

Electron pairing on the edge?

Robust electron pairing in the integer quantum Hall effect regime

H.K. Choi, I. Sivan, A. Rosenblatt, M. Heiblum, V. Umansky, D. Mahalu

arXiv:1409.4427 (2014)

Recommended with a commentary by Felix von Oppen, Freie Universität Berlin

The basic phenomenology of the integer quantum Hall effect is readily rationalized within an edge state picture. When placing a two-dimensional electron system into a strong perpendicular magnetic field, the single-electron states are macroscopically degenerate Landau levels, equally spaced in energy by $\hbar\omega_c$ in terms of the cyclotron frequency ω_c . At the sample edges, the Landau levels bend up in energy, eventually crossing the Fermi energy. Whenever an integer number of Landau levels are filled, this leads to a gapped excitation spectrum in the bulk but gapless excitations at the edge. Each filled Landau level contributes one gapless edge channel, which is chiral as the edge excitations circulate around the sample edge in one direction only. Classically, this can be interpreted as $\mathbf{E}\times\mathbf{B}$ drift with the electric field \mathbf{E} originating from the confinement potential. The quantization of the Hall conductance to an integer multiple of e^2/h is then related to the integer filling of the Landau levels.

What happens to this picture when taking electron-electron interactions into account? According to standard lore: Not much for a single edge channel (Landau level filling $\nu=1$)! For a single channel, its chiral nature effectively protects its Fermi liquid nature. For several edge channels ($\nu=2$ or larger), the situation is more subtle. Interchannel interactions can induce the phenomenon of charge partitioning known from Luttinger liquids¹: When electrons are tunneling into one of the edge channels, their charge will in general partition and propagate in non-integer charge packets in the various edge channels. This effect is quite subtle and typically does not leave a trace in *dc* conductance measurements. However, it is in principle detectable in *ac* measurements and recent experiments may have been successful in observing it [1,2].

It is also against this backdrop that an apparent observation of electron pairing in integer quantum Hall systems comes as a surprise. Choi and collaborators at the Weizmann Institute provide several pieces of experimental evidence for electron pairing in the regime of Landau level filling factor $\nu=3$ and 4. Here, I want to sketch the two central ones, which are based on Aharonov-Bohm periods and shot-noise measurements, respectively.

¹ This is sometimes also referred to as charge fractionalization, but I prefer 'partitioning' - because the phenomenon is associated with the injection process rather than the edge itself.

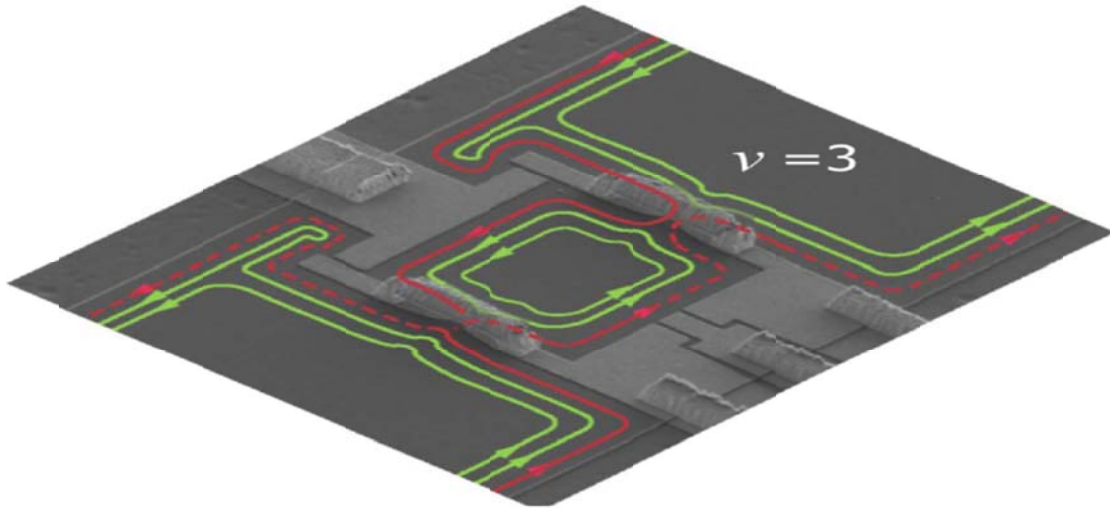


Figure 1: Scanning electron microscopy image of the Fabry-Perot interferometer, including schematic edge channels for the case of Landau level filling $\nu=3$. The source (drain) contacts the edge channels at the lower right (left). The stadium-shaped interferometer region at the center is connected to source and drain through two quantum point contacts, which are tuned to transmit only the outermost (red) edge channel.

The measurements employ an electronic Fabry-Perot interferometer based on quantum Hall edge channels (see Fig. 1). The partially transparent mirrors of the analogous optical interferometer are replaced by quantum point contacts. The first quantum point contact transmits the edge channels incident from the source into the stadium-shaped interferometer. The second controls the exit from the interferometer to the drain. The point contacts are tuned such that only the outermost edge channel is (partially) transmitted. Electrons entering into the interferometer can make multiple roundtrips along the edge of the stadium, contributing multiple partial amplitudes to the total transmission (and hence the conductance of the structure). The relative phase of these partial amplitudes depends on the enclosed Aharonov-Bohm flux BA which is controlled by the enclosed area A and the magnetic field B . Thus one expects that the conductance of the Fabry-Perot interferometer is flux periodic with period of the flux quantum $\phi_0=h/e$.²

This is indeed what the authors observe for Landau level fillings smaller than about 2.5 and larger than 4.5. But remarkably, for Landau level fillings in the range from 2.5-4.5, the Aharonov-Bohm period halves, becoming $h/2e$ instead of h/e . One possible explanation is that the effective charge of the entities, which accumulate the Aharonov-Bohm phase is $2e$ instead of e . Of course, there may be other explanations for this behavior. For instance, odd numbers of round trips within the interferometer could for some reason be strongly suppressed. However, the authors argue that this interpretation is in conflict with additional measurements.

To provide further evidence for electron pairing, the authors perform shot noise measurements. Shot noise arises from the discrete nature of the charge carriers and

² It is actually not entirely obvious that the electronic Fabry-Perot interferometer works in this way and the authors had to take certain experimental precautions to ensure this.

provides access to their charge. Sure enough, they find that shot noise measurements yield carrier charges, which are consistent with the Aharonov-Bohm measurements: For fillings less than 2.5 or larger than 4.5, shot noise gives a carrier charge of e , but for 2.5-4.5, the charge changes to $2e$.

What is the origin of these surprising observations? I do not know but there are a few facts that may guide the search for an explanation. The most familiar mechanism for electron pairing, namely the BCS instability towards Cooper pairing, relies on pairing time-reversed states. Since quantum Hall systems are chiral, it is certainly far from clear how any variant of BCS theory would apply here.

Another clue may be provided by the shot noise measurements. The charge $2e$ is observed only in the interferometer setup. The stadium-shaped interferometer can be viewed as a 'quantum dot' connected to source and drain by quantum point contacts. If the shot-noise measurement is performed on a single quantum point contact and thus without 'quantum dot', the observed charge is always just the electron charge e . This suggests that the pairing is not really a property of the edge states themselves, but is somehow associated with the presence of the quantum dot. At the same time, the authors find their observations for interferometers of different sizes, ranging from 2-12 μm^2 .

Further clues are provided by experiments with an additional quantum point contact within the interferometer, which (partially) backscatters the inner edge channel into a central Ohmic contact (not shown in Fig. 1). The Ohmic contact dephases the inner edge channel and this seems to rapidly quench the observation of the $h/2e$ periodic Aharonov-Bohm oscillations. It will be interesting to see how these intriguing observations will eventually be explained!

[1] H. Kamata, N. Kumada, M. Hashisaka, K. Muraki, and T. Fujisawa, *Fractionalized wave packets from an artificial Tomonaga-Luttinger liquid*, Nature Nanotechnology **9**, 177-181 (2014).

[2] H. Inoue, A. Grivnin, N. Ofek, I. Neder, M. Heiblum, V. Umansky, and D. Mahalu, *Charge Fractionalization in the Integer Quantum Hall Effect*, Phys. Rev. Lett. **112**, 166801(2014).