Electron interferometry in quantum Hall edge channels

Jérôme Rech,[1] Claire Wahl,[1] Thibaut Jonckheere,[1] and Thierry Martin[1]

[1] *Aix Marseille Université, Université de Toulon, CNRS, CPT, UMR 7332, 13288 Marseille, France*
e-mail address: jerome.rech@cpt.univ-mrs.fr

I. ELECTRON QUANTUM OPTICS

Electron quantum optics aims at transposing quantum optics experiments, allowing for the controlled preparation, manipulation and measurement of single electronic excitations in ballistic quantum conductors.

High-mobility 2D electron gases are a perfect testbed for conducting this task as several building blocks of quantum optics can readily be recreated in this context. First, the phase-coherent ballistic propagation of electrons is ensured by chiral edge states of the integer quantum Hall effect (IQHE). After propagation, these electrons collide at a quantum point contact (QPC), a tunable tunnel barrier mimicking a beamsplitter. The only missing ingredient finally appeared recently in the form of an on-demand single electron source (SES), opening the way to all sorts of interference experiments.[1]

II. THE HONG-OU-MANDEL SETUP

The Hong-Ou-Mandel[2] (HOM) interferometer is a celebrated tool of quantum optics. It allows to probe the degree of indistinguishability of two photons. When they collide on a beamsplitter at the same time, they exit in the same outgoing channel, showing a sudden vanishing of the output coincidence rate. This bunching phenomenon is a direct consequence of the bosonic statistics.

In a recent work,[3] we studied, from a theoretical standpoint, the outcome of this experiment at the single electron level, where two independently emitted electrons travel along counter-propagating opposite edge states and meet at a QPC, in the integer quantum Hall regime at filling factor $\nu = 1$. This goes beyond the simple transposition of an optics setup as several major differences exist between photons and electrons. In particular, electrons differ because of their statistics, the presence of the Fermi sea, and the possibility of holes.

We showed that valuable physics is encoded in the noise properties of the system, in particular the zero-frequency current correlations measured at the output of the QPC (R/L being right- and left-movers)

$$S_{\mathrm{HOM}} = \int dt dt' \left[\langle I_R^{\mathrm{out}}(t) I_L^{\mathrm{out}}(t') \rangle - \langle I_R^{\mathrm{out}}(t) \rangle \langle I_L^{\mathrm{out}}(t') \rangle \right] . \tag{1}$$

We predicted that the current correlation exhibits a dip as a function of the time delay δT between injections, whose shape is in direct correspondence with the one of the injected wavepackets. When δT vanishes, this HOM

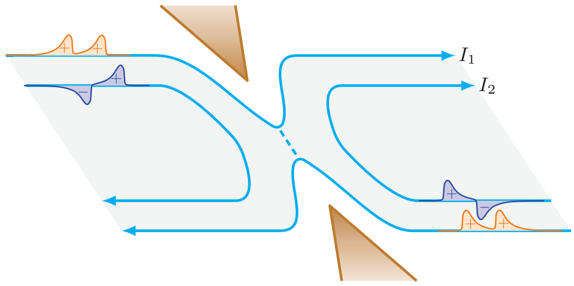

FIG. 1. The setup: two opposite edge states, each made out of two interacting co-propagating channels, meet at a QPC, and an electronic wavepacket is injected on both incoming outer channels.

dip extends down to zero signaling the existence of a unique outcome for the collision (a single electron in each output channel), a signature which we could tie back to the Pauli principle. Our work also suggests the possibility of asymmetric dips when different wavepackets collide, or even an HOM peak in the case of electron-hole collision.

The experimental realization of an electronic HOM interferometer in the IQHE soon followed,[4] albeit performed in the slightly different regime of filling factor $\nu > 1$, due to technical constraints. The puzzle with these results is that although the HOM dip clearly appears on top of a flat background contribution, it does not vanish as predicted for $\nu = 1$, therefore signaling interesting effects happening beyond this simple picture. Indeed, another important difference between photons and electrons is the presence of interactions, and electron quantum optics offers a fascinating playground to explore the emergence of many-body physics. In a subsequent work,[5] we proposed an interaction-based decoherence scenario which explains these striking experimental results.

III. NOISE AS A PROBE FOR FRACTIONALIZATION AND DECOHERENCE

We consider a quantum Hall bar at $\nu = 2$, in the strong coupling regime and at finite temperature. There, each edge state is made out of two co-propagating channels coupled via Coulomb interaction, as shown in Fig. (1). This is expected to lead to energy exchange between channels, and to charge fractionalization.

Our noise calculations rely on an accurate model of the injection of electrons, their propagation along the edges, and their scattering at the QPC. We introduce a prepared state consisting in a single exponential wavepacket

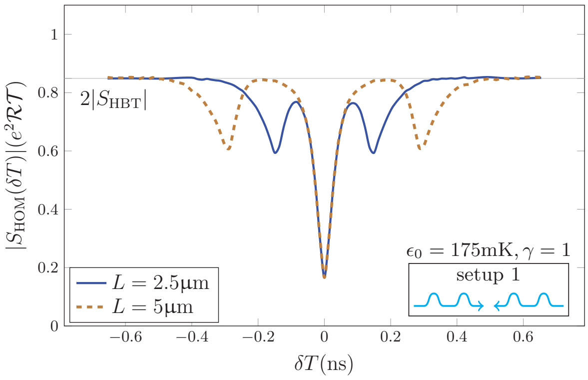

FIG. 2. Modulus of S_{HOM} as a function of the time delay for wide packets in energy (injection energy $\epsilon_0 = 175\mathrm{mK}$ and energy resolution $\gamma = 1$) and two propagation lengths.

deposited on the outer channel, thus mimicking the SES in its optimal regime of operation. Each edge is then modeled as a chiral Luttinger liquid with both intra- and inter-channel interactions, which upon diagonalization naturally brings about two freely propagating collective modes: a fast charged mode and a slow neutral one. We compute the correlations of output current in the HOM setup as a function of the time delay between right- and left-moving injected electrons, and reveal three characteristic signatures in the noise. The interference pattern is provided in Fig. (2) for a given set of parameters.

First, a central dip appears for zero time delay, corresponding to the interference of both fast and slow-right-moving excitations with their left-moving counterparts. As observed in the experiment, this dip never quite reaches zero in our calculations, and its depth strongly correlates with the energy resolution of the injected wavepackets. This is actually a probing tool of the degree of indistinguishability of the excitations colliding at the QPC. Because of the strong inter-channel interaction, some coherence of the injected object is lost in the co-propagating channels which do not scatter, and this Coulomb-induced decoherence is responsible for the dramatic reduction of contrast of the HOM dip.

Interestingly, smaller satellite dips appear in the noise at finite δT and seem to vanish for well-resolved wavepackets in energy. These correspond to interference between excitations traveling at different velocities, and provide an interesting noise signature of the interference of charged modes with neutral ones.

A more quantitative comparison between experimental and theoretical results is currently under way,[6] and already shows a remarkable agreement with no adjustable parameters. However, a major challenge still remains unsolved: the HOM dip bears a striking independence on the injection energy from the SES. This is in stark contrast with the $\nu = 1$ case, where the shape of the dip is directly related to the overlap of the injected wavepackets and thus depends crucially on the injection energy. This naturally brings about the question of the content in energy of the excitations colliding at the QPC. What does the new many-body state resulting from interactions over the propagation length truly look like? Could the noise be used as a way to reconstruct the decohered state which tunnels at the QPC?

IV. THE FRACTIONAL CASE

Interactions dramatically change the nature of the excitations, and the HOM interferometry offers the possibility to probe the incoherent mixture of fractionalized electronic excitations induced by Coulomb interactions. A natural extension of this work consists in studying a system where the ground state itself is a strongly correlated state of matter: the fractional quantum Hall effect (FQHE). There, one would be dealing not with electrons, but with single quasiparticles with fractional charge and statistics which should lead to dramatically new physics.

This constitutes a challenge at various levels, as a lot of open questions remain, from the nature of the quasiparticle injector to the results of an interferometry setup in the spirit of the HOM one. Indeed, the single electron source is clearly not the best candidate to generate on-demand single quasiparticles in the FQHE. Can single quasiparticles be dynamically emitted? What setup would guarantee the emission of on-demand single quaisparticles with little to no charge fluctuations?

The link between the measurement of low frequency noise correlations and the statistics of the carriers is well known. HOM interferometry with photons or electrons allows to probe the statistics through second order coherence, whether this is also enough to access the fractional statistics of quasiparticles is still under debate and deserves to be explored.

ACKNOWLEDGMENTS

We are grateful to D. Ferraro, G. Fève, B. Plaçais and P. Degiovanni for useful discussions.

[1] G. Fève et al., Science **316**, 1169 (2007).
[2] C.K. Hong, Z.Y. Ou and L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987).
[3] T. Jonckheere, J. Rech, C. Wahl and T. Martin, Phys. Rev. B **86**, 125425 (2012).
[4] E. Bocquillon et al., Science **339**, 1054 (2013).
[5] C. Wahl, J. Rech, T. Jonckheere and T. Martin, Phys. Rev. Lett. **112**, 046802 (2014).
[6] V. Freulon et al., in preparation (2015).