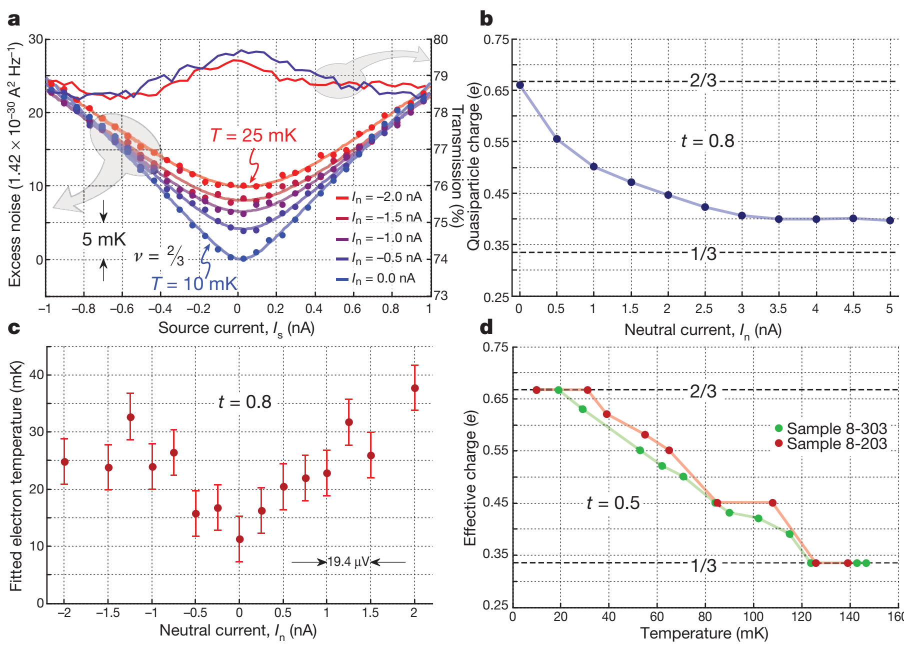

Figure 3 | The effect of impinging the neutral mode simultaneously with the charge mode on the QPC constriction at $\nu_b = 2/3$. a, The conductance and total noise as a function of source 1 current I_s for different I_n. The change in the nonlinear transmission probability as I_n increases is negligible. The excess noise increases, the partitioned quasiparticle charge diminishes, and the temperature of the quasiparticles increases as I_n increases. **b,** Charge evolution as a function of I_n. The charge starts at $e^* = 2e/3$ and drops to $e^* = 0.4e$. **c,** Temperature evolution of the partitioned quasiparticles as a function of I_n. The temperature, fitted from **a**, increases by approximately 15–25 mK at $I_n = 2$ nA. Error bars show ±1 s.d. (=±4 mK). **d,** The dependence of the quasiparticle charge on temperature[28].

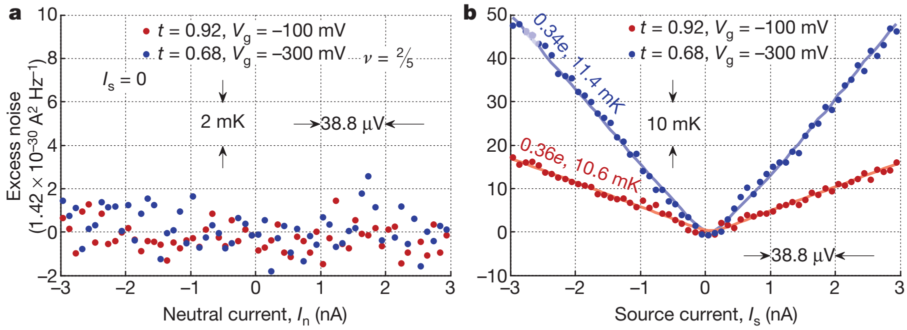

Figure 4 | Measurements at fractional state $\nu_b = 2/5$. **a**, Injecting only I_n, with two different transmissions of the QPC constriction, did not result in any excess shot noise. **b**, Similarly, injecting both I_n and I_s (and plotting the excess noise as a function of I_s at two different transmissions) did not have any effect on the excess noise.

interactions and in the presence of disorder. In our measurements we observed a barely marginal effect of an upstream neutral mode, leaving this fractional state for future studies.

Measurements of the $\nu_b = 5/2$ state

We turn now to the $\nu_b = 5/2$ state. Although the expectations are that this fractional state is of non-Abelian nature, thus supporting a neutral Majorana mode, the nature of the state as well as the presence of the neutral mode have not been established thus far. A Pfaffian state with an unreconstructed edge will not have an upstream neutral mode[24]. An anti-Pfaffian state with a disorder-dominated but unreconstructed edge will have three upstream neutral Majorana modes[10,11]. If the edge is reconstructed, as may be expected for a smooth confining potential, then the Pfaffian and anti-Pfaffian states can both have a single upstream neutral Majorana mode[25]. An experiment that could distinguish these four possibilities has been proposed[13]. If the edges were not disorder-dominated, then the anti-Pfaffian state would have the wrong two-terminal conductance for the same reason as the $\nu_b = 2/3$ state[10,11]. However, in the absence of a microscopic theory it is very difficult to make definite statements, and thus a detection of an upstream neutral mode can only strengthen belief in the non-Abelian nature of the $\nu_b = 5/2$ state.

For these measurements, we used a different heterostructure with the same contact configuration. The details of such a heterostructure have been reported[26] (see also Fig. 6 legend). Clear signatures of the $\nu_b = 5/2$ state were observed with $R_{xx} \approx 0$ at $B = 5$ T. The first and the most important result is shown in Fig. 6a, where only source 2 was charged. Excess noise was observed with an approximate quadratic increase with I_n. This proves, right from the start, the presence of an upstream neutral mode. Although the increase of noise was the smallest among the fractional states being tested, it was in relative terms the highest, as the actual current that was carried by the fractional state was the smallest (as 4/5 of the current is carried by the first two, lower lying, integer Landau levels). Similarly, the excess noise due to current arriving from source 1, when charged, was strongly affected by I_n, with an apparent increase of the quasiparticles' temperature while their charge dropped (Fig. 6c and d). Again, as in the $\nu_b = 2/3$ state, this temperature increase cannot account for the charge drop[27]. The charge dropped with I_n from $e^* = 0.75e$ at $I_n = 0$ nA to $e^* = 0.32e$ at $I_n = 10$ nA. A similar evolution of the charge, but as a

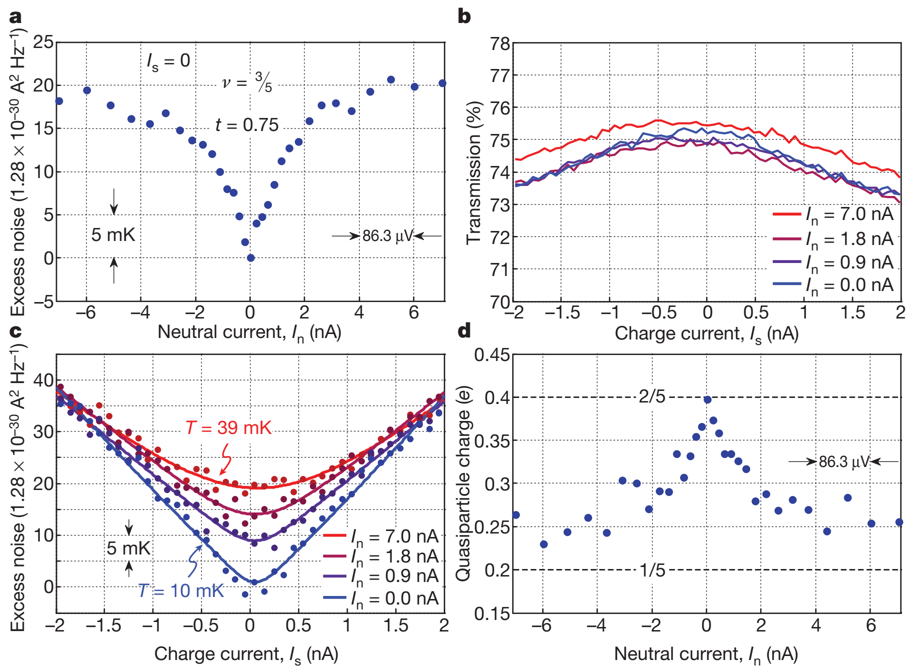

Figure 5 | Testing for the existence of the neutral mode at $\nu_b = 3/5$. **a**, Excess noise as a function of injecting I_n—direct evidence of an upstream neutral mode. **b**, The dependence of the nonlinear conductance as a function of I_s on the presence of I_n. The relative change is small, amounting to a fraction of a per cent. **c**, The dependence of the excess noise as a function of I_s on the presence of I_n. The noise increases, the quasiparticle charge drops, and the temperature of the quasiparticles increases. **d**, The dependence of the quasiparticle charge on I_n (extracted from **c**).

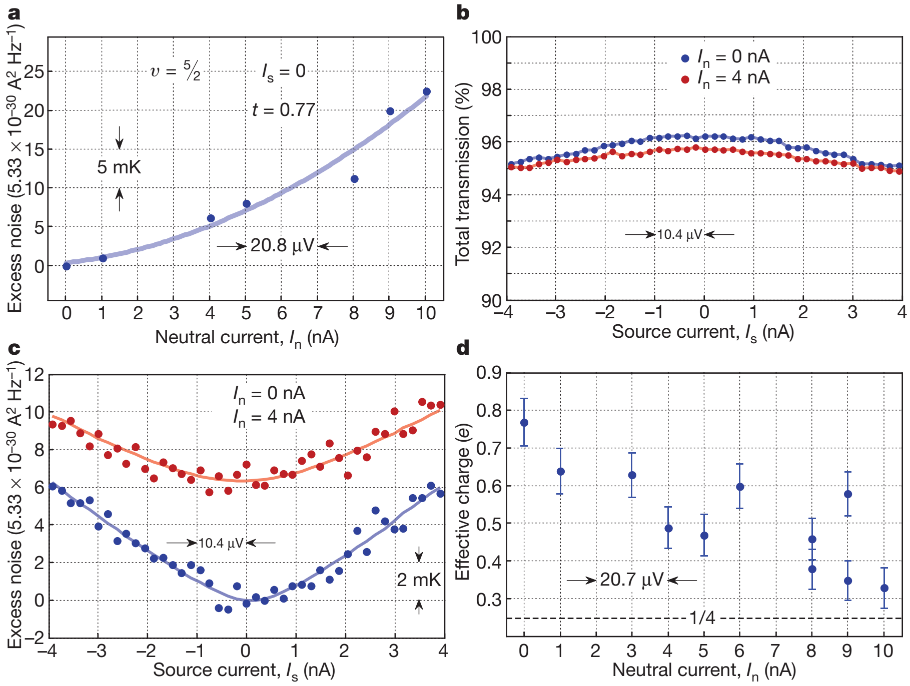

Figure 6 | Testing for the existence of the neutral mode at $\nu_b = 5/2$. The 2DEG used for these measurements was embedded in a 30-nm-wide quantum well, which was doped on both sides, buried approximately 160 nm below the surface of the heterostructure. The carrier density was 3×10^{11} cm^{-2} and the low temperature dark mobility was $>3 \times 10^7$ cm^2 V^{-1} s^{-1}. **a,** Excess noise as a function of injecting I_n provides direct evidence of an upstream neutral mode. **b,** The dependence of the nonlinear conductance as a function of I_s on the presence of I_n. The relative change in the transmission is very small, amounting to $\ll$1%. As 80% of the total current flows in the two underlying edge channels ($\nu = 1$ and $\nu = 2$), the effective transmission is about 77%. **c,** The dependence of the excess noise as a function of I_s on the presence of I_n. **d,** The dependence of the quasiparticle charge on I_n (extracted from **c**). The charge drops from $e^* \approx 0.75e$ to $e^* \approx 0.32e$. By limiting the temperature to 50 mK while fitting the charge we estimated the error in the charge (error bars, ±1 s.d.).

function of temperature, has been reported recently[27]. The nonlinear transmission also changed, albeit by a very small amount (Fig. 6b).

Discussion

We have presented evidence for the existence of neutral modes in the fractional states $\nu_b = 2/3$, 3/5 and 5/2, using a QPC constriction as a detector. Our findings can be summarized as follows. (1) A flux of neutral quasiparticles emitted from a biased ohmic contact does not carry current or shot noise. Moreover, a neutral mode impinging on a macroscopic ohmic contact does not increase its temperature by a measurable amount. (2) An flux of neutral quasiparticles impinging on a QPC constriction having a finite transmission t results in excess shot noise. The excess noise is approximately proportional to $t(1 - t)$ and to the injected current. The upstream energy flux, in the odd-denominator fractions, seems to be correlated with the ratio between the number of upstream and downstream modes. (3) Having a neutral mode impinging on a QPC constriction, while a charge mode is simultaneously being partitioned, alters dramatically both the noise and the deduced partitioned quasiparticle charge. The charge reduces inversely in proportion to the injecting voltage. (4) In the same experiment, the temperature of the simultaneously partitioned quasiparticles increases as the injecting voltage increases. However, the temperature increase is too small to account for the observed drop in charge. The mechanism responsible for modifying the tunnelling cross-section of the quasiparticles in the QPC constriction is not currently understood. (5) Assuming a temperature dependent energy decay of T^{-2}, the typical length scale is ~100 µm at 25 mK for $\nu_b = 2/3$ (see Supplementary Information). (6) Observing an upstream neutral mode in the even-denominator fraction $\nu_b = 5/2$ rules out, according to present theories, an Abelian wavefunction of this state, and thus narrows down the spectrum of possible states (see above).

We trust that with this relatively easy method of observing the so-called 'elusive neutral modes', new studies of their properties will be launched, possibly shedding new light on their characteristics—not revealed via their charge carrying nature.

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