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Spin-charge separation of fractionally charged excitations studied with current noise measurement

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Abstract

Electrons propagating along a quantum Hall edge split into collective excitations in charge and spin modes due to the inter-channel interaction. While this spin-charge separation has been hypothetically considered for elementary charge *e*, the charge may be arbitrary and can be a fraction of *e*. Here we address spin-charge separation of fractional charges generated from a local fractional quantum Hall region in a quantum point contact. The resulting state is analyzed with current noise emanating from a second quantum point contact. We find consistency with previous works for integer charges.

1. Introduction

Electron transport in a one-dimensional conductor is intriguing as the Fermi liquid theory is no longer valid, and Tomonaga Luttinger Liquid (TLL) model describes the system in a better way [1-3]. The quantum Hall (QH) state with spin-up and -down chiral edge channels at Landau filling factor $\nu = 2$ offers an ideal playground to explore many-body effects in TLL. For example, collective excitations in the spin and charge modes travel with different velocities. This spin-charge separation has been identified by shot noise measurement [4] and time-resolved charge detection [5].

Fractional QH (FQH) effect, where the Hall conductance is quantized at fractional values of e^2/h, appears due to the strong electron correlation [6]. Fractional charges like $e/3$ tunnel through a narrow constriction in the weak backscattering regime [7, 8]. However, spin-charge separation for fractional charges has not been investigated as the FQH effect and the TLL with different spins appear at different ν. Recently, we find that fractional charge tunneling takes place through a local FQH state in a quantum point contact (QPC) even with an integer QH state in the bulk [9]. This allows us to study spin-charge separation for fractional charges.

Here, we address how fractionally charged excitations generated from a local FQH state propagate along the $\nu = 2$ edge channels. Combining the conductance and current noise measurements, we obtain experimental results suggesting that fractional charges are separated into spin and charge modes. Our observation will deepen our understanding of fractional charge transport, and may help us to develop novel topological devices with fractionally charged anyons.

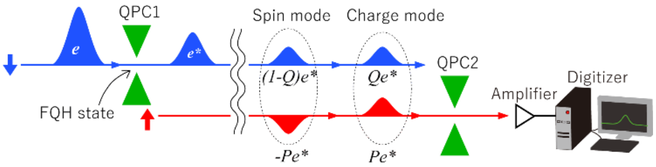

Fig. 1. Principle of our experiments. Fractional charges excited at QPC1 propagate and split into spin and charge wave packets due to the inter-channel interaction. The electron- and hole-like wave packets in the spin-up channel are scattered at QPC2, and the generated low-frequency noise is detected.

2. Principle of experiment

Figure 1 shows the schematic of the setup for co-propagating spin-up and -down channels at $\nu = 2$. A local FQH state is formed at the 1st QPC (QPC1), where spin-down fractional charge e^* ($< e$) is scattered to the right. Each time a charge wave packet with e^* is generated in the spin down channel, the interaction between the channels splits it into two collective wave packets; the fast charge packet with charge Qe^* in the spin-down channel and charge Pe^* in the spin-up channel, and the slow spin packet with spin-down charge $(1-Q)e^*$ and spin-up charge $-Pe^*$ [4]. Here, P and Q are determined by the so-called mixing angle θ: $P = (\sin\theta)/2$ and $Q = (1 + \cos\theta)/2$ $(0 \le \theta \le \pi/2)$. θ is related to the asymmetry of the two channels (pure charge and spin modes at $\theta = \pi/2$, their mixed modes at $\theta < \pi/2$, and non-interacting channels at $\theta = 0$). As the charge packet travels much faster than the spin packet, the distance between the charge and spin wave packets is comparable to the propagation length of the charge packet [5].

The spin-charge separation can be investigated by scattering the spin-up electrons at the 2nd QPC (QPC2), leading to current noise in the output channel. In the absence of QPC2, however, successive pairs of positive (Pe^*) and negative ($-Pe^*$) packets cannot be detected with low-frequency noise measurement. The 2nd QPC is required to randomize the pairs to produce measurable noise. Thus, detection of finite noise after QPC2 confirms the spin-charge separation [5]. Note that conventional current measurement is insensitive to the spin-charge separation because the net charge along the spin-up channel is always zero.

3. Experimental setup

Measurements were carried out at 20 mK in a dilution refrigerator on a device with two QPCs (QPC1 and QPC2) fabricated in an AlGaAs/GaAs heterostructure with electron density, $n = 3 \times 10^{15}\ \mathrm{m}^{-2}$, and mobility, $1.6 \times 10^{6}\ \mathrm{cm}^2/\mathrm{V \cdot s}$ (Fig. 2). The magnetic field is 5.4 T, corresponding to ν = 2. We apply voltage V on the source, and measure reflection current I_1 from QPC1 and total transmission current I_2 through QPC1 and QPC2. We also detect current noise (S) of the total transmission current with a cold amplifier and a resonant LC circuit [10-13].

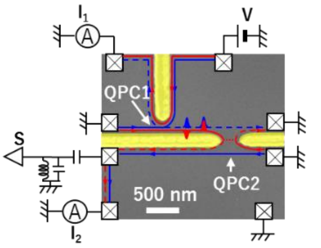

Fig. 2 An SEM image of our sample. Fractional charge excitation in QPC1 is confirmed by measuring noise S with fully opened QPC2. Its spin-charge separation is studied by weakly opening QPC2 only for spin-up electrons as illustrated.

4. Fractional charge excitation

First, we verify that fractional charges are excited at QPC1 by measuring the current noise with QPC2 fully opened. Figure 3(a) shows the obtained noise S_1 as a function of the injection current at the source, $I(\equiv 2e^2V/h)$. Here, the differential conductance of QPC1 at $V = 0$ was $G_1 = 1.3e^2/h$, where only spin-down electrons are scattered. The linear increase around $I \sim 0$ can be analyzed with a relation, $S_1 = |2e^*IF_1|$, with effective charge e^* and partitioning factor $F_1 \equiv \sum_{i=\uparrow,\downarrow} \tau_{1i}(1-\tau_{1i})/2$ for transmission probability τ_{1i} for $i = \uparrow$ and $\downarrow$. By assuming $\tau_{1\uparrow} = 1$ and $\tau_{1\downarrow} = 0.3$ for $G_1 = 1.3e^2/h$, we find fractional charge tunneling with $e^* \sim 1/3$ in the low $|I|$ region and $e^* \sim 0.1$ in the high $|I|$ region (the dashed lines).

Focusing on the low-$|I|$ region, we summarize $S/2eI$ as a function of G_1 in Fig. 3(b), where the observed G_1 dependence is well explained with F_1 at fixed $e^* = e/3$ (the dashed line). This implies that fractional charges are excited at QPC1 even with the ν = 2 integer QH state in the bulk.

In the high-$|I|$ region, the effective charge e^* is much smaller than that in the low-$|I|$ region. While we do not know the mechanism of this reduction, the small finite noise can be regarded as generation of fractional charge e^*, which may not be rational.

5. Spin-charge separation of fractional charge

Next, we investigate the spin-charge separation of fractional charges by setting QPC2 in the tunneling regime only for spin-up electrons. For this transmission probability $\tau_{2\uparrow}$, the overall noise S_{1-2} with QPC1 and QPC2 is expected to be

$$S_{1-2} = 2PF_{2\uparrow}S_1, \quad \cdots (1)$$

where the noise is reduced from S_1 with a factor that shows a pair of wave packets (Pe^* and $-Pe^*$) being partitioned with factor $F_{2\uparrow} \equiv \tau_{2\uparrow}(1-\tau_{2\uparrow})$. We determined $\tau_{2\uparrow}$ from a separate measurement (not shown) for the differential conductance G_2 ($< e^2/h$) of QPC2, and evaluate P from Eq. (1).

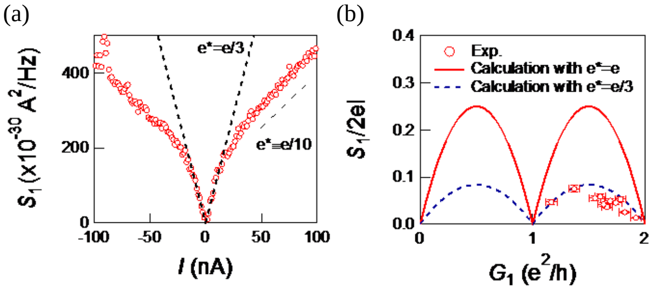

Fig. 3 (a) Current noise S_1 as a function of injection current I at $G_1 = 1.3e^2/h$. (b) $S_1/2eI$ as a function of G_1. The data points follow the partition noise with $e^* = e/3$ (blue dashed curve).

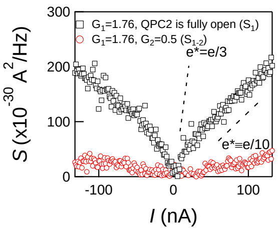

Fig. 4 (a) S_1 (black squares) with QPC2 fully opend ($G_2 = 2e^2/h$) and S_{1-2} (red circles) with $G_2 = 0.5e^2/h$ as a function of I taken at $G_1 = 1.76e^2/h$.

Figure 4 shows I dependence of S_1 (squares) with QPC2 fully opened and S_{1-2} (circles) with $G_2 = 0.5e^2/h$, where QPC1 is set at $G_1 = 1.76\, e^2/h$ for both data sets. S_{1-2} is significantly reduced from S_1 but remains finite. This reduction suggests $P = 0.4 \pm 0.1$, which is close to the symmetric case ($P = \sin(\pi/2)/2$=0.5). This value is comparable to the previous reports for integer charges, P = 0.38–0.41 in Ref. 4, and P = 0.3 in Ref. 5. The experiment demonstrates that the spin-charge separation is not limited to integer charges but works also for fractional charges.

6. Summary

We have investigated spin-charge separation of fractionally charged excitations by using a local FQH state. While the analysis is reliable in the high-$|I|$ region with small e^*, further tests are encouraged in the low-$|I|$ region with well-defined rational $e^* = e/3$.

Acknowledgements

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