Anomalous Chiral Luttinger Liquid Behavior of Diluted Fractionally Charged Quasiparticles

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(March 22, 2022)

Fractionally charged quasiparticles in edge states, are expected to condense to a chiral Luttinger liquid (CLL). We studied their condensation by measuring the conductance and shot noise due to an artificial backscatterer embedded in their path. At sufficiently low temperatures backscattering events were found to be strongly correlated, producing a highly non-linear current-voltage characteristic and a non-classical shot noise - both are expected in a CLL. When, however, the impinging beam of quasiparticles was made dilute, either artificially via an additional weak backscatterer or by increasing the temperature, the resultant outgoing noise was classical, indicating the scattering of independent quasiparticles. Here, we study in some detail this surprising crossover from correlated particle behavior to an independent behavior, as a function of beam dilution and temperature.

PACS numbers: 73.43.Fj, 71.10.Pm, 73.50.Td

When electrons, confined to two dimensions, are subjected to an extremely strong magnetic field, their orbits quantize and Landau levels are formed. Electrons that occupy only a fraction $\nu = l/m$ (called filling factor, with $m$ odd and $l$ integer) of the first Landau level form the so-called Laughlin quasiparticles. Being independent each quasiparticle carries a charge $e/m$ [1]. The main characteristics of that regime are the zeros of the longitudinal conductance and the exact plateaus of the transverse conductance $g = \nu e^2/h$, with $e$ the electron charge and $h$ Plank’s constant. This is the well-known fractional quantum Hall effect (FQHE) [2]. The current, carried by the quasiparticles, flows in narrow, one-dimensional like, strips along the edges of the sample in quantized edge states [3]. Wen predicted [4] that being confined to the edge the fractionally charged quasiparticles are expected to form a non-Fermi liquid (FL) system, a chiral Luttinger liquid (CLL). The validity of the CLL model can be tested, for example, by studying the effect of a backscattering potential on the conductance and on the shot noise. Such potential induces charge density wave in the 1D channel, leading to correlation among the scattering events - not like in a FL where the events are independent. Typically, even the weakest backscattering potential is expected to quench the longitudinal conductance at zero temperature with a non-linear I-V characteristic that is highly temperature sensitive [5-8]. The resultant shot noise, in turn, is predicted to be non-classical (non-Poissonian), with a voltage (or current) dependent scattered charge [9,10].

What had been already known? In the weak backscattering regime, at sufficiently high temperature (greater than the characteristic backscattering energy), correlation among scattering events is weak with a classical-like shot noise. Noise is proportional to the reflected current and the quasiparticle charge [11] , as was demonstrated for filling factor $\nu = 1/3$ and $\nu = 2/5$ by deducing a quasiparticle charge $e/3$ and $e/5$, respectively [12-14]. In the strong backscattering regime [9-11] only electrons, or bunched quasiparticles, are allowed to tunnel through opaque barriers [15]. Contrary to that well established behavior, a most recent experiment proved that highly dilute quasiparticles (quasiparticles arrive one by one) traverses an opaque barrier without bunching, namely, the scattered charge is nearly $e/3$ [16]. This unexpected result cannot be presently explained by theory. This unexpected behavior led us to concentrate on the transport of $e/3$ quasiparticles in very dilute beams (10 $\sim$ 20 %) or in the fully occupied regime, and at a wide range of electron temperature (20 $\sim$ 120mK). While finding an excellent agreement with the CLL prediction for fully occupied beams at low temperature - low energy regime, we observed a clear transition toward an independent particle behavior of highly dilute beams. We conclude that beam dilution plays a qualitative similar role to that of temperature, a regime where theory is still lacking [17].

Measurements were conducted at bulk conductance $g_Q = e^2/3h$ plateau (B $\sim$ 13.1T). Two QPCs were formed in a two-dimensional electron gas (2DEG), embedded in a GaAs-AlGaAs heterojunction, as seen in Fig. 1a. QPC1 was used to dilute the quasiparticle beam and QPC2 to serve as the backscattering potential. A many-terminal-configuration was employed in order to prevent multiple scatterings between the two QPCs and keep the input and output conductance constant, $e^2/3h$ - independent of the transmission of each QPC [15,16]. The differential conductance was measured with AC excitation of 1.5$\mu$V at 3Hz superimposed on DC bias. The spectral density S of the shot noise was measured as a function of DC current at a center frequency of 1.4MHz and bandwidth of 30kHz (determined by a LC resonant circuit; see Refs. 12-13 for more details). Voltage fluctuations in termi-
nal A were amplified by a low noise cryogenic amplifier followed by a spectrum analyzer, which monitored the average square of the amplified fluctuations.

![Diagram of the fabricated device](image)

FIG. 1. (a) Schematic diagram of the fabricated device and the measurement set up. The device is fabricated in a 2DEG with mobility $2 \times 10^6 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and carrier density $1.1 \times 10^{11} \text{cm}^{-2}$, at 4.2K. Current is injected via source S and is scattered by QPC1 toward QPC2. Transmission of each QPC is measured by measuring the currents at drains D1 and D2. Shot noise is measured by monitoring the voltage fluctuation at Ohmic contact a, after amplification by a cryogenic amplifier with input current noise $6.7 \times 10^{-29} \text{A}^2/\text{Hz}$. The noise spectrum is filtered by a LC circuit, which is tuned to a center frequency of 1.4MHz (with bandwidth of 30kHz). Multiple terminals assure constant sample conductance $e^2/3h$ and a constant equilibrium noise. (b) Summary of the differential conductance measured at 23mK for different settings of the QPC constriction. It is plotted against an applied voltage normalized by two effective scattering potentials, $V_{DS}/t_B$ ($t_B = 28\mu V$ and $t_B = 16\mu V$ are measured at $V_g = -0.107V$ and $-0.093V$, respectively). The theoretical prediction at 0K is shown for comparison. (c) Differential conductance of QPC1 as a function of $V_{DS}$ measured at 23mK, for a few backscattering potential strengths (gate voltage is $-83mV$, $-75.5mV$, $-65.5mV$, $-50.5mV$, $-43mV$, and $-38.5mV$, from bottom to top). (d) Similar data as in C but measured at 120mK (gate voltage is $111mV$, $-101mV$, $-91mV$, $-81mV$, $-71mV$, $-61mV$, and $-51mV$, from bottom to top).

The temperature $T$ of the electrons was determined by measuring the equilibrium noise, $S = 4k_BTg$, with $g$ the sample conductance. Shot noise was determined by subtracting the DC current independent noise from the total noise signal.

Figures 1c and 1d show typical differential conductance of a single QPC (say QPC1) as a function of the applied voltage $V_{DS}$ at electron temperatures $T=23$mK and $T=120$mK, respectively, for different backscattering potential strengths (determined by the gate voltage of the QPC). At the lower temperature, even a relatively weak backscattering potential (with a saturated reflection $r \sim 0.3$ or transmission $t = g/qQ \sim 0.7$), reflects almost fully the current at zero applied voltage. The differential conductance was compared with Fendley’s et al. prediction [9,10] in Fig. 1b, which poses a universal dependence on the applied voltage normalized by the so-called impurity strength, $t_B$, at zero temperature. An excellent fit with experiment is seen at the low energy regime for $t_B$ in the range $10 \sim 40\mu eV$ (with $k_BT \ll t_B$), as theory requires. At high bias the differential conductance is expected to exceed $gQ = e^2/3h$, however we have never observed it in the experiments. This can be justified if we note that in that range short-range, non-universal, physics is dominant, making the agreement poor. When the temperature increased to 120mK (Fig. 1d), the non-linearity weakened significantly - resembling a FL behavior.

While independent particle scattering is stochastic, with a classical-like shot noise, correlated particles scattering leads to non-universal shot noise that depends on the type of the correlation. We recall the expression of shot noise for independent scattering events at finite temperatures [18]:

$$S = 2qV_{DS}gQt(1-t) \left[ \coth \left( \frac{qV_{DS}}{2k_BT} \right) - \frac{2k_BT}{qV_{DS}} \right] \quad (1)$$

with $q$ the partitioned charge. We plot in Fig. 2a the differential conductance (in the inset) and shot noise both measured at different temperatures with a relatively weak backscattering potential (saturated $t \sim 0.8$). At the lowest temperature, 23mK, the differential conductance dipped near $V_{DS} = 0$ and the shot noise deviated considerably from the independent particle behavior. The noise is seen to increase fast with increasing current - indicative of a high effective charge, while later it saturates - indicative of a smaller effective charge. The expected noise of independently scattered charges (Eq. 1) with $q = e/3$ was plotted for comparison. As the temperature increased the measured nonlinearity weakened and the measured shot noise at 120mK agreed with the classical prediction. Such, high temperature, charge determination had been extensively employed before in order to determine the charge of the quasiparticles [12–14].
FIG. 2. The shot noise and differential conductance for a single QPC. (a) Shot noise due to a weak backscattering potential measured at various temperatures, 23, 49, 69 and 120mK. Solid lines are the expected shot noise for non-interacting quasiparticle with charge $e/3$. Inset: The differential conductance of the QPC at the same temperatures. Note the strong non-linearity at lower temperatures. A clear crossover from interacting to non-interacting behavior is seen as the temperature increases. This is evident at 120mK, where a linear dependence of the noise on voltage (above some 40µV) is observed. (b) Shot noise due to strong backscattering potentials measured at 23mK. The voltage on the gates of the QPC is -0.23V and -0.19V. Note the negative slope of the noise at high applied voltage ($dS/dV_{DS} < 0$). Inset: The differential conductance of the QPC for the same gate voltages of the QPC.

To stress further the fact that scattering events of quasiparticles at the lowest temperature are correlated we plotted in Fig. 2b the conductance and shot noise for a stronger backscatterer (saturated $t \sim 0.6$). Remarkably, the noise saturated or even changed the sign of the slope with increasing bias to above 70µV. In other words, adding high-energy quasiparticles to the beam lowered the noise of the low-energy quasiparticles. Since the backscattering strength is independent of bias (not shown here), stochastic partitioning could never explain such noise behavior. This is a clear and direct observation of the interaction among electrons in a CLL.

One can naively ask whether an artificial decrease of the average occupation of the incoming states might weaken the correlation among scattering events, hence rendering the scattered quasiparticles independent - much like a temperature increase.

FIG. 3. Shot noise resulting from a diluted beam (with average occupancy $t_1 \sim 0.2$) impinges on QPC2 with transmission $t_2$. Noise generated by QPC1, $S_1$, in squares and the total noise measured at A, $S_{total}$, in circles. The deduced noise generated by QPC2, $S_2$, is plotted in triangles and is compared with shot noise expected for a binomial partitioning of quasiparticles with charge $q_2$ (plotted in solid line). Insets: The differential transmission of QPC2, $t_2$, of an impinging beam of dilute quasiparticles. The transmissions are only slightly energy dependent. (a) $S_2$ generated by a relatively open QPC2, $t_2 \sim 0.8$, and the deduced effective charge $q_2 = 0.39e$. (b) $S_2$ generated by a relatively pinched off QPC2, $t_2 \sim 0.4$, and the deduced effective charge $q_2 = 0.54e$.

This can be tested via employing the diluting technique first presented in Ref. 16 (shown in Fig. 1A). The relatively open QPC1 backscatters dilute quasiparticles with an average occupation of each state determined by its transmission toward QPC2, $t_1 \approx 0.1 \sim 0.2$. This beam is already noisy, hence, the noise $S_{total}$ at terminal A is calculated via the superposition principle [19], $S_{total} = t_2^2 \cdot S_1 + S_2$, with $S_1(S_2)$ the noise of QPC1(2). The noise $S_2$ - the own contribution of QPC2 - indicates whether partitioning events at QPC2 are correlated or independent. We find $S_2$ by measuring $S_{total}$, $S_1$, and $t_2$ as function of voltage, and use:

$$S_2(V_{DS}) = S_{total}(V_{DS}) - \int_{V=0}^{V_{DS}} t_2^2(V) \cdot \frac{dS_1(V)}{dV} \cdot dV \quad (2)$$

with the integral accounting for the dependence of $t_2$ on...
Two examples of the noise produced by a dilute beam, with average occupation $t_1 \sim 0.2$, are shown in Fig. 3. One for the dilute beam impinging on a relatively open QPC2 ($t_2 \sim 0.8$) and one when QPC2 is rather pinched ($t_2 \sim 0.4$). The first striking behavior (insets of Fig. 3) is the apparent linearity, namely, the weak dependence of $t_2$ on the voltage, in contrast with the behavior seen in Fig. 1c. Moreover, the resultant noise $S_2$ (Figs. 3a and 3b) is classical even at the lowest temperature. Yet, contrary to the results of Comforti et al. [16], who observed quasiparticles tunnelling through opaque barriers, here, at a significantly lower temperature, dilute quasiparticles tend to bunch at strong backscatters.

With a classical behavior of noise $S_2$ at low temperatures (Fig. 3), one can determine an effective scattered charge across a wide temperature range. The expected $S_2$ at zero temperature, due to partitioning of charges $q_2$ can be written as:

$$S_2 = 2q_2I \cdot t_1t_2(1 - \tilde{t}_2)$$  \hspace{1cm} (3)

with $I$ the injected DC current at terminal S, $\tilde{t}_2 = t_2[(e/3)/q_2]$ is the transmission of the particle flux (rather than particle current), each particle with charge $q_2$ [15,16]. Generalizing Eq. 2 to finite temperatures allowed to extract an effective charge as function of transmission $t_2$ at different temperatures. Apparently, the temperature plays a significant role in the determination of the effective charge $q_2$ (Fig. 4), while the dependence on small occupations is weak (similar results for 0.1 and 0.2 occupations). The charge seemed to increase monotonically as $t_2$ decreased, however, as the temperature increased the effective charge was always smaller. This clearly shows that quasiparticle tunnelling through opaque barriers [16] is due to the weaker correlation among quasiparticles resulting from higher temperatures.

Note that recently Kane and Fisher predicted [17] that at zero temperature and for an infinitesimal occupation of the impinging quasiparticles only electrons will tunnel even if the QPC is highly transparent. We didn’t observe such an effect yet, however, recall that our temperature and occupation are finite and might not fall in the calculated range of parameters. We studied here correlation among fractionally charged quasiparticles that scattered off an artificial impurity in the FQHE regime ($\nu = 1/3$). Adding a new parameter, the occupation of the impinging quasiparticles, enabled the differentiation between independent particle-like behavior and condensation of the scattered quasiparticles to a highly correlated phase, a Chiral Luttinger Liquid. Moreover, we find a strong similarity between diluting the quasiparticle beam and increasing the temperature - both reduce the particle-particle interaction, rendering the quasiparticles independent. Hence, dilution can be employed as a powerful tool to affect interaction while keeping the ground state of the system at zero temperature.

Acknowledgements We wish to thank Yang Ji for his help during experiment. The work was partly supported by the Israeli Academy of Science, the German-Israel Foundation(GIF) and the German Israeli Project Coopera -tion (DIP).

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