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Generation of energy selective excitations in quantum Hall edge states

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We operate an on-demand source of single electrons in high perpendicular magnetic fields up to 30 T, corresponding to a filling factor \( \nu < 1/3 \). The device extracts and emits single charges at a tunable energy from and to a two-dimensional electron gas, brought into well defined integer and fractional quantum Hall (QH) states. It can therefore be used for sensitive electrical transport studies, e.g. of excitations and relaxation processes in QH edge states.

Charge transport in two-dimensional electron gases placed in a strong perpendicular magnetic field is ruled by chiral edge states. These edge states are now being exploited routinely in fundamental physics experiments, e.g. in electron interferometers. Moreover, gapless neutral edge excitations have been predicted, though not yet directly observed in experiments using quantum point contacts to generate edge excitations, as performed in e.g. Refs. 8 and 9. Additional counterpropagating edge excitations in the fractional quantum Hall (QH) state have also been predicted but were not found in studies of edge magneto plasmons. Only very recently a shot noise experiment found first indications for a neutral counterpropagating mode.

In this paper we demonstrate a new method to generate triggered single energy selective excitations in integer and fractional QH edges to probe possible edge excitations and relaxation processes. Furthermore, this method allows to precisely control the emission statistics of the electrons, which opens the possibility for efficient time resolved measurements.

We adapt a structure that has previously been employed as high precision current source, both in the dc and ac regime. A schematic of our device and an electron micrograph are shown in Fig. 1. It was realized in an AlGaAs/GaAs heterostructure. A 700 nm wide constriction was wet-etched inside a two-dimensional electron gas. The device was contacted at source (S) and drain (D) using an annealed layer of AuGeNi. The constriction is crossed by Ti-Au finger gates G1 and G2. A quantum dot (QD) with a quasibound state \( \psi \) is formed by applying voltages \( V_1 \) and \( V_2 \) to G1 and G2, respectively; a third gate G3 is not used and set to ground. The corresponding potential landscape along the constriction is shown in Fig. 1(a). An additional sinusoidal signal of power \( P_{RF} \) and frequency \( f \) is coupled to G1 and varies both the height of the barrier and the energy \( \varepsilon(t) = \varepsilon_1 \cos \omega t + \varepsilon_0 \) of the quasibound state \( (\omega = 2\pi f) \). During the first half cycle \( \varepsilon(t) \) drops below the chemical potential \( \mu_S \) and \( \psi \) is loaded with an electron with energy \( \mu_S - E_L \) [see Fig. 1(b)]. During the second half-cycle, \( \varepsilon(t) \) is raised sufficiently fast above \( \mu_D \) and the electron can be unloaded to the drain with an excess energy \( E_U \). This process, resulting into a quantized current \( I = e \cdot f \) with e the electron charge, is non-adiabatic and requires that the loaded QD state is raised sufficiently fast through the chemical potentials \( \mu_{S/D} \) to avoid unwanted charge transfer. The scheme can be generalized to a quantized transport of \( n \) electrons per cycle, i.e. \( I = n \cdot e \cdot f \), where \( n \) can be derived from the decay cascade model.

The current is accompanied by a periodic excitation in the drain at energy \( E_U \) above \( \mu_D \). Upon application of a strong perpendicular magnetic field \( B \), transport in S and D takes place via edge channels, marked symbolically with green arrows in Fig. 1(b). Using the dynamical QD it is now possible to trigger single energy selective excitation quanta of the QH edge state.

The number of electrons emitted into D per cycle may be tuned using \( V_2 \), as shown in Fig. 1(b) for a measurement carried out in a \(^3\)He cryostat with a base temperature of 300 mK. Under zero-field conditions approximately one
The distribution of the emission times is peaked at $t_c = \beta^{-1} \ln (\beta/\Gamma_0^2)$ with $\beta \equiv g \omega/2$. The width of the corresponding energy distribution is then given by $\Delta E_U = 2/\beta$. Hence, to obtain a narrow emission energy distribution one may optimize the barrier shape of $G_2$ to maximize $s$. The lowest achievable $\Delta E_U$ is limited by the quantum-mechanical uncertainty of energy, on the order of $h \Gamma_2(t_c) = (g/2) \hbar \omega$. For the frequencies chosen in this experiment the minimal $\Delta E_U$, lies in the $\mu$eV range.

The derivation above also shows that the emission energy $E_U = \varepsilon(t_c) - \mu_D$ depends on the frequency $\omega$ and the tunnel rate $\Gamma_2^0$ logarithmically,

$$E_U \approx \varepsilon_1 \omega t_c = \Delta E_U \ln \left( \frac{\varepsilon_1 \omega}{\Delta E_U \Gamma_2^0} \right).$$

Since typically $\Gamma_2^0$ depends on $V_2$ exponentially, the gate voltage can be readily used to tune the emission energy, i.e. $E_U \propto -|\varepsilon| V_2$. To ensure single triggered excitation events (within a certain error margin) $V_2$ may be tuned only within the plate voltage range, i.e. where $I \approx f$. The highest energy is obtained for the transition voltage, $V_T$, where $I = f$ switches to $I = 0$, i.e. close to the negative side of the plateau where $\Gamma_2^0$ is minimal (see Fig. 2). From Eq. (1) it follows that increasing the modulation amplitude $\varepsilon_1$ enhances $E_U$ only logarithmically. To extend the energy range efficiently, the bias voltage $V_B \equiv (\mu_D - \mu_S)/|\varepsilon|$ may be made more negative, decreasing $\Gamma_2^0$ since the condition $\varepsilon = \mu_D$ will then take place earlier in the cycle, i.e. $E_U \propto -|\varepsilon| V_B$. At the same time the chance for emitting an additional electron increases, as seen from the inset in Fig. 2. This behaviour is consistent with the decay cascade model considering that the time $t_c$ at which the decay cascade starts is given by $\varepsilon(t_c) \equiv \mu_S$. The corresponding escape rate at $G_1$, $\Gamma_1(\varepsilon(t_c))$, controls the number of electrons captured per cycle. To remain in the quantized regime, $V_2$ and consequently $\Gamma_2^0$ have to be decreased as indicated by the arrow in the inset of Fig. 2 leading to an additional enhancement of $E_U$ according to Eq. (1). Hence, combining the $f - V_B$ - and $V_2$ - dependence an excitation energy range up to several tens of $\mu$eV should be possible using this technique. Despite the potentially large energy, the heating of the edge state can be kept at a minimum by choosing a sufficiently low frequency. Furthermore, this energy selective and time controlled excitation source could be combined with selective edge mode detection and a time-gated detector technique for sensitive studies of the underlying transport processes.

For the presented excitation source we require that the gates $G_1$ and $G_2$ coincide with the border of the undisturbed QH liquid, in order to avoid broadening of the energy distribution $p(E_U)$. In previous studies of this dynamical QD in perpendicular magnetic field, such as in Refs. 21 and 22, the electron density of states and the corresponding filling factor of the leads connecting to the QD via $G_1$ and $G_2$ could not be established. In those works a wire of constant nominal width was employed, where side wall depletion may result in varying electron densities inside the wire, different from the undisturbed...
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been reported in Refs. 17 and 22. In Ref. 17 quantiza-
directly from a fractional QH edge state.

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tured QH liquid. We conclude this from the oscillations in
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which coincide with the super-
modifying the decay
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variation inferred from the
variation observed in Ref. 22 does
not correspond to the
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variation inferred from the charge carrier density specified. This observation indi-
cation of the charge of the fractional quantum Hall quasi-
particle.

Finally we note that charge pumping from fractional
edge states as demonstrated here may be developed fur-
ther into the realization of a fractional charge pump as proposed by Simon 24 which may be used as a measurement of the charge of the fractional quantum Hall quasiparticle.

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