Bosonization and Unruh-DeWitt Detectors for Laboratory Realized Quantum Electrical Engineering

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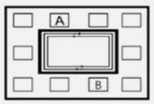
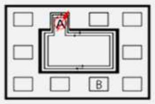
INTRODUCTION

- Quantum Transduction from Helical Luttinger Liquids to spin-qubits, provide a quantum bus that allows for all-to-all qubit connectivity.
- Understanding and evaluating quantum information as it is spread out from qubits onto fields will provide insight into flying qubit practicality.
- Unruh-Dewitt Detectors are a possible avenue into exploring this regime.

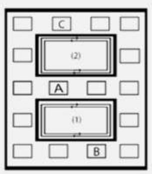
A CARTOON MODEL



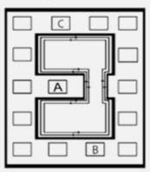
(a) Qubit A can access all qubits on the system via left- and right-movers.



(b) Opening up qubits will cause interactions with the left- and right-movers.



(c) Adding another block of qubits restricts of our left- and right-movers to paths (1) or (2).



(d) Opening the bulk between the blocks gives Qubits B and C direct access to the entirety of the qubits.

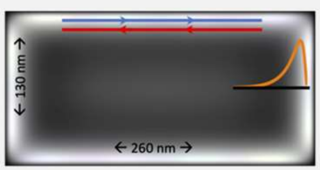


FIG. 3: Simulation of HgTe QW edge state on a 200 × 400 atom (130 × 260 nm) bar.

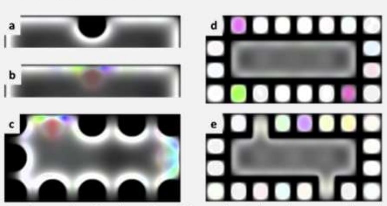


FIG. 4: A new electronic quantum bus for spin qubits. **a** A gated region moves the edge state. **b** A local magnetic field "cuts" the edge state in two pieces. **c** A snapshot of a 12 qubit all-to-all connected device, 10 qubits at 15.0 V local gate (appear dark in these electron density plots), two qubits at 0.0 V gate exposed to the edge state. **d** A 20 qubit device with gates placed in a regular grid to create trapped electron qubits. **e** Releasing the gate between two of the qubits and center region enables communication.

MOTIVATIONS

- All-to-all Transduction allows for specialized error correcting code.
- Laboratory ready quantum computing using flying qubits to send/receive information.
- Employ Helical Luttinger Liquids into the arena of Quantum Computers.
- Could these techniques be utilized in a field of Quantum Electrical Devices?

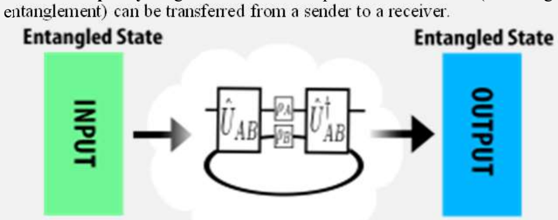
EXPERIMENT

- HgTe is a prototypical example of an experimentally viable Helical Luttinger Liquid.
- Spin qubits along the perimeter provide access points to implant information into the Luttinger Liquid.
- Right and Left moving fermions provide flying qubits for computation.

QUANTUM INFORMATION

- Calculations of Channel Capacity provide insight into the ability of the quantum computer.

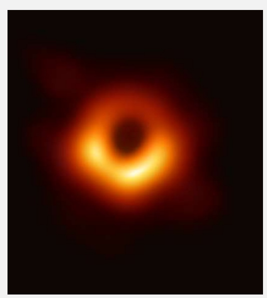
Channel Capacity: Highest rate at which quantum information (including entanglement) can be transferred from a sender to a receiver.



$$\Xi_{AB}(\rho_A) = \mathrm{Tr}_B\{U_{AB}(\rho_A \otimes \rho_B)U^\dagger_{AB}\}$$

- Quantum Channels are required to preserve entanglement.
- If separable states exist at any point in the process the channel is broken, and Capacity goes to Zero.
- Perfect channels aim to have channel capacity of one at infinite process iterations.
- Entanglement Entropy is often employed when discussing channel capacity.

UNRUH-DEWITT DETECTORS

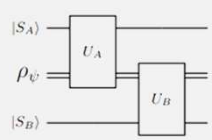


- These models were originally designed to understand light-matter interactions in extreme gravitational scenarios. Specifically, for accelerating detectors to observe the Unruh effect and in the neighborhood of a Black Hole.
- Recently, physicists interested in relativistic quantum information in quantum computers have been exploring this regime using UDW detector models.
- Practically, the detector is used to couple a two-level system and a field. Smearing the information out onto a larger Hilbert space.

- Simidzija et. al. has shown that two rank one unitaries can create a channel with a non-zero capacity.

$$U_\nu = \exp\left(iJ_{\nu 2}\mu_{\nu 2} \otimes O_{\nu 2}\right)\exp\left(iJ_{\nu 1}\mu_{\nu 1} \otimes O_{\nu 1}\right).$$

- We want our observables to be of the same field, but instead we have both Right- and Left-moving electron fields.



RIGHT- & LEFT-MOVER QUANTUM CHANNEL

HELICAL LUTTINGER LIQUID

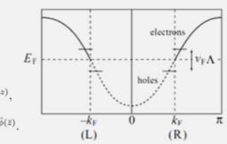
- Bosonization of our Helical Luttinger Liquid takes the Right- and Left-movers, and models them as a single Bosonic field allowing us to create a non-zero quantum channel.

Fermionic HLL Hamiltonian

$$\mathrm{H}_{int}(t) = J\chi(t)\int_{\mathbb{R}} dy\; p(x(t),y)\mu(t)(\psi^\dagger_+\psi_+ - \psi^\dagger_-\psi_-)$$

Bosonize

$$\psi_+(z) = \frac{1}{\sqrt{2\pi}}e^{-i\sqrt{4\pi}\phi(z)}, \qquad \psi^\dagger_+(z) = \frac{1}{\sqrt{2\pi}}e^{i\sqrt{4\pi}\phi(z)},$$
$$\psi_-(\bar z) = \frac{1}{\sqrt{2\pi}}e^{i\sqrt{4\pi}\bar\phi(\bar z)}, \qquad \psi^\dagger_-(\bar z) = \frac{1}{\sqrt{2\pi}}e^{-i\sqrt{4\pi}\bar\phi(\bar z)}.$$



1-D dispersion shows linear relations in the neighborhood around the fermi points.

Bosonic HLL Hamiltonian

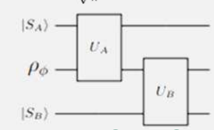
$$\mathrm{H}^B_{int}(t) = J\chi(t)\int_{\mathbb{R}} dy\; p(x(t),y)\mu(t)\left(\frac{1}{\sqrt{\pi}}(\partial_z\phi + \partial_{\bar z}\bar\phi)\right)$$

Redefine fields

$$\varphi = \phi + \bar\phi$$
$$\Pi = \frac{1}{v}\partial_t\varphi$$

$$\mathrm{H}^B_{int}(t) = J\chi(t)\int_{\mathbb{R}} dy\; p(x(t),y)\mu(t)\left(\frac{1}{\sqrt{\pi}}\Pi\right)$$

This Hamiltonian provides one simple rank one unitary gate and subsequently provides a channel with zero capacity. A small adjustment completely solves this problem.



SINGLE BOSONIC FIELD IMPLANTED INTO THE QUANTUM CHANNEL

RESULTS

- Given that nature is finicky, we want many options to explore our quantum channels. Luckily, this model provides just that.
- One option is allowing for terms we suppressed in the fermion density. These terms provide a second rank one unitary gate that does not commute from the principles of Heisenberg exchange.

$$\mathrm{H}_{int}(t) = \chi(t)\int_{\mathbb{R}} dy\; p(x(t),y)J_A\mu_A(t)(\psi^\dagger_+\psi_+ - \psi^\dagger_-\psi_-) + J_B\mu_B(t)(\psi^\dagger_+\psi_- - \psi^\dagger_-\psi_+)$$

Bosonize

$$\mathrm{H}^B_{int}(t) = \chi(t)\int_{\mathbb{R}} dy\; p(x(t),y)\left(J_A\mu_A(t)\left(\frac{1}{\sqrt{\pi}}\Pi\right) + J_B\mu_B(t)\left(\frac{1}{2\pi}\cos\sqrt{4\pi}(\varphi)\right)\right)$$

This final Hamiltonian is one solution of many that proves from the prescription in Simidzja et. al., that the simplest quantum channel provides a non-zero capacity.

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