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Time dependent electronic transport in chiral edge channels

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HIGHLIGHTS

- We discuss Coulomb interaction effects on charge propagation along quantum Hall edge channels.
- Various experimental works are connected and analyzed in a unified theoretical framework.
- Low frequency transport is described by a lumped element model.
- High frequency transport is described by edge magnetoplasmon propagation.
- Interchannel magnetoplasmon scattering leads to electron fractionalization and decoherence.

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ABSTRACT

We study time dependent electronic transport along the chiral edge channels of the quantum Hall regime, focusing on the role of Coulomb interaction. In the low frequency regime, the a.c. conductance can be derived from a lumped element description of the circuit. At higher frequencies, the propagation equations of the Coulomb coupled edge channels need to be solved. As a consequence of the interchannel coupling, a charge pulse emitted in a given channel fractionalized in several pulses. In particular, Coulomb interaction between channels leads to the fractionalization of a charge pulse emitted in a given channel in several pulses. We finally study how the Coulomb interaction, and in particular the fractionalization process, affects the propagation of a single electron in the circuit. All the above-mentioned topics are illustrated by experimental realizations.

1. Introduction

The theoretical study of the dynamical properties of electronic transport in mesoscopic conductors has been pioneered by Markus Büttiker and his collaborators in the 1990s [1–4]. Following the description of the dc conductance of multichannel mesoscopic conductors as the coherent scattering of electronic waves [5], they studied the frequency dependent conductance $G(\omega)$ arising when the conductor terminals are driven by a time dependent voltage excitation. The latter case turns out to bring more complexity than the dc one, in particular as the role of Coulomb interaction is crucial. In the dc case, the current is expressed as a function of both the probability to be transmitted from one contact to the other and the difference between the electrochemical potentials of the contacts. In most of the cases, the effects of Coulomb interaction can be disregarded and remarkably, the conductance can be expressed as a function of the scattering amplitudes of non-interacting electronic waves. In the ac case, the time dependent current resulting from the variation of the electrochemical potential of the contacts gives rise to a time dependent accumulation of charges in the conductor which in turn leads to the variation of the electrostatic potential mediated by the long range Coulomb interaction. It is clear that this contribution to the ac current which directly stems from Coulomb interaction is crucial. Indeed, if one simply applied scattering theory as in the dc case, no current would be predicted to flow between contacts capacitively coupled, as scattering theory only predicts non-zero conductance between contacts which are physically connected by some transmission probability. The method introduced by Büttiker and coworkers in Refs. [1–4] follows two steps. In the first one, the ac current is calculated in a scattering formalism assuming a fixed value of the electrochemical potential of the contacts and of the electrical potential in the conductor. In the second one, the electrical potential is self-consistently calculated by relating the potential to the charges accumulated in the conductor using the capacitance matrix. Following these two steps, two time scales naturally appear. The first one, related to the non-interacting scattering description is the time of flight of non-interacting electron through the

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conductor of length l, $\tau_1 = l/v$. The second one is related to the Coulomb interaction through the conductor capacitance C and the typical impedance of a mesoscopic sample: $\tau_2 = hC/e^2$. Combining these two time scales by $1/\tau = v/l + e^2/hC$, one can define the important concept of electrochemical capacitance C_μ defined by $1/C_\mu = 1/C + hv/e^2 l$, where the second term is the quantum capacitance of the conductor. The electrochemical capacitance is central to describe the effects of interactions in quantum conductors such as mesoscopic capacitors [1] but also the inductive like [4] behavior of quantum wires. Another major concept of time dependent transport is the charge relaxation resistance R_q [1] which together with the electrochemical capacitance defines the time it takes for charges to relax from the mesoscopic conductor to a macroscopic reservoir (contact). It differs from the dc resistance given by the Landauer formula. In particular, for a single mode quantum coherent conductor, $R_q = h/2e^2$ [1,6,7], independently of the probability for charges to be transmitted from the conductor to the reservoir. Remarkably, this universal behavior is robust to strong electron–electron interactions [8–10]. Mesoscopic capacitors and charge relaxation resistance have applications beyond the obvious understanding of the dynamics of charge transfer in mesoscopic conductors such as dephasing induced by charge fluctuations [11–13] or the efficiency of mesoscopic detectors [14,15].

The present paper will address more specifically time dependent electronic transport along the chiral edge channels of the quantum Hall regime. The motivation is twofold. Firstly, chiral edge channels provide an ideal system to test quantum laws of electricity beyond the dc limit. The ballistic and one dimensional nature of propagation, which can be implemented on long distances, realizes a simple set of interacting single mode quantum wires. However, one specificity of quantum Hall systems distinguishes them from usual wires: chiral propagation is enforced by the strong magnetic field. This specificity makes chiral edge channels particularly useful to study quantum coherence effects in time dependent situations. Indeed, the coherence of electron beams can be probed in electronic interferometers [16]. When time-dependent drives are applied, quantum coherent electronics can be pushed to the single electron scale where one studies the evolution of a single electron wavefunction in a quantum conductor. These electron quantum optics experiments [17] are the second motivation of this work. They have been pioneered by Markus Büttiker as well in many ways: mesoscopic capacitors are used as single electron emitters [18–20] which statistical properties can be accessed through the measurement of electronic noise [21–24] or the study of distribution of waiting times between successive electron emissions [25–27]. Next, the coherence properties of single electron states [28,29] can be probed in the electronic analog of the Hanbury–Brown and Twiss [30] or Hong–Ou–Mandel geometry [31] following a proposal by M. Büttiker and his collaborators [32] and paving the way for the coherent manipulations of a few charge quanta in quantum conductors based on multiparticle interference effects [33–35]. Remarkably, these experiments [36] have been so far well accounted for by the time dependent Floquet scattering theory [37,38] of the mesoscopic capacitor which builds on the generic scattering theory of time dependently driven mesoscopic conductors discussed above in the introduction.

While the study of single electron coherence is a strong motivation of the work presented in this paper, quantum coherence effects on time dependent transport will not be directly addressed. However, the purpose of the manuscript is to discuss the role of Coulomb interaction in charge propagation in quantum Hall systems and to connect it to the issue of single electron coherence. This question naturally arises as, on one hand, understanding and manipulating single electron coherence rely on a single-particle picture where interactions are disregarded. On the other hand, as mentioned above, Coulomb interaction plays a prominent role in time dependent charge propagation.

The paper will first review the lumped element description of Hall conductors at high frequency based on the calculation of the circuit emittance introduced in Ref. [39]. In particular the role of the electrochemical capacitance in the ac properties of Hall conductors will be extensively discussed. At higher frequency the lumped element description of the circuit breaks down and propagation effects need to be taken into account. The ac conductance then stems from the propagation of edge magnetoplasmons. The role of Coulomb interaction between edge channels will then be discussed as the coupling leads to the emergence of new propagation eigenmodes responsible for the fractionalization of the charge propagating in a given channel. Finally, fractionalization will be discussed at the single electron level, addressing the question of the death of the elementary quasiparticle caused by the Coulomb interaction. All the above-mentioned topics will be illustrated with various experimental realizations (with an emphasis put on our own). We would like to emphasize that the data presented are extracted from already published works. The purpose of this manuscript is to connect together various experimental approaches and discuss them in a unified theoretical framework inspired by the seminal works of Markus Büttiker and his collaborators.

2. Emittance of a Hall bar

We consider a generic quantum Hall circuit schematically represented in Fig. 1. Electronic transport occurs along the quantum Hall edge channels [40–42] located at the edges of the sample, the number of flowing channels at each edge being fixed by the number of occupied spin polarized Landau levels (the filling factor N). The metal-like edge channels are separated by dielectric regions [43]. They are electrically connected to ohmic contacts acting as electronic reservoirs and imposing the electrochemical potential V_α of the channels emerging from contact α. They are in capacitive influence with each other and with nearby metallic gates. In a time dependent situation, the electrochemical potential $V_\beta(t)$ of the reservoirs or gates is subject to a periodic modulation: $V_\alpha(t) = V_\alpha e^{-i\omega t}$. We are interested in the time dependent current response $I_\alpha(t)$ flowing from contact α, defining the multiterminal ac conductance:

$$I_\alpha = \sum_\beta G_{\alpha\beta}(\omega) V_\beta \tag{1}$$

For low enough drive frequency, $G_{\alpha\beta}(\omega)$ can be expanded at first order in ω, providing the first correction to the well known dc-conductance, see Eq. (2), and defining the emittance $E_{\alpha\beta}$ as done by Christen and Büttiker in Ref. [39].

$$G_{\alpha\beta}(\omega) = G^{(dc)}_{\alpha\beta} - i\omega E_{\alpha\beta} \tag{2}$$

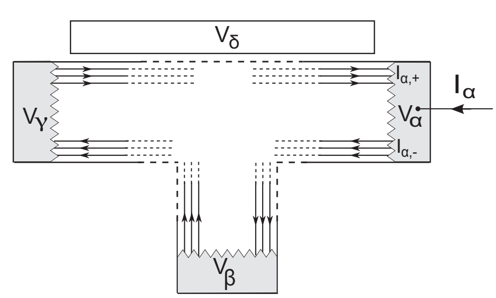

Fig. 1. Schematics of a generic Hall bar sample. Ohmic contacts and metallic gates are driven by time dependent electrochemical potentials V_α.