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Anomalous chiral Luttinger liquid behavior of diluted fractionally charged quasiparticles

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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 nonlinear current-voltage characteristic and a nonclassical 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.

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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 $g = \nu e2/h$, with e the electron charge and h the 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 one-dimensional 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 nonlinear I-V characteristic that is highly temperature sensitive.[5–8] The resultant shot noise, in turn, is predicted to be nonclassical (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 classicallike 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$20%) or temperature (20$\sim$120 mK). 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 ($B \sim 13.1$ T). Two quantum point contacts (QPC's) were formed in a two-dimensional electron gas (2DEG), embedded in a GaAs-AlGaAs heterojunction, as seen in Fig. 1(a). 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 QPC's 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 μV at 3 Hz 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 1.4 MHz and bandwidth of 30 kHz (determined by a LC resonant circuit; see Refs. 12 and 13 for more details). Voltage fluctuations in terminal **A** were amplified by a low noise cryogenic amplifier followed by a spectrum analyzer, which monitored the average square of the amplified fluctuations. 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 1(c) and 1(d) 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

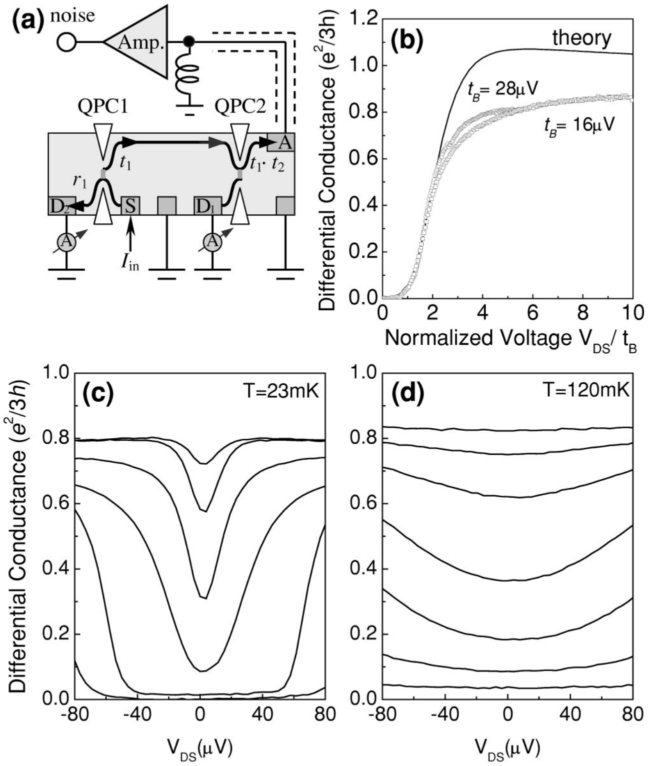

FIG. 1. (a) Schematic diagram of the fabricated device and the measurement setup. The device is fabricated in a 2DEG with mobility 2×10^6 cm^2 v^{-1} s^{-1} and carrier density 1.1×10^{11} cm^{-2} at 4.2 K. Current is injected via source **S** and is scattered by QPC1 toward QPC2. Transmission of each 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 6.7×10^{-29} A^2/Hz. The noise spectrum is filtered by a LC circuit, which is tuned to a center frequency of 1.4 MHz (with bandwidth of 30 kHz). Multiple terminals assure constant sample conductance $e^2/3h$ and a constant equilibrium noise. (b) Summary of the differential conductance measured at 23 mK for different settings of the QPC constriction. It is plotted against an applied voltage normalized by two effective scattering potentials, V_{DS}/t_B ($t_B=28$ μV and $t_B=16$ μV are measured at $V_g=-0.107$ V and -0.093 V, respectively). The theoretical prediction at 0 K (Refs. 9 and 10) is shown for comparison. (c) Differential conductance of QPC1 as a function of V_{DS} measured at 23 mK, for a few backscattering potential strengths (gate voltage is -83 mV, -75.5 mV, -65.5 mV, -50.5 mV, -43 mV, and -38.5 mV, from bottom to top). (d) Similar data as in (c) but measured at 120 mK (gate voltage is 111 mV, -101 mV, -91 mV, -81 mV, -71 mV, -61 mV, and -51 mV, from bottom to top).

$t=g/g_Q\sim0.7$), reflects almost fully the current at zero applied voltage. The differential conductance was compared with Fendley's *et al.* prediction[9,10] in Fig. 1(b), 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 μeV (with $k_BT\ll t_B$), as theory requires). At high bias the differential conductance is expected to exceed $g_Q=e^2/3h$, however, we have never observed it in the experiments. This can be justified if we note that in that range short-range, nonuniversal, physics is dominant, making the agreement poor. When the temperature increased to 120 mK [Fig. 1(d)], the nonlinearity weakened significantly—resembling a FL behavior.

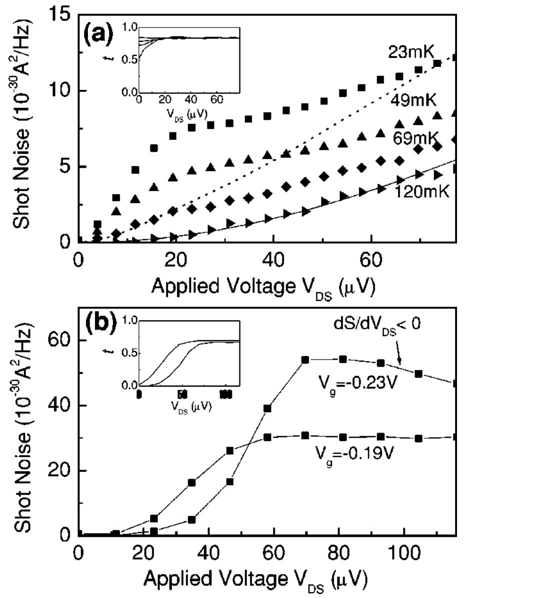

FIG. 2. The shot noise and differential conductance for a single QPC. (a) Shot noise due to a weak backscattering potential measured at various temperatures, 23, 49, 69, and 120 mK. Solid lines are the expected shot noise for noninteracting quasiparticle with charge $e/3$. Inset: The differential conductance of the QPC at the same temperatures. Note the strong nonlinearity at lower temperatures. A clear crossover from interacting to noninteracting behavior is seen as the temperature increases. This is evident at 120 mK, where a linear dependence of the noise on voltage (above some 40 μV) is observed. (b) Shot noise due to strong backscattering potentials measured at 23 mK. The voltage on the gates of the QPC is -0.23 V and -0.19 V. 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.

While independent particle scattering is stochastic, with a classicallike shot noise, correlated particles scattering leads to nonuniversal 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]

$$S=4k_BTg+2qV_{DS}g_Qt(1-t)\left[\coth\left(\frac{qV_{DS}}{2k_BT}\right)-\frac{2k_BT}{qV_{DS}}\right], \tag{1}$$

with q the partitioned charge. We plot in Fig. 2(a) the differential conductance (in the inset) and shot noise both measured at different temperatures with a relatively weak backscattering potential (saturated $t\sim0.8$). At the lowest temperature, 23 mK, 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 120 mK 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]

To stress further the fact that scattering events of quasiparticles at the lowest temperature are correlated, we plotted in Fig. 2(b) 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 70 μV. 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. This can be tested via employing the *diluting technique* presented in Ref. 16 [shown in Fig. 1(a)]. The relatively open QPC1 backscatters dilute quasiparticles with an average occupation of each state determined by it transmission toward QPC2, $t_1\approx 0.1\sim 0.2$. This beam is already noisy, hence, the noise S_{tot} at terminal **A** is calculated via the superposition principle,[19] $S_{total}=t_2^2 S_1+S_2$, 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_{tot}, S_1, and t_2 as function of voltage, and use

$$S_2(V_{DS})=S_{tot}(V_{DS})-\int_{V=0}^{V_{DS}} t_2^2(V)\frac{dS_1(V)}{dV}dV, \qquad (2)$$

with the integral accounting for the dependence of t_2 on V_{DS}. 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 impinged 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. 1(c). Moreover, the resultant noise S_2 [Figs. 3(a) and 3(b)] is classical even at the lowest temperature. Yet, contrary to the results of Comforti *et al.*,[16] who observed quasiparticles tunneling 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

$$S_2=2q_2 I t_1 t_2(1-\tilde{t}_2), \qquad (3)$$

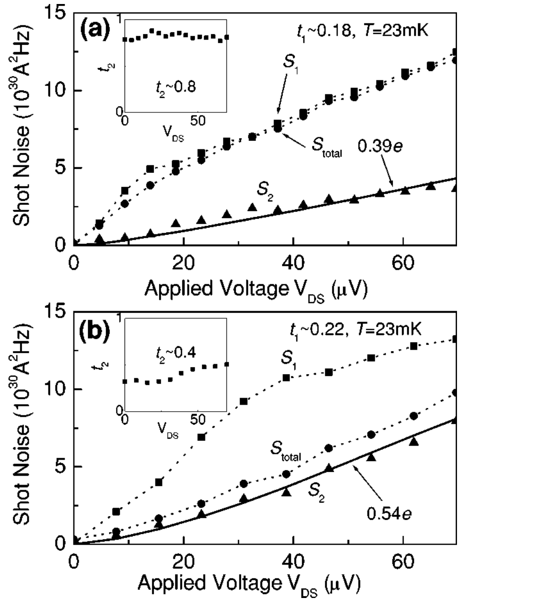

FIG. 3. The shot noise resulting from a diluted beam (with average occupancy $t_1\sim 0.2$) impinges on QPC2 with transmission t_2. Noise generated by QPC1, S_1, in squares and the total noise measured at **A**, S_{total}, in circles. The deduced noise generated by QPC2, S_2, is plotted in triangles 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 $q_2=0.54e$.

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

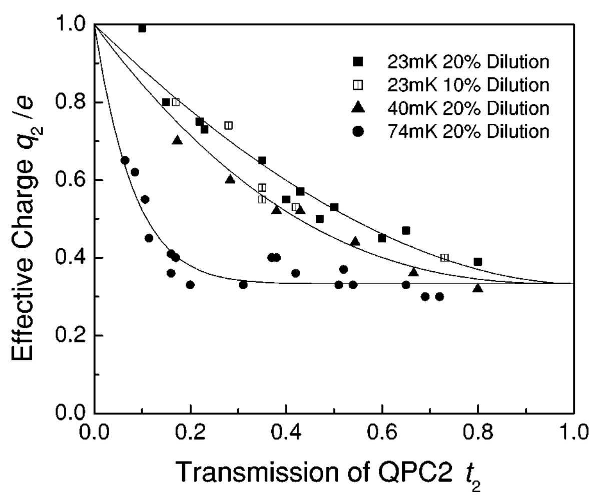

FIG. 4. Charge of partitioned particles by QPC2, q_2, as function of transmission t_2. The solid lines are just guidelines to the eye. At $T=23$ mK measurements were done for beam occupations of 0.1 and 0.2. The higher the temperature is, the smaller t_2 needs to be in order to observe bunching by the backscattering potential.

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 tunneling 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 did not 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 particlelike 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*.

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