

Interferometry and entanglement detection at the nanoscale

For many decades, interferometry has been a fundamental tool to disclose the classical and quantum properties of light. Optical interferometry is now also at the heart of a new quantum-based technologies with applications in metrology, imaging, and quantum information processing. In the solid state world, controlled quantum interference experiments appeared more recently when, thanks to the advances in fabrication, the wavelike nature of electrons could be tested in transport measurements. The observation of Aharonov–Bohm oscillations in the electric current and the Landauer–Büttiker formulation of quantum transport in terms of electronic transmission amplitudes signaled the beginning of quantum electronic interferometry. In this field we have recently initiated an intense investigation of interference effects in quantum Hall bars systems that led us to develop a novel architecture for edge-states interferometry. Within this context, our most recent research efforts focused on the manipulation of edge-state transport with the controlled introduction of artificial scattering centers. Our research activity in nanoscale-interferometry includes also the study of interference effects for the detection of electronic entanglement via current-noise correlations measurements, the study of excess noise and electron-electron interactions in quantum wires, as well as the study of interference effects in signaling processes implemented over quantum networks.

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Among the different possible implementations of edge state interferometers, the adoption of chiral fractional quantum Hall channels offers intriguing perspectives thanks the non-trivial interaction mechanisms existing between edge excitations living at the boundary of different fractional quantum Hall states. Recent breakthroughs in the study of interference effects in quantum transport has been the experimental realization of electronic Mach–Zehnder (MZ) and Hanbury–Brown–Twiss (HBT) interferometers using edge states in a quantum Hall bar. Along this line we have proposed an alternative architecture for implementing electronic interferometry in quantum Hall bars which exploits scattering among parallel edge channels [1]. In contrast to previous developments, this one employs a simply connected mesa admitting serial concatenation of building elements closer to optical analogs. We have discussed the implementations of Mach–Zehnder and Hanbury–Brown–Twiss interferometers (Fig. 1) together with structures yet unexplored in quantum electronics.

Within this context, our most recent experimental activity has focused on a new strategy for the fabrication of tunable

point junctions between two quantum Hall edge states, one in the integer and one in the fractional regime [2]. Such junctions offer a valuable experimental feedback for understanding the mechanism of edge interaction between regions in the integer and fractional regime but they remained so far elusive and difficult to implement in practice. We realized our devices exploiting the concept of particle-hole duality that allowed circumventing some of

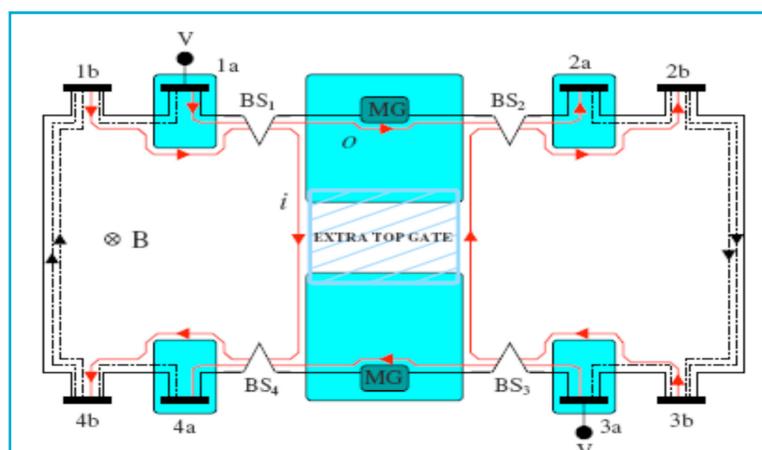


FIG. 1

Implementation of the Hanbury–Brown–Twiss interferometer with edge states. The shaded areas represent top gates that define regions of filling factor 1. In the rest of the sample, instead, we assume 2. Red lines represent the edge channels effectively taking part to the interferometer, BS1 and BS2 are beam splitters, while the gate MG is used to vary the shape and length of the outer edge channel.

the technical difficulties for the fabrication of the devices. The description of the setup and the SEM image of the junction are shown in Fig.2 panels c and d, respectively. We demonstrated that in a real quantum Hall junction transport is largely controlled by the local carrier density (i.e. filling factor) at the constriction point. These results provide relevant information for the realization of edge-state beam splitters of Ref. [1] in the fractional quantum Hall regime.

Another topic attracting a growing interest in the field of interferometry is related to entanglement characterization. On one hand, we have shown that current correlations at the exit ports of a beam splitter originated by crossing two nanowires (Fig. 2) can be used to detect electronic entanglement for a fairly general

input state [Fig. 3]. This includes the situation where electron pairs can enter the beam splitter from the same port, or be separated due to backscattering. The scheme that we have proposed allows to discriminate between occupation-number and degree-of-freedom entanglement. On the other hand, we have discussed an implementation of the entanglement witness, a method to detect entanglement with few local measurements, in systems where entangled electrons are generated both in the spin and orbital degrees of freedom [4]. We have addressed the efficiency of this method in various setups, including two different particle-hole entanglement structures, and we demonstrate that it can also be used to infer information on the possible dephasing afflicting the devices.

Fig. 2.

(a) Results of finite bias transport spectroscopy between an quantum Hall liquid at filling factor $1/3$ and 1 . (b) Comparison between conduction curves at bias 0 , 200 , 400 and 600 microV and theoretical predictions for two selected limit cases: a discrete system of N_s (top axis) uncorrelated tunneling centers in the strong coupling regime (hollow blue circles); range of conductance G oscillation for a quantum Hall line junction. (c) Sketch of the device structure and (d) scanning electron picture of the junction region. From [2].

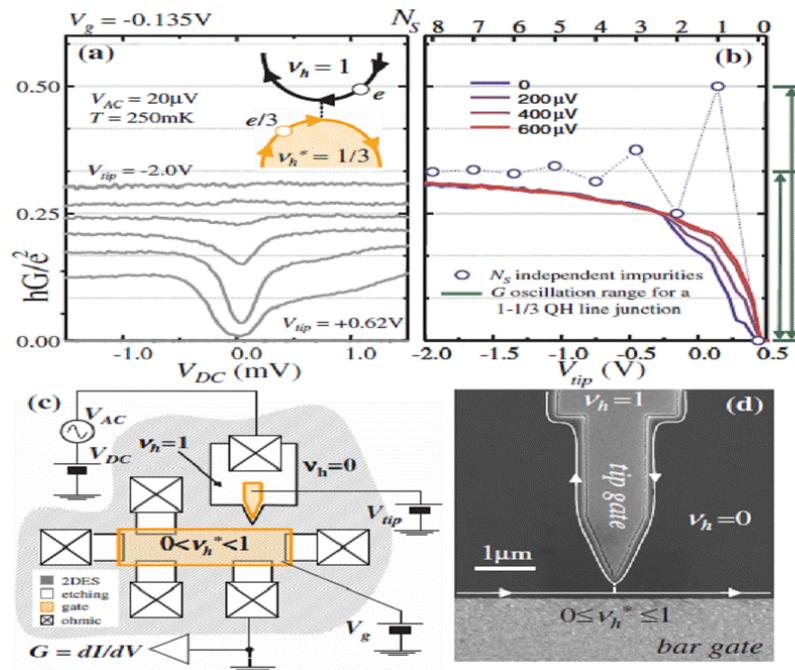
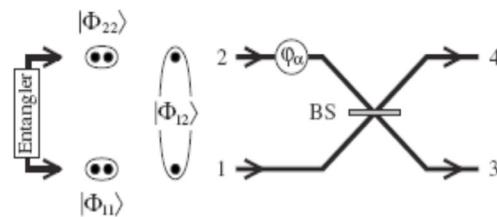


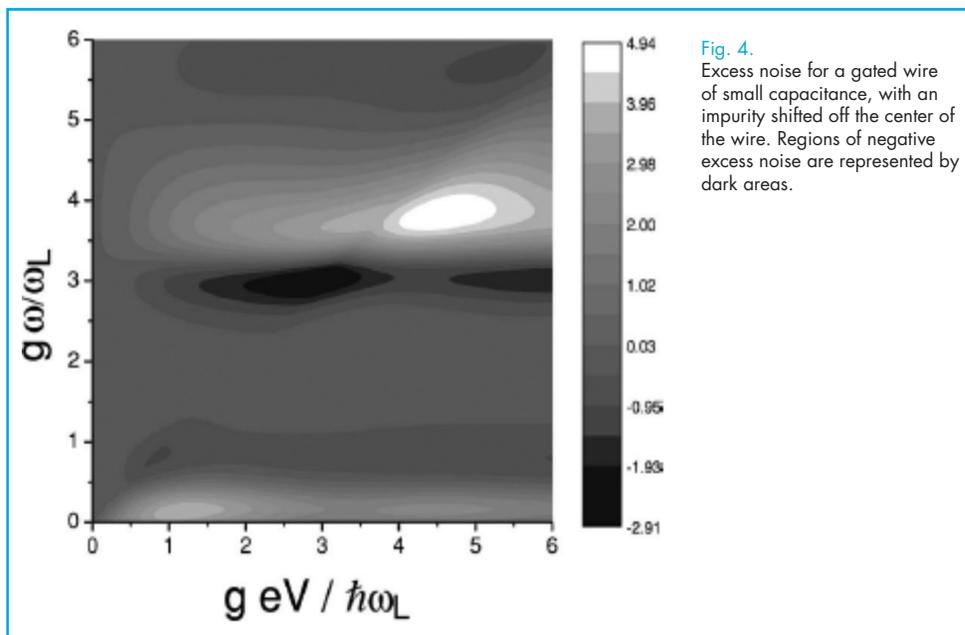
Fig. 3.

Sketch of the analyzer proposed in Ref. [3]. An external entangler prepares electron pairs and injects them into ports 1 and 2. The electrons are allowed to enter the analyzer from the same port and from different ports case, or in any superposition of the previous cases. Electrons propagating along lead 2 undergo an additional orbital or spin dependent controllable phase shift white circle in the figure, before impinging on a 50% beam splitter BS. Current correlations are measured at 3 and 4. From [3].



In our analysis of nanoscale interferometry we have also investigated the current noise of a quantum wire capacitively coupled to a gate in the quantum regime [5] and the conductance in a Fabry-Perot quantum wire configuration [6]. Specifically in the set-up analyzed in [5] both the shot noise and the finite-frequency noise have been analyzed in different regimes, ranging from large to small ratios between the geometrical and the quantum capacitance. In particular, we have demonstrated that the quantity

usually termed excess noise can become negative in various situations even at zero temperature (Fig. 4). Furthermore, we have estimated that such negative excess noise can be observed with state-of-the-art techniques using on-chip noise detection schemes. We therefore expect that these predictions can be verified in current experimental realizations of ballistic 1D conductors, such as quantum wires based on GaAs/AlGaAs heterostructures or single-wall carbon nanotubes.

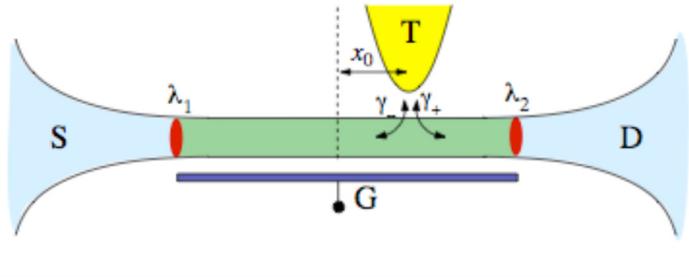


The scheme analyzed in [6] is schematically shown in Fig. 5. Here the wire is coupled to a third terminal (tip), and we allow for an asymmetry of the tip tunneling amplitudes of right and left moving electrons. For such set-up we analyze configurations where the tip acts as an electron injector or as a voltage-probe, and show that the transport properties of this three-terminal set-up exhibit very rich physical behavior. For a non-interacting wire we find that a tip in the voltage-probe configuration affects the source-drain transport in different ways, namely by suppressing the conductance, by modulating the Fabry-Perot oscillations, and by reducing their visibility. The combined effect of

electron electron interaction and finite length of the wire, accounted for by the inhomogeneous Luttinger liquid model, leads to significantly modified predictions as compared to models based on infinite wires. We show that when the tip injects electrons asymmetrically the charge fractionalization induced by interaction cannot be inferred from the asymmetry of the currents flowing in source and drain. Nevertheless interaction effects are visible as oscillations in the non-linear tip-source and tip-drain conductances. Important differences with respect to a two-terminal set-up emerge, suggesting new strategies for the experimental investigation of Luttinger liquid behavior.

Fig. 5.

Sketch of the set-up. A quantum wire is connected to metallic electrodes, denoted as source (S) and drain (D), respectively. A third electrode, denoted as tip (T), injects electrons into the wire at position x_0 . The contact resistances are accounted for by two delta-like scatterers (red spots in the figure). From [6].

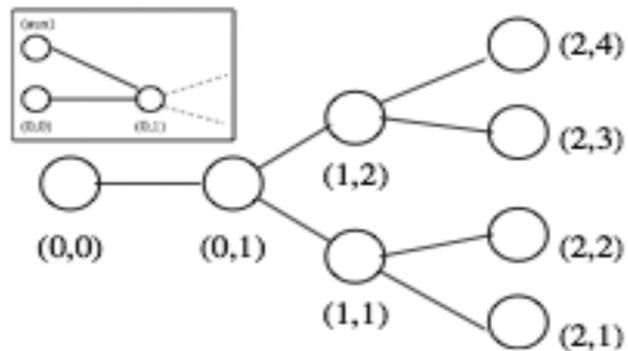


As mentioned in the introductory section, quantum interferometry plays also a fundamental role in efficiently routing the propagation of “signals” over networks of coupled quantum objects (say magnetic impurities). In a recent paper [7], we exploited this effect to improve the efficiency of excitation propagation in a binary-tree configurations (see Fig. 5). For a binary tree of order 2, a simple protocol

is presented which allows one to achieve arbitrary high transfer fidelity. It does not require fine-tuning of local fields and two-node coupling of the intermediate spins. Instead it assumes simple local operations on the intended receiving node: their role is to break the transverse symmetry of the network that induces an effective refocusing of the propagating signals.

Fig. 6.

Schematic of the set-up. Here a collection of spins are coupled via a ferromagnetic Heisenberg interaction according to the edge of the graph and the system is prepared into the ground state. At some initial time t an excitation is introduced in the system in the node $(0,0)$ of the figure. The goal of the protocol is to be able to recover such excitation from a selected node on the right. From [7].



References

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