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Quantum computing using novel topological qubits at Nokia Bell Labs

Physical systems that can be switched between quantum states by simple topological manipulation of charges provide the best path for building a functional quantum computer.

At Bell Labs, we are working on a quantum switch, or qubit, constructed from an ensemble of thousands of interacting electrons, in which the collective quantum state of the ensemble can be switched between two distinct states by a topological manipulation of the charges. The nature of the large electron ensemble and the specific topological charge movements needed to switch states make it resistant to de-coherence, the undesirable scrambling of states pervasive in other quantum computing approaches.

Our physical system is a collection of electrons confined to move in a plane at the interface between two materials grown one atomic layer at a time through a process called molecular beam epitaxy. The pristine nature of this interface allows the mutual repulsion of the like-charged electrons to dominate. When cooled to millikelvin temperatures with a large magnetic field applied perpendicular to the plane of electrons, charge repulsion causes these electrons to form a 'liquid', whose energy is minimized by the electrons arranging equidistant from one another. The excitations of this uniform charge density liquid are charges that are a fraction of the electron charge depending upon the electron to magnetic field ratio: at one electron and three magnetic field lines, the excitation charges are e/3. Thus, different liquids and different associated charge excitations form depending upon this ratio. An electron liquid will generally form for an integral number of electrons and an odd number of magnetic field lines per area, but the 'fundamental particle' for this system is one electron and two magnetic field lines. These particles, called composite fermions, do not themselves condense to form a charge liquid, but can form a liquid when they pair up. Just as electrons can pair to form a superconductor, a macroscopic quantum state, these composite fermions can also pair to form a macroscopic quantum state, an electron liquid, in this case possessing e/4 charge excitations. However, this is a unique liquid.

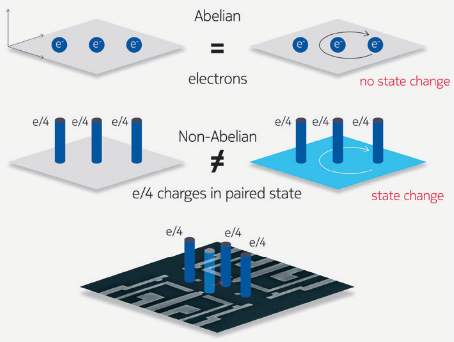

Figure 1. ***Topological qubit operation and prototype***. *Topological qubit quantum states in the correlated two-dimensional electron system (2DES) can be switched by winding or braiding charges. In the composite fermion paired state, the e/4 excitation braiding shown here induces switching from one state to another, which includes the entire 2DES and the excitations (a non-Abelian system); no such state change occurs for braiding electrons (Abelian system). In the prototype qubit (bottom graphic), moving an e/4 from one side of the device to the other switches the topological state of the qubit, a NOT operation.*

This composite fermion pairing state has a dramatic property[1-4]: when the excitations of this liquid are wrapped around one another, the entire system (electron liquid and excitations) changes from one fundamental quantum state to another (**see Figure 1.**). These two states form the basis for the topological qubit, with wrapping or braiding the excitations around one another the essential quantum state switching mechanism. Note that such a state change does not occur if two *electrons* are wrapped around one another, or even if braiding two e/3 charges from the liquid at one electron and three magnetic field lines: only the composite fermion pairing state demonstrates this topological property. Experiments at Bell Labs[5] have shown this controlled switching from one topological state to another.

Microscopic metal electrodes deposited on top of the material can be used to switch the quantum state by moving charges around one another; these charge movements are the foundation of topological quantum computing. Note from the Figure that to switch topological states we braid one e/4 charge between two e/4 charges fixed in position electrostatically. The illustrated braid is a logical NOT operation. At Bell Labs, we are working to demonstrate the first such qubit device in 2017.

Once such a qubit structure has been created, we can tile it across the sample and the qubits are essentially linked as they have the same background correlated electron state. Other operations (e.g. Hadamard, phase) are accomplished by combinations of either braiding charges between the fixed charges or inducing charge exchanges between the fixed positions using top electrodes. Quantum computations are then accomplished by applying such operations in serial fashion as prescribed by quantum algorithms: examples are Grover's algorithm (quantum search) or Shor's algorithm (number factorization), both discovered at Bell Labs.

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