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Editors' Suggestion

Correlated Double-Electron Additions at the Edge of a Two-Dimensional Electronic System

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We create laterally large and low-disorder GaAs quantum-well-based quantum dots that act as small two-dimensional electron systems. We monitor tunneling of single electrons to the dots by means of capacitance measurements and identify single-electron capacitance peaks in the addition spectrum from occupancies of one up to thousands of electrons. The data show two remarkable phenomena in the Landau level filling factor range $\nu = 2$ to $\nu = 5$ in selective probing of the edge states of the dot: (i) Coulomb blockade peaks arise from the entrance of two electrons rather than one; (ii) at and near $\nu = 5/2$ and at fixed gate voltage, these double-height peaks appear uniformly in a magnetic field with a flux periodicity of $h/2e$, but they group into pairs at other filling factors.

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Motivation

- Long history of these types of devices
  - First *R.Ashoori et al.,* ***PRL*** *64, 681 (1990)*
- Improved sample quality enables new insights

Results

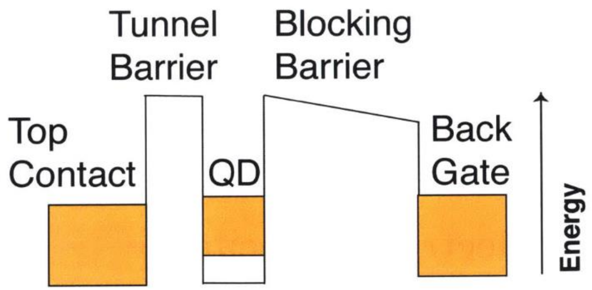
- Hints of Pairing in $\nu = 5/2$ fractional hall states

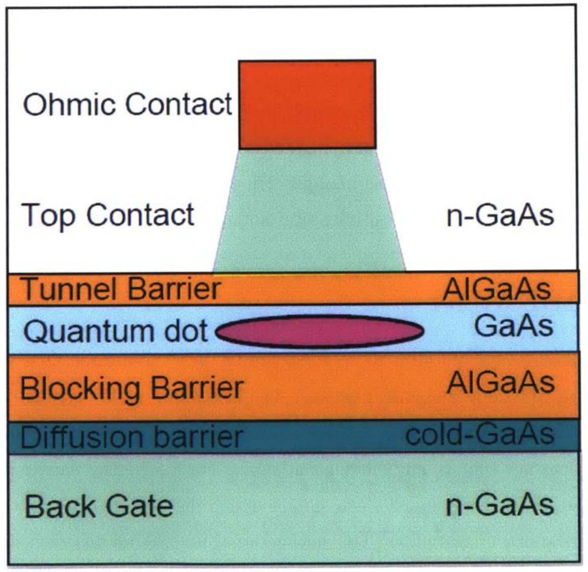
Sample fabrication

Quantumwell, 11.5nm deep (from top electrode)

Deposit ohmic contact(material), etch selectively to AlGaAs,

	substrate	GaAs (undoped)	
1	bottom initial growth	GaAs (intrinsic)	3000 Å
2	bottom blocking barrier	$Al_{0.323}Ga_{0.677}As$	4000 Å
3	bottom electrode	GaAs (n+, 4×10^{18})	2000 Å
4	bottom electrode	GaAs (n+, 1×10^{18})	1000 Å
5	bottom spacer	GaAs (intrinsic)	30 Å
6	cold growth/diffusion barrier	GaAs (intrinsic)	30 Å
7	blocking barrier	$Al_{0.323}Ga_{0.677}As$ (intrinsic)	600 Å
8	quantum well	GaAs (intrinsic)	230 Å
9	tunnel barrier	$Al_{0.323}Ga_{0.677}As$ (intrinsic)	90 Å
10	top spacer	GaAs (intrinsic)	25 Å
11	top electrode	GaAs (n+, 1×10^{18})	200 Å
12	top electrode	GaAs (n+, 4×10^{18})	400 Å
13	top electrode	Delta doped top layers	25 Å × 8
	top surface		





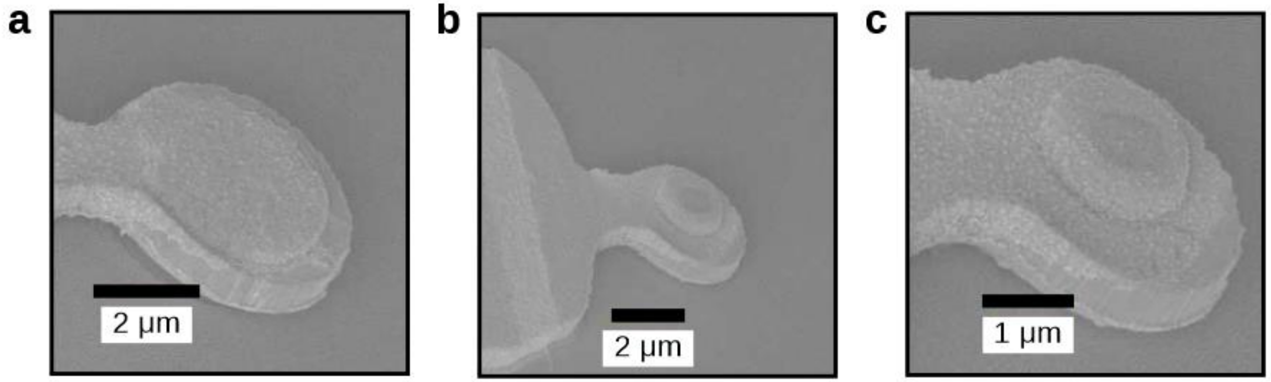
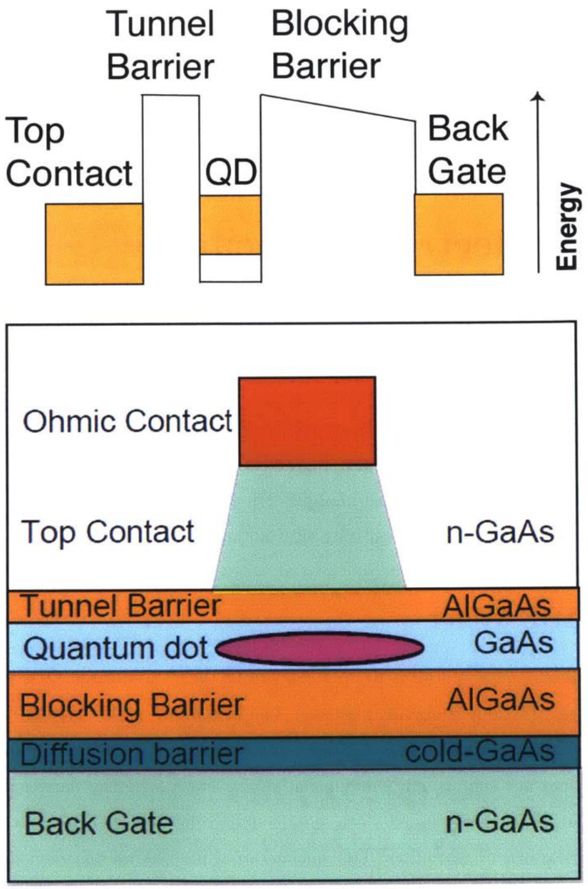


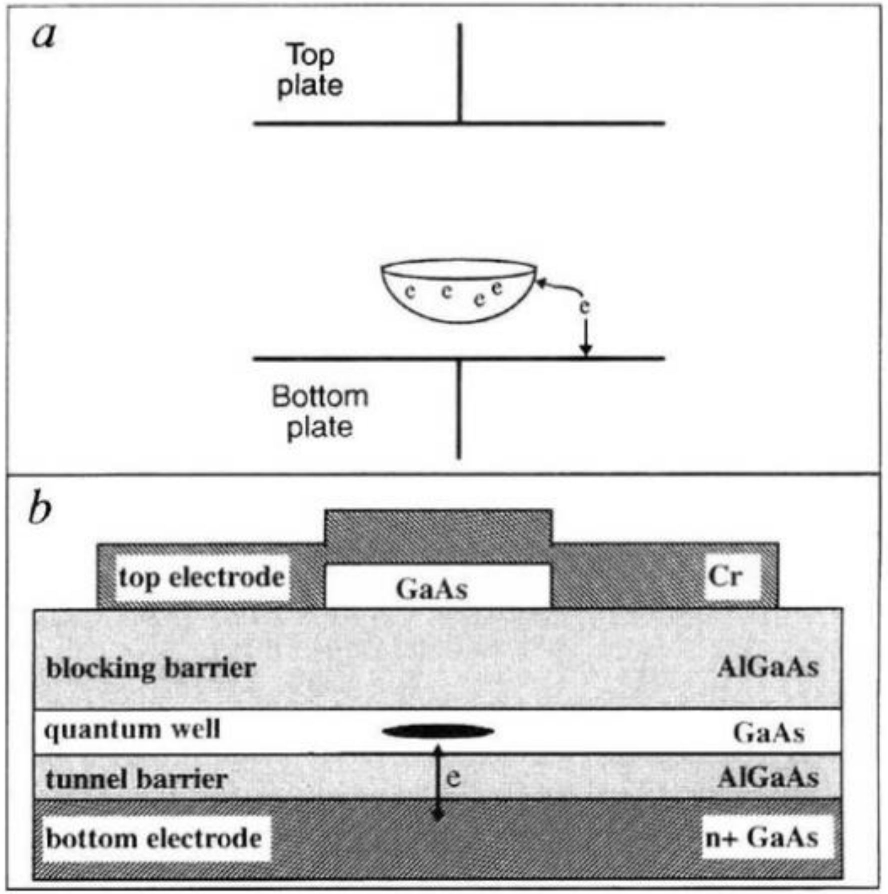
FIG. S1. SEM images of completed devices.

original sample design

New sample design

- no shottky Barrier
- no modulation doping





Ashoori, R. Electrons in artificial atoms. *Nature* **379,** 413–419 (1996).

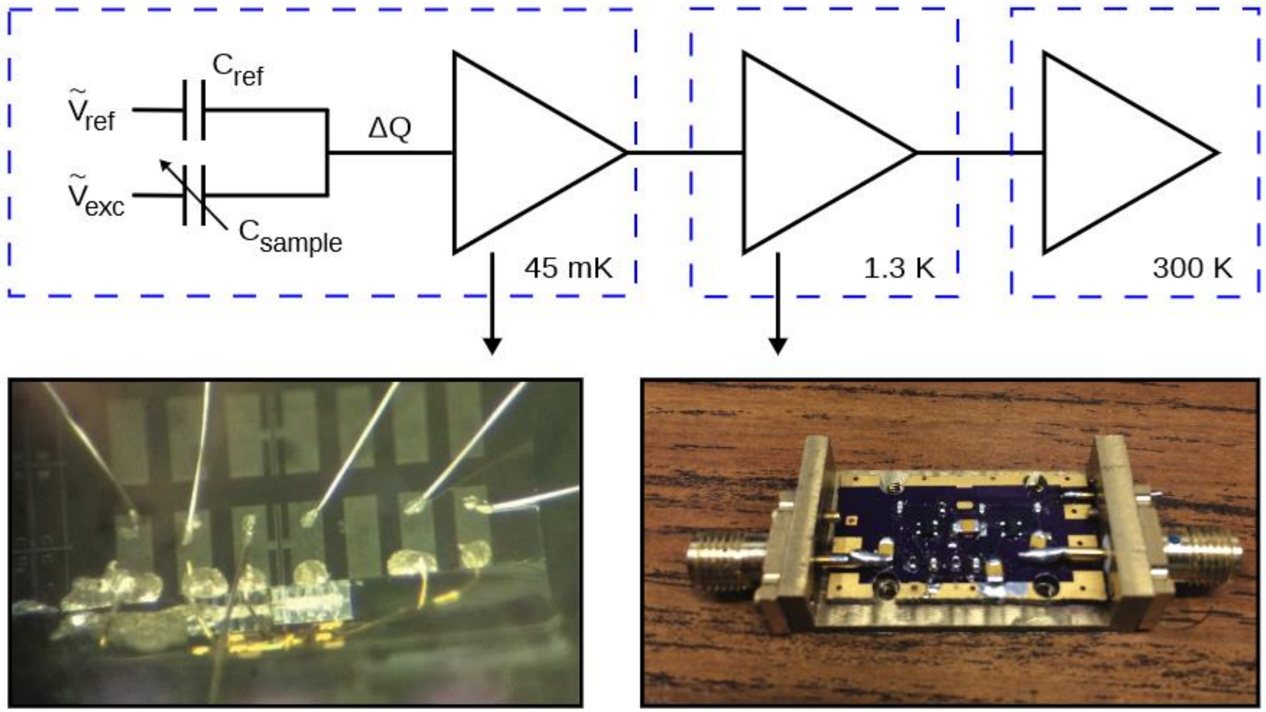
Capacitance spectroscopy

- Balance condition:

$$\frac{V_{ref}}{Z_{ref}} + \frac{V_{exc}}{Z_{sample}} = 0$$

- V_{ref} 180° out of phase

- → $C_{sample} = C_{ref}\frac{V_{ref}}{V_{exc}}$

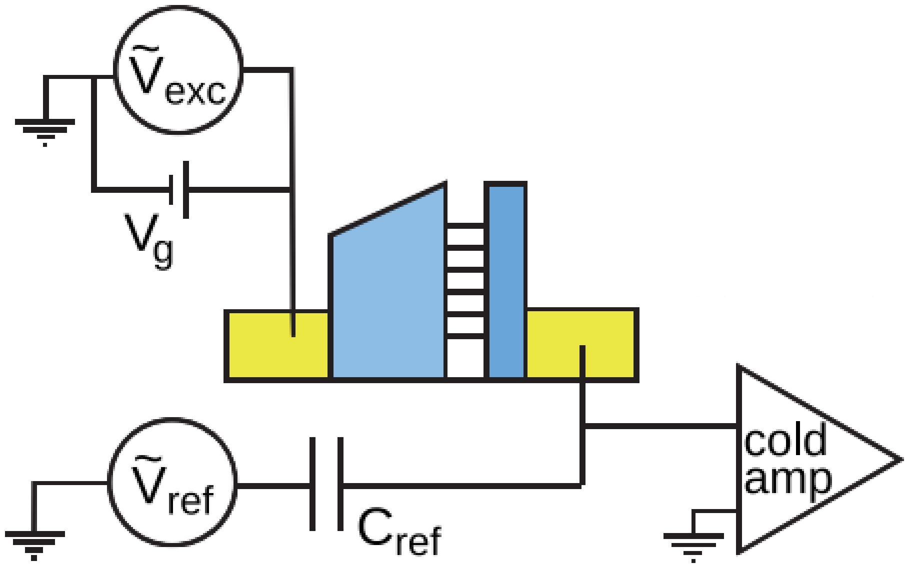


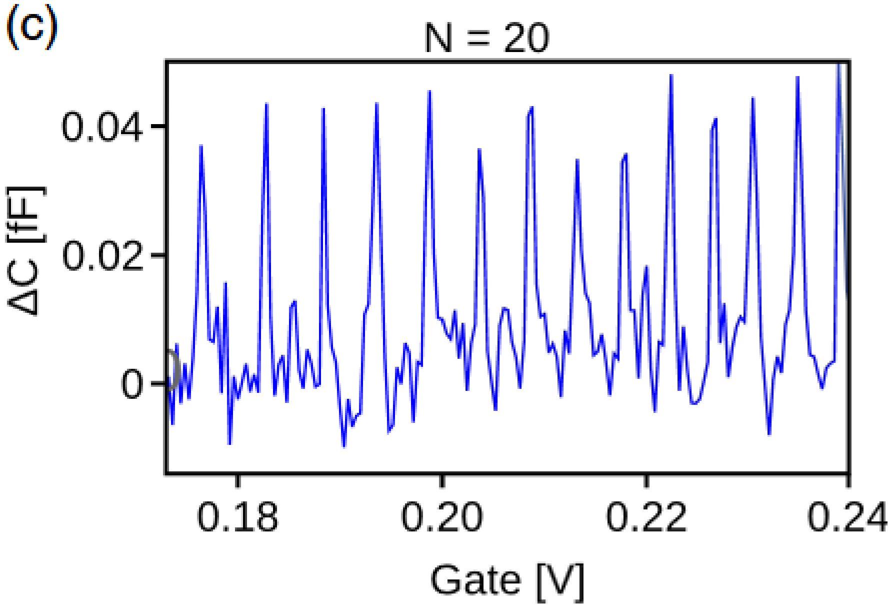
- Typical values:

$$V_{exc} = 200\mu V \;@\; 247kHz$$

Typical measurement

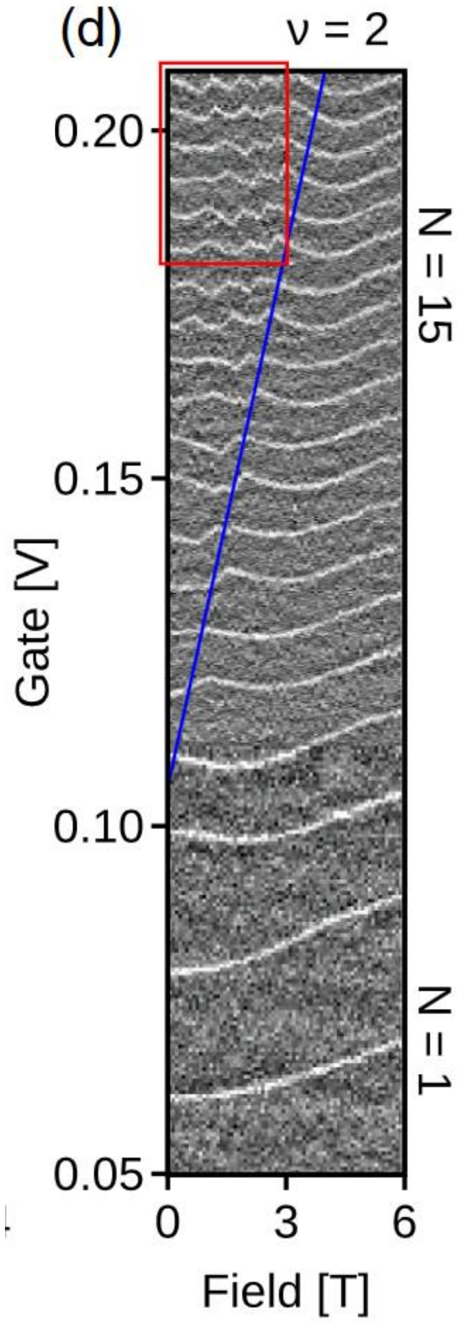
- Small dot (120nm)
- Single electron addition

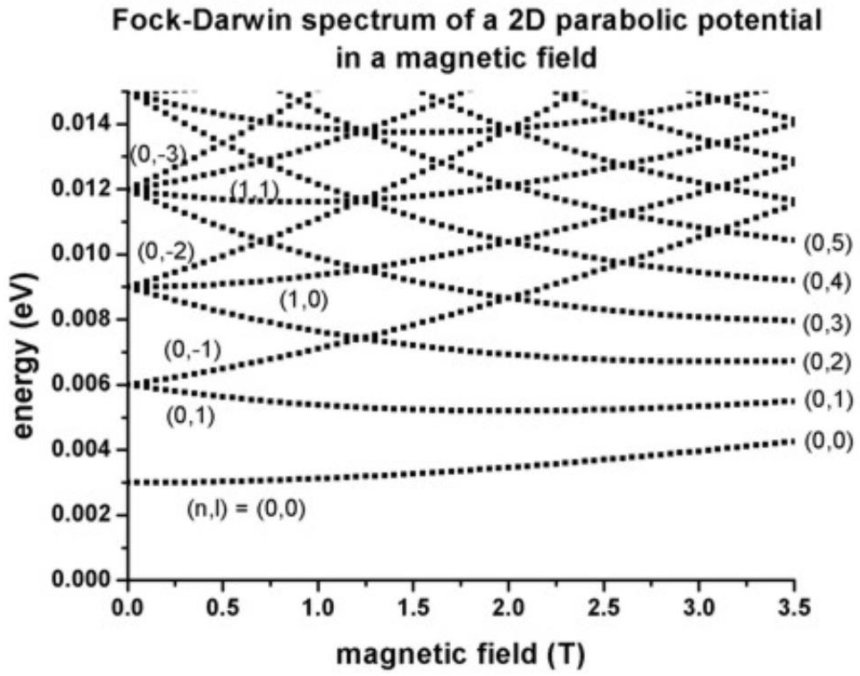


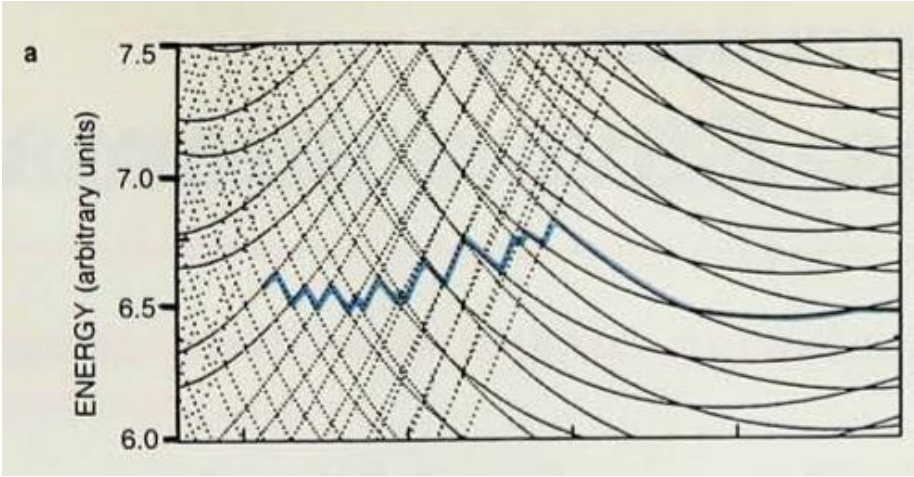


Small Dot in magnetic field

- Fock Darwin Spectrum in Magnetic Field





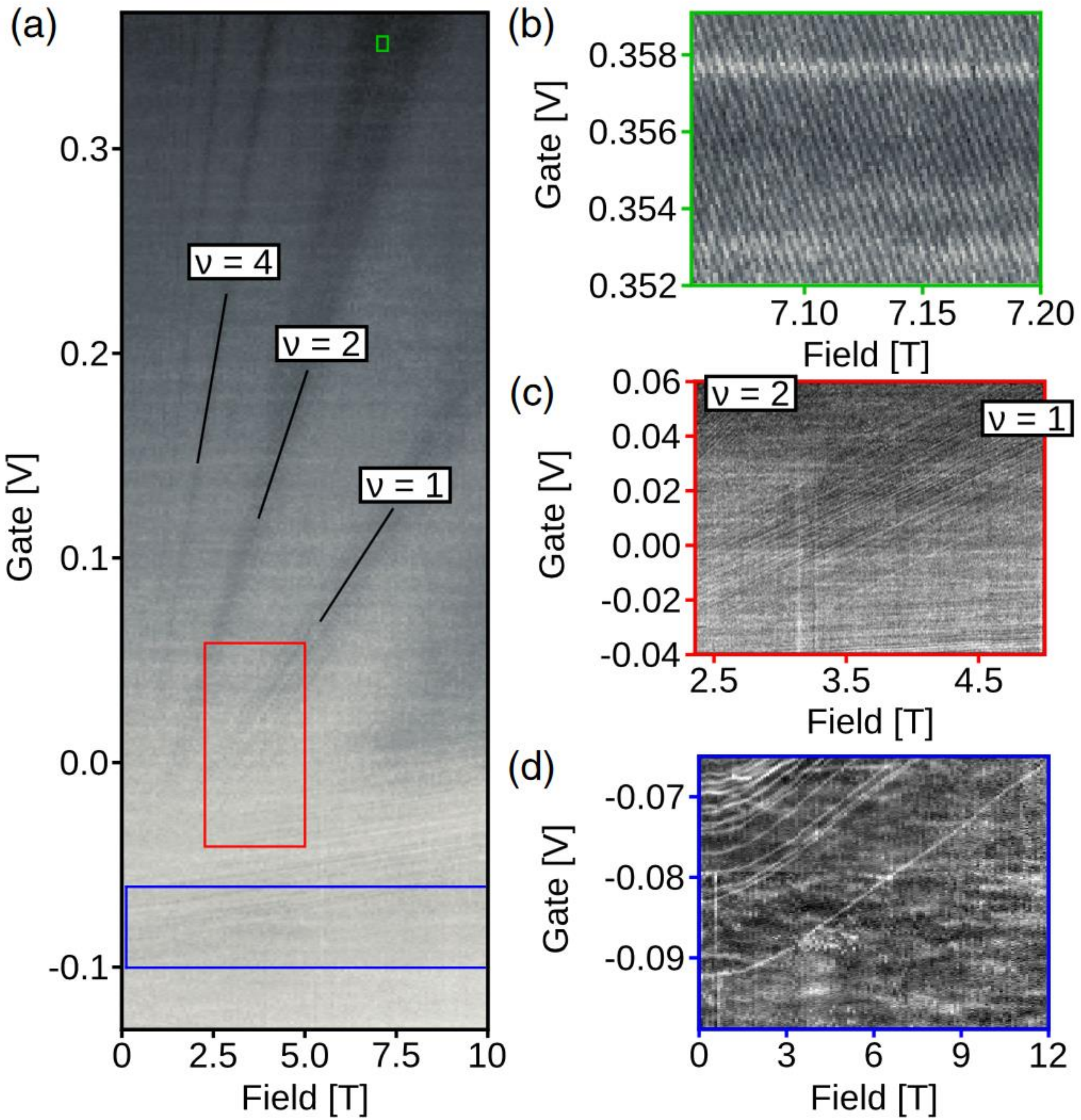


M. Kastner, Physics Today **46**, 1, 24 (1993)

Large dot in magnetic field

- Larger Dot (~800nm)
  - Quantum Hall physics

- Green: electron addition near $\nu = 5/2$
- Red: localized states near integer fillings
- Blue: First few electron in magnetic field



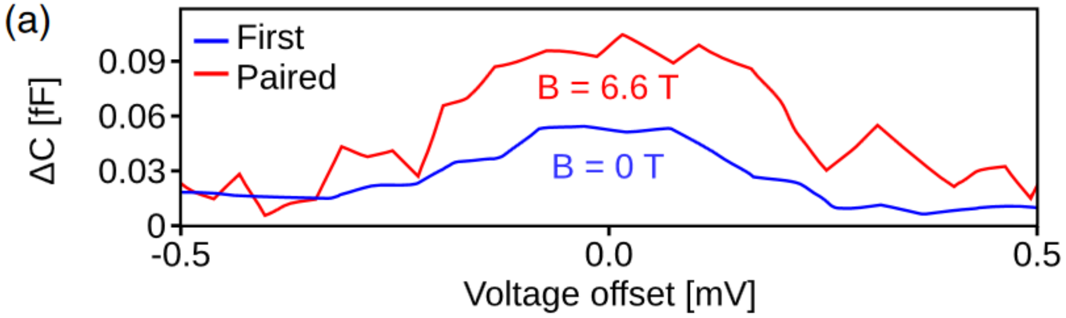
New observations

New observations

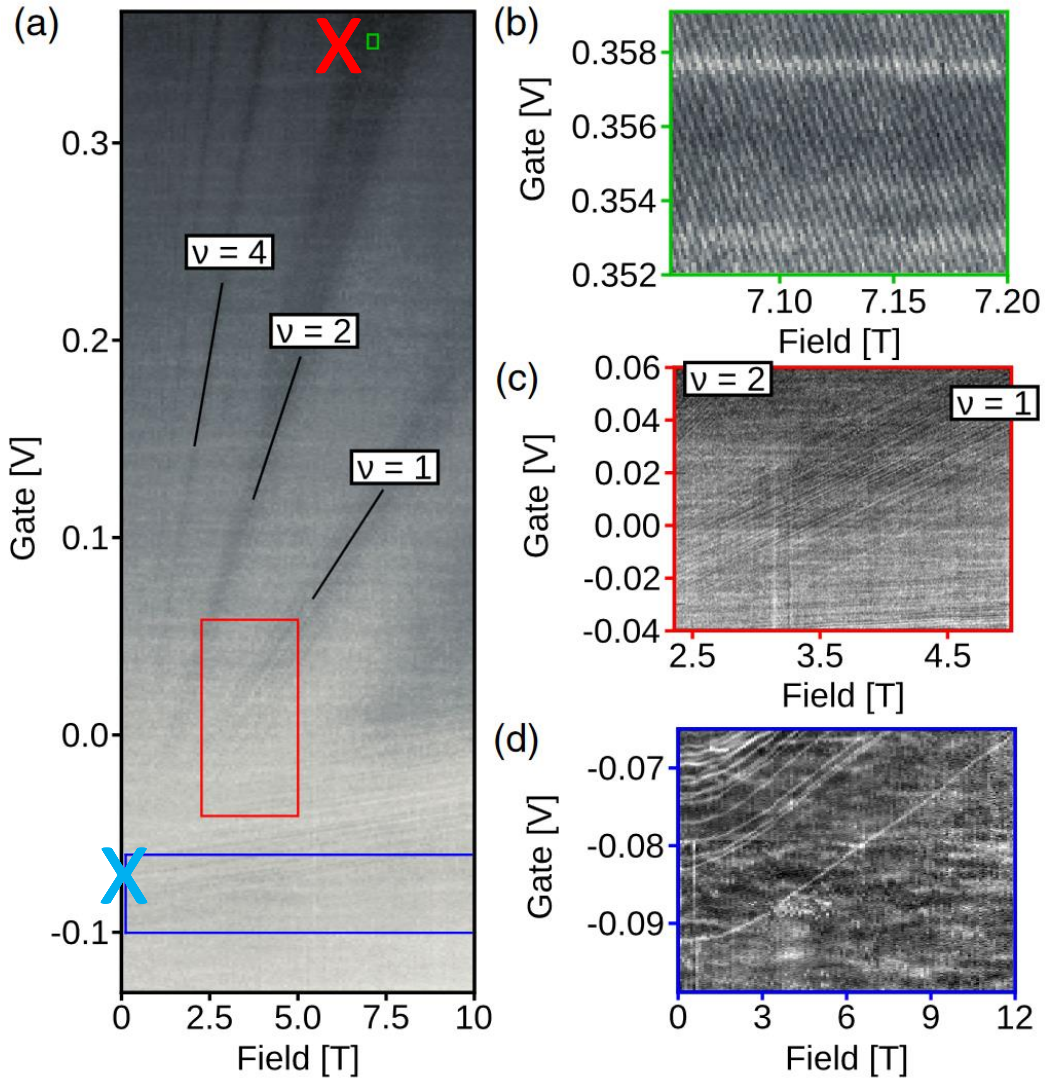
1. Doubling of peak height
2. Doubling of addition frequency
3. Bunching of double height peaks

1 Paired addition of electrons

- Capacitance change doubles for addition to edgestates
- Peakheight is proportional to tunneling charge
  → $2e^{-}$ additon

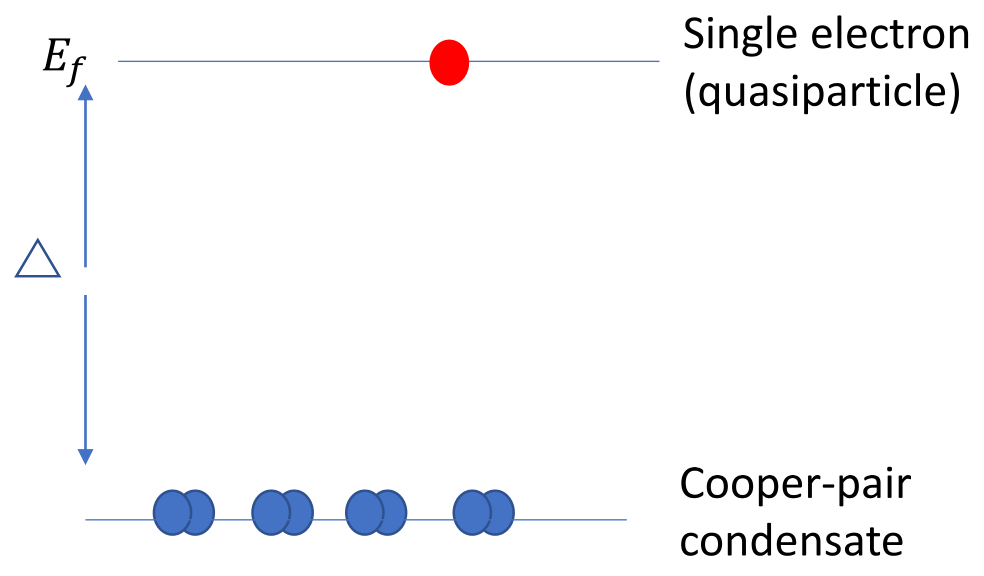


0.3655 V; −0.0795 V



Implication: coulomb blockade violation

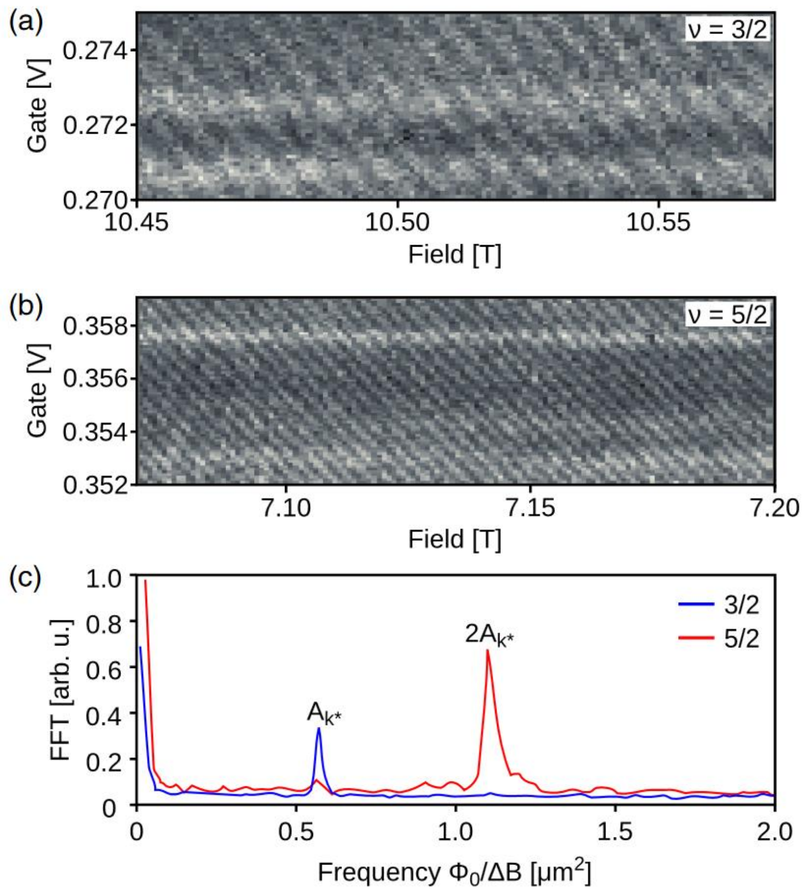
- Analogy:
  Charging in a superconductor
  - Single electron addition $\Delta E = E_c + \Delta$
  - Cooper pair addition: $\Delta E = 2E_c$
  - Pair addition favourable for $\Delta > E_c$
- Strong interactions in Integer QHE?



2 Addition frequency doubling

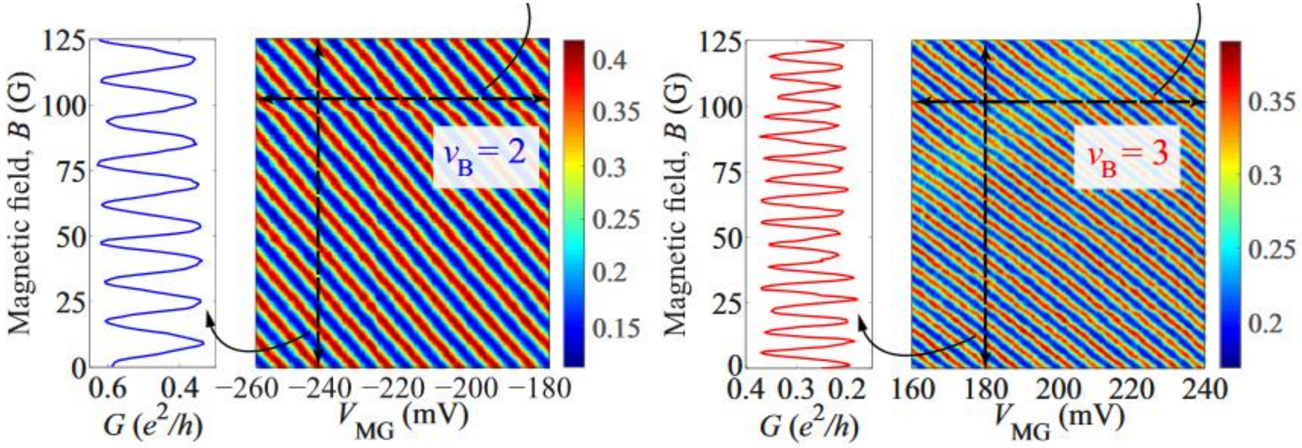
- a) $\Delta B = h/e$ at $\nu = \frac{3}{2}$ outside double addition range ($\nu = 2$ to $\nu = 5$)

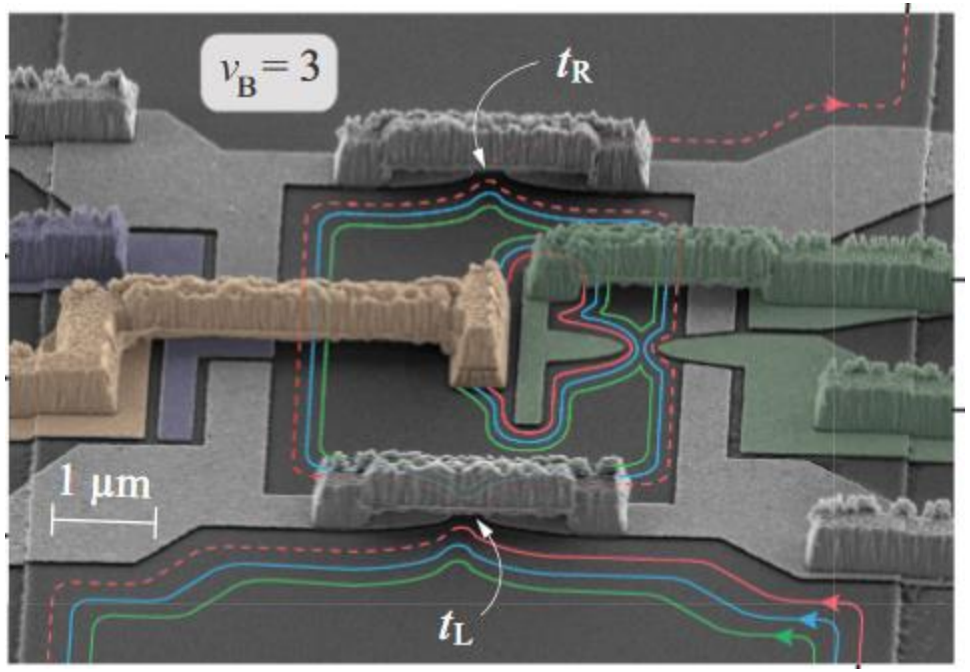
- b) $\Delta B = h/2e$ at $\nu = \frac{5}{2}$
  Essentialy from ($\nu = 2$ to $\nu = 5$)



2 Addition frequency doubling

- flux periodicity of h/2e observed for ν>2.5

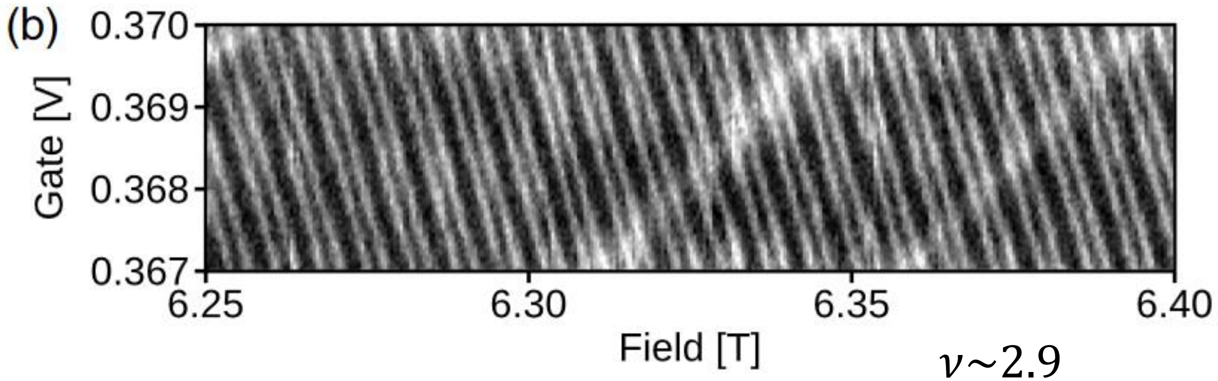




I.Sivan et al., *Interaction-induced interference in the integer quantum Hall effect*, ***PRB 97,*** 125405 (2018)

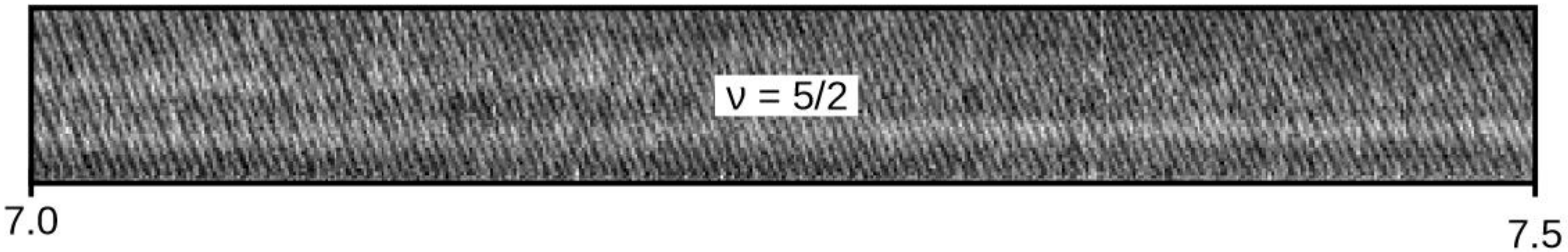
3 Bunching of pair addition

- Double Addition lines bunch up between $\nu = 2$ and $\nu = 5$
- Bunching vanishes at $\nu = 5/2$



$\nu \sim 2.9$

Bunching stops near ν = 5/2



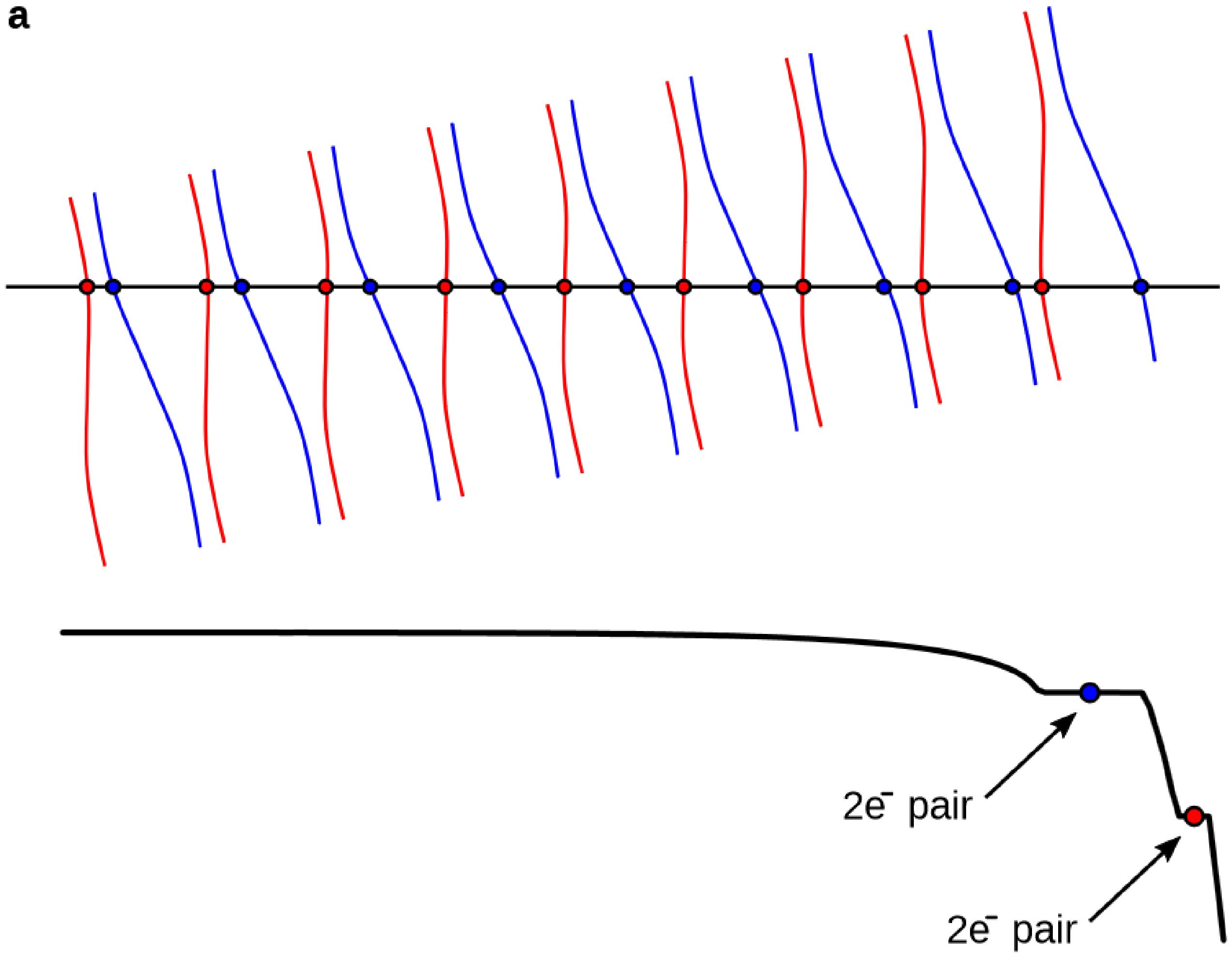
3 Bunching of pair addition

- Speculation:
  - Electron-pairs tunnel into same edgestate
  - different addition peaks, belong to different edgestates

  →different area/Flux period

Doesnt explain why double addition happens

a



Outlook

- Behaviour around $\nu = 5/2$ maybe related to pairing mechanism []
- Pulsed capacitance spectroscopy may reveal full electronic structure
  - Condensate gaps, and quasiparticle peaks around every addition peak
- Requierements:
  - Higher sensitivity (SET for sensing)

O. E. Dial, R. C. Ashoori, L. N. Pfeiffer, and K. W. West, High-resolution spectroscopy of
two-dimensional electron systems,Nature448, 176 (2007)