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Measurements of the thermal edge conductance in a fractional quantized Hall state, with very surprising results at ν = 5/2.

1. Observed quantization of anyonic heat flow
Authors: M. Banerjee, M. Heiblum, A. Rosenblatt, Y. Oreg, D. E. Feldman, A. Stern, and V. Umansky
Nature **545**, 77 (2017)

2. Observation of half-integer thermal Hall conductance
Authors: M. Banerjee, M. Heiblum, V. Umansky, D. E.Feldman, Y. Oreg, and A. Stern
arXiv:1710.00492

Recommended with a commentary by Bertrand I. Halperin, Harvard University

When a two dimensional electron system is in a quantized Hall state, it will necessarily have propagating low-energy excitations at its edges, but will not have mobile charged excitations in the bulk. In addition to the quantized electrical Hall conductance, it has been predicted that the edge states will give a quantized contribution to the thermal Hall conductance, which we may write as $\kappa_{xy} = K\, \kappa_0\, T$, where $\kappa_0 = (\pi^2 k_B^2/3h)$, and T is the temperature, while K is a quantum number that is equal to the chiral central charge of the boundary conformal field theory [1]. The quantum number K must be an integer for quantized Hall states with abelian excitations, but it will be a half-integer for a non-abelian state with a chiral Majorana mode at the boundary. The value of K is equal to the difference in the number of right-moving and left-moving edge modes, with Majorana modes counted as half, and it is a topologically protected property of the quantized Hall state, which cannot be modified by reconstruction at the edge.

In so far as one can neglect thermal conduction by phonons or any bulk electronic excitations at low temperatures, a two-terminal measurement of the thermal conductance with contacts connected to the edge of a quantized Hall state will be determined by the absolute value of κ_{xy}. However, experimental measurement of the thermal conductance in a fractional quantized Hall state has posed a number of highly non-trivial challenges. The Heiblum group, in a set of beautiful experiments, has surmounted these difficulties, using an approach based on earlier work by Jezouin, *et al.*, who measured thermal conductances in the integer quantum Hall regime [2].

The first of the two papers cited above reports results for quantized Hall states in GaAs, with filling factors ν equal to 1, 2, 1/3, 2/3, 3/5 and 4/7, for which the predicted values of K are 1, 2, 1, 0, -1 and -2, respectively. In each case, the measured thermal conductance value was in excellent agreement with the predictions. The second paper reports measurements at fractions in the second Landau level. While the results for states with $\nu = 7/3$ and 8/3 were in agreement with predictions, the results obtained for the even-denominator quantized Hall state at $\nu=5/2$ were in dramatic disagreement with expectations.

For many years, it has been believed that the 5/2 state can be understood as an adiabatic perturbation of either the Pfaffian state, proposed by Moore and Read in 1991, or its particle-hole conjugate, the "Anti-Pfaffian" [3]. The two states are topologically distinct, with predicted values, respectively, of K=7/2 and K=3/2. However, the experimental result obtained by Banerjee, *et al.* at ν=5/2, was K=5/2!

The theoretical possibility of a quantized Hall state with ν=5/2 and K=5/2 had been discussed previously, and was given the name of PH-Pfaffian by Son in 2015 [4-6]. However, numerical calculations, including exact diagonalizations of finite systems and DMRG analyses, have consistently favored the Pfaffian or Anti-Pfaffian over a state with the quantum numbers of the PH-Pfaffian [7]. What is going on here?

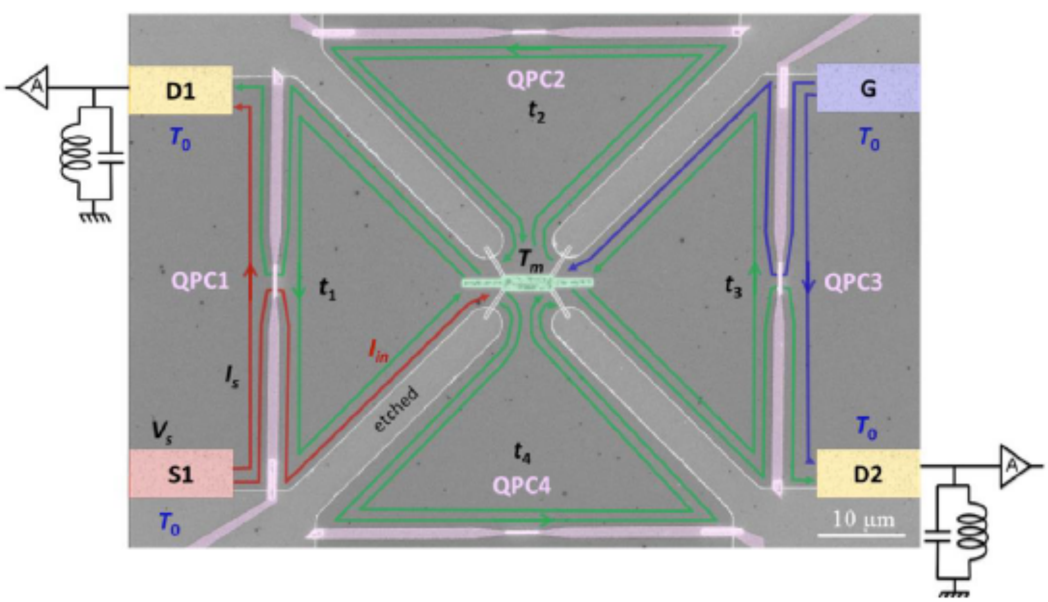
Several theoretical works have explored the possibility that a state with K=5/2 might be stabilized by disorder [5,8,9]. While this may be possible in principle, it is far from clear that such a state would occur in a model with parameters appropriate to the experimental system. In a large part of the parameter range, it seems that there is either no intermediate state between the Pfaffian and Anti-Pfaffian, or the intermediate state is a "thermal metal", with quantized Hall conductance but no quantized thermal conductance [8-10]. One should therefore keep an open mind about the possibility that, contrary to the predictions of existing numerical calculations, a state with K=5/2 may, in fact, be the correct ground state for the system *without* disorder.

The figure below shows the heart of the device used to measure the thermal conductance in the first paper of Banerjee, *et al*. The device is fabricated on a high-mobility two-dimensional electron gas contained in a GaAs-AlGaAs heterostructure. The device contains a floating ohmic contact (green) at the center, and a quantum point contact opening (QPC) in each of the four gates (violet) along the sides. The diagonal trenches (light gray) insure that current can flow from one quadrant to another only by passing through the floating contact. The example shown is at ν=2, in a configuration with QPC2 and QPC4 closed but with QPC1 and QPC3 *partially* open, so only the outermost edge state can pass through. When a voltage V_s is applied to source S, a current $I_{in} = V_s e^2/h$ passes through QPC1 and enters the floating contact. Current leaving the contact will end up equally in drains D1 and D2. Calculations show that a part P_Q of the input power, given in this case by $P_Q = I_{in}V_s/4$, will be converted to heat in the floating contact. If one can neglect the effect of phonons, this heat will be conducted to D1 and D2 by the quantized Hall edge states, and the temperature rise of the floating contact should be $\Delta T = P_Q/2\kappa$, where $\kappa = |K|\,\kappa_0 T$ is the thermal conductance of each one of the two active edges. (The temperature T in the last formula should be taken to be the mean of the temperature of the contact and the temperature of the drain, if ΔT is not small.) The temperature rise of the floating point contact is measured by Johnson noise thermometry using resonant circuits and amplifiers attached to D1 and D2. The effects of phonons can be eliminated by comparing measurements made with different numbers of open QPCs.

In states where there are counter-propagating modes on each edge, a condition for accuracy of the measurements is that the length L of the edge (here about 150μm) should be longer than the equilibration length. This was checked in the experiments, and corrections due to lack of perfect equilibration were shown to be small, except in the case of ν=2/3, where, due to the special situation when K=0, they needed to be taken into account.

The device used to measure the thermal conductance at ν = 5/2 differed in several details from that shown in the figure below. In particular, the quantum point contacts were replaced by an extended line gate on top of an HfO_2 dielectric layer, which allowed for lower depletion voltages and more stable operation. In addition, the wafer was designed with a particular doping scheme and tailored aluminum concentrations, in order to minimize parallel thermal conduction in the doping layer while maintaining electrical quality. Numerous other fine points, as well as consistency checks on the experiments, are discussed in the two papers.

The thermal measurements of fractional quantized Hall states by Banerjee, *et al*. represent a major technological achievement. It remains for us to understand the very surprising results at ν=5/2.



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