Particle-hole symmetry without particle-hole symmetry in the quantum Hall effect

Dima Feldman
Brown University

P. T. Zucker and D. E. Feldman, PRL **117**, 096802 (2016);
M. Banerjee, M. Heiblum, A. Rosenblatt, Y. Oreg, D. E. Feldman, A. Stern, and V. Umansky, Nature **545**, 75 (2017);
M. Banerjee, M. Heiblum, V. Umansky, D. E. Feldman, Y. Oreg, and A. Stern, arXiv:1710.00492.

Theoretical proposals at ν=5/2

Numerous ways to build Cooper pairs!

- Pfaffian state
- 331 state
- K=8 state
- $SU(2)_2$ state
- anti-Pfaffian state
- anti-331 state
- anti- $SU(2)_2$ state
- and so on

Numerics favors Pfaffian and anti-Pfaffian

Pfaffian and anti-Pfaffian states

- numerics supports Pfaffain and anti-Pfaffian states in the absence of disorder and Landau level mixing
- poor results for the energy gap
  - strong disorder
  - LLM parameter ~ 1.3
- Small energy differences for proposed states

  [J. Biddle *et al., Phys. Rev. B* **87**, 235134 (2013)]
- no QHE at realistic LLM in numerics

  [K. Pakrouski *et al*., *Phys. Rev. X* **5**, 021004 (2015);

  E. H. Rezayi, *Phys. Rev. Lett.* **119**, 026801 (2017)]

Experimental results

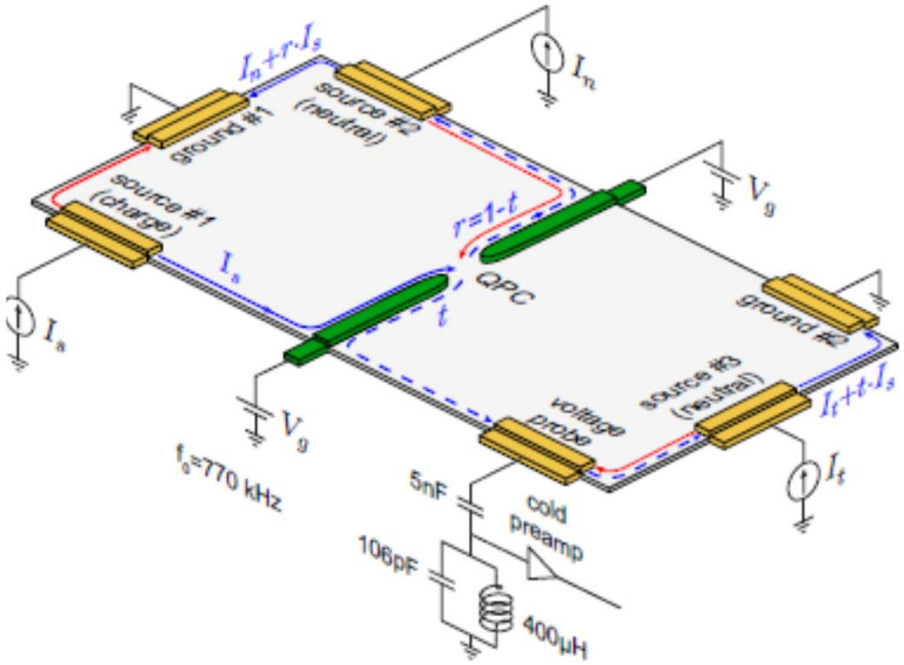
- Charge **e/4**
- Controversial results for spin polarization
- Fabry-Perot interferometry identical for all non-Abelian states and can be identical for Abelian states [**A. Stern, B. Rosenov, R. Ilan, and B.I. Halperin, PRB 82, 085321 (2010)**]

Upstream modes

Topologically protected

Edge reconstruction

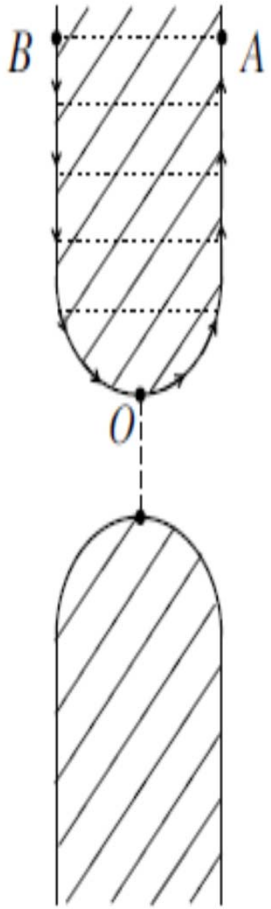
Upstream neutral modes



Observation of a topologically protected upstream neutral mode [A. Bid *et al.*, Nature **466**, 585 (2010); M. Dolev *et al*., PRL **107**, 036805 (2011)]. Compatible with anti-Pfaffian. Incompatible with Pfaffian.

The observed physics at ν=5/2 is similar to ν=8/3. It differs from the filling factors such as 7/3 where no topologically protected upstream modes are present but edge reconstruction is possible [H. Inoue *et al*., Nature Comm. **5**, 4067 (2014).]

Tunneling



Theory: $G \sim T^{2g-2}$

- Pfaffian: $g = \frac{1}{4}$
- Anti-Pfaffian: $g = \frac{1}{2}$

Experiment: $g_{\text{exp}} > g_{\text{theor}}$

Experiment gives an upper bound on g
The upper bound of 0.4 is consistent with Pfaffian and excludes anti-Pfaffian

I. P. Radu *et al.*, *Science* **320**, 899 (2008); X. Lin *et al.*, *Phys. Rev. B* **85**, 165321 (2012); S. Baer *et al.*, *Phys. Rev. B* **90**, 075403 (2014); H. Fu *et al.*, *PNAS* **113**, 12386 (2016).

Filling factor 1/2

[D. T. Son, *Phys. Rev. X* **5**, 031027 (2015)]

Imagine exact particle-hole symmetry between filling factors f and $1-f$.

The theory can be made explicitly symmetric by assuming that composite fermions are Dirac particles.

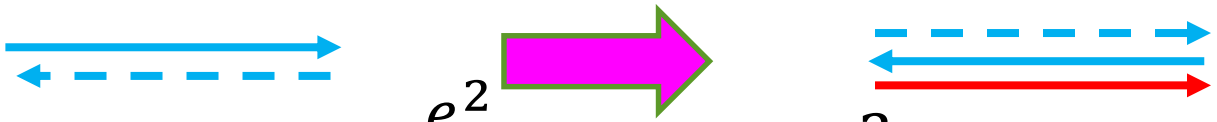
There is evidence that the theory might be, surprisingly, equivalent by the HLR theory of composite fermions.

What about Cooper pairing of Dirac particles in the *s*-channel?

PH-Pfaffian state

s-pairing of Dirac fermions

Particle-hole symmetry:



$$G = \frac{e^2}{2h}; \quad k = \pi^2 T/6h$$

Edge theory:

[see also S.-S. Lee *et al.*, *PRL* **99**, 236807 (2007)]

$$-\frac{2}{4\pi}[\partial_t \varphi \partial_x \varphi + v_c \partial_x \varphi \partial_x \varphi] + i\psi(\partial_t - v_n \partial_x)\psi$$

$$\psi = \psi^+$$

Wave function:

$$\int \{d^2 s_i\} \mathrm{Pf}\left\{\frac{1}{\bar{s}_i - \bar{s}_j}\right\} \prod (s_i - s_j)^2 \exp[-2|s_i|^2 + 2\bar{s}_i z_i - |z_i|^2]$$

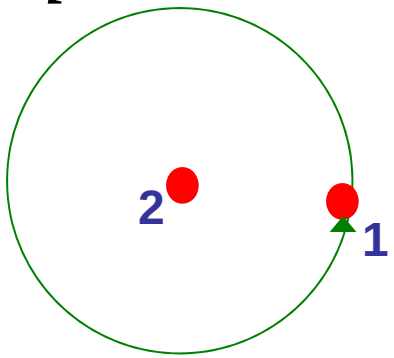
The same topological order in a different context:

L. Fidkowski *et al.*, *PRX* **3**, 041016 (2013); P. Bonderson *et al.*, *J. Stat. Mech.* P09016 (2013)

PH-Pfaffian state

$$\nu = 5/2$$

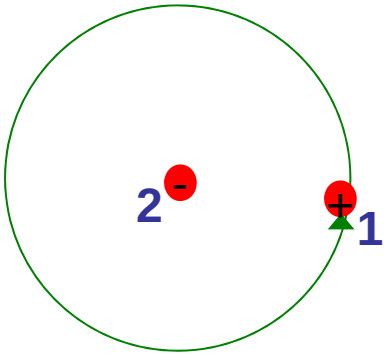
$$q = e/4;\ \text{non - Abelian statistics}$$



$$\left|\psi_f\right\rangle \neq \exp(i\theta)\left|\psi_i\right\rangle$$

Several states at given quasiparticle positions

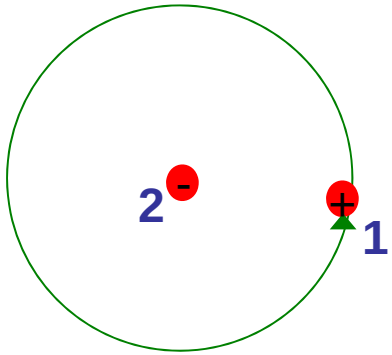
Vacuum superselection sector $\left|1\right\rangle$



$$\psi \to \psi$$

$$\theta = \pi/2$$

Fermion sector $\left|\varepsilon\right\rangle$



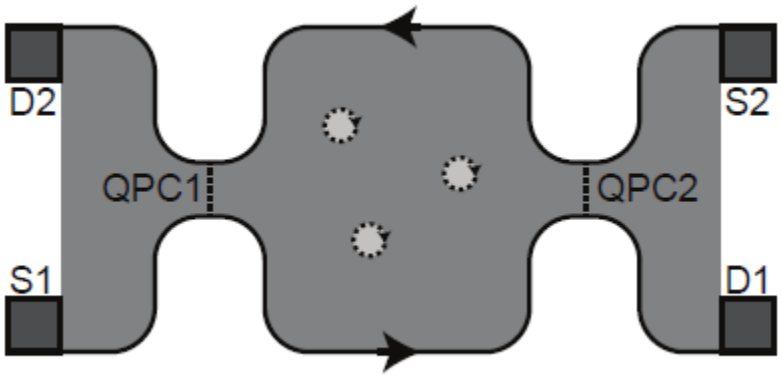
$$\psi \to -\psi$$

$$\theta = -\pi/2$$

$$\alpha\left|1\right\rangle\left|\ \right\rangle + \beta\left|\varepsilon\right\rangle\left|\ \right\rangle \to i\alpha\left|1\right\rangle\left|\ \right\rangle - i\beta\left|\varepsilon\right\rangle\left|\ \right\rangle$$

Comparison with the experiment

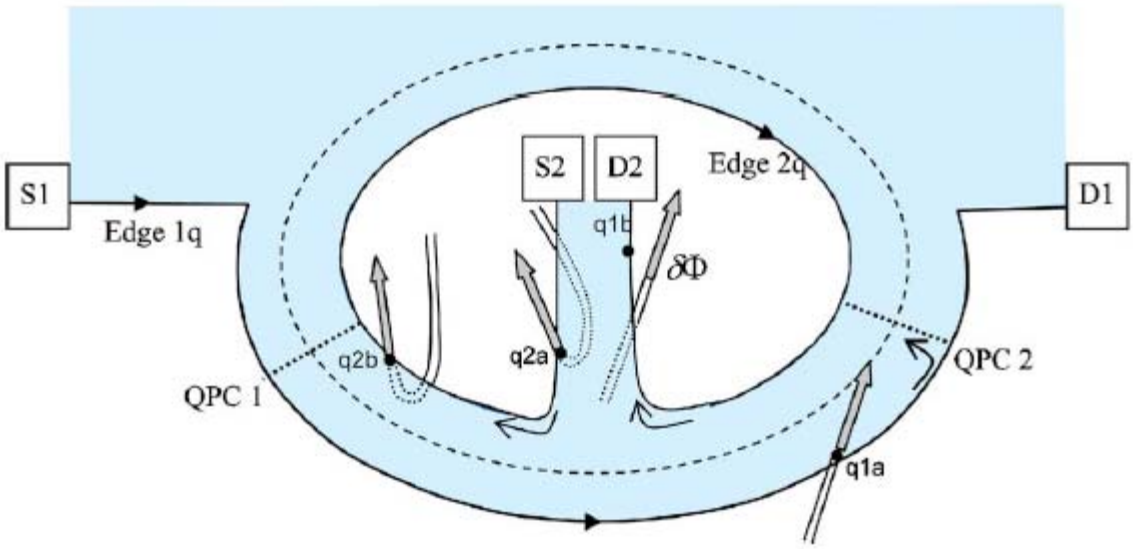
- An upstream neutral mode
- Tunneling exponent $g = \frac{1}{4}$
- Topological even-odd effect



New experimental signatures

Thermal Hall conductance $\frac{\pi^2 k^2 T^2}{6h}$

Mach-Zehnder interferometry



No magnetic field dependence of the current.
Shot noise diverges at some magnetic fields.

Thermal transport

Thermal conductance of a bosonic chiral channel
$\kappa = 1$ in units of $\pi^2 k^2 T/3h$

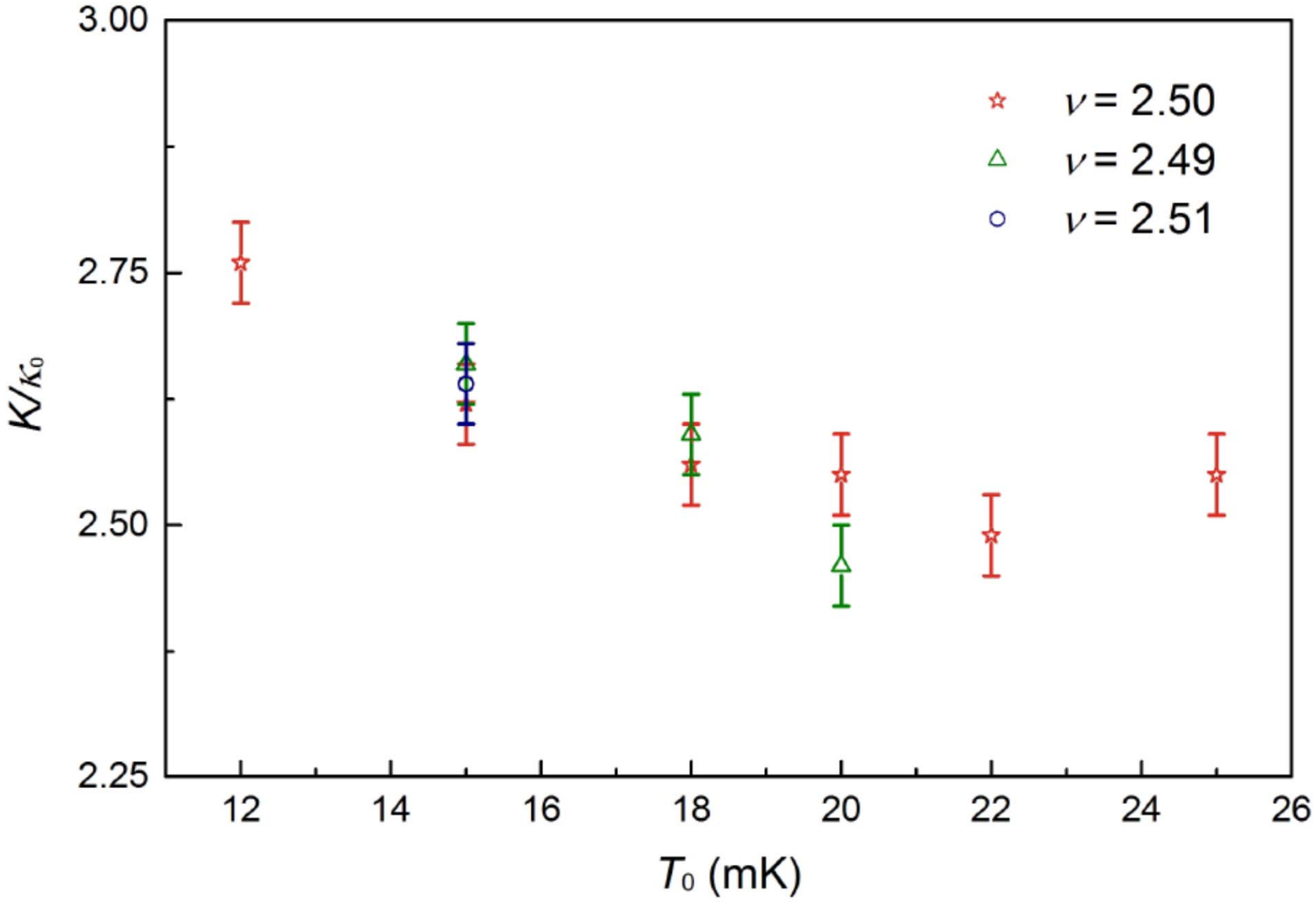
Thermal conductance of a Majorana channel
$\kappa = 1/2$ in units of $\pi^2 k^2 T/3h$

Excellent agreement of experiment and theory at *f*=1/3, 3/5, 4/7
[M. Banerjee, M. Heiblum, A. Rosenblatt, Y. Oreg, D. E. Feldman, A. Stern, and V. Umansky, *Nature* **545**, 75 (2017)]

At $f = 2/3$, $\kappa = 0.25 - 0.33$.
Equilibration of two channels at different temperatures, $\kappa \sim \xi/L$.
Equilibration length ξ is longer at lower temperatures.
At $f = 5/2$ one expects a faster grows of ξ but κ depends on $\exp(-\text{const}\, L/\xi)$.
In most states operators $\sim \psi_i \psi_j \partial_x \varphi_c$ contribute to equilibration.
In the PH-Pfaffian state one gets $\sim \psi \partial_x \psi \partial_x \varphi_c$.

Thermal conductance at f=5/2

M. Banerjee, M. Heiblum, V. Umansky, D. E. Feldman, Y. Oreg, and A. Stern, arXiv:1710.00492



Closing Argument

- PH-Pfaffian topological order is consistent with all experiments
- Numerics with the particle-hole symmetric Hamiltonians supports states that break the particle-hole symmetry
- Realistic Hamiltonians have no symmetry
- The ground state is not symmetric, yet the topological order is compatible with the particle-hole symmetry
- A complicated phase diagram is possible

[C. Wang *et al.*,arXiv:1711.11557; D. F. Mross *et al.*, arXiv:1711.06278; B. Lian and J. Wang, arXiv:1801.10149]