

CNR-NANO (PISA)
NEST Laboratory
Scuola Normale Superiore



*INVESTIGATION OF HYBRID JOSEPHSON JUNCTIONS
FOR TOPOLOGICAL APPLICATIONS*

Dr. Matteo Carrega

Outline

- ▶ Topological states of matter
- ▶ Hybrid 2DEG Josephson junction
- ▶ Coexistence of Quantum Hall and superconductivity
- ▶ New tunable JJ geometry

Topological states

NEWS IN FOCUS

PHYSICS

Nobel for 2D exotic matter

Physics award goes to theorists who used topology to explain strange phenomena.

BY ELIZABETH GIBNEY AND
DAVIDE CASTELVECCHI

David Thouless, Duncan Haldane and Michael Kosterlitz have won the 2016 Nobel Prize in Physics for their theoretical explanations of strange states of matter in 2D materials, known as topological phases.

The British-born trio's work in the 1970s and 1980s laid the foundations for predicting and explaining bizarre behaviours that experimentalists discovered at the surfaces of materials, and inside extremely thin layers. These include superconductivity — the ability to conduct without resistance — and magnetism in very thin materials. At the time, these mathematical theories were quite abstract, said Haldane in an



Physics prizewinners Michael Kosterlitz (left), David Thouless (centre) and Duncan Haldane (right).

Topology in condensed matter

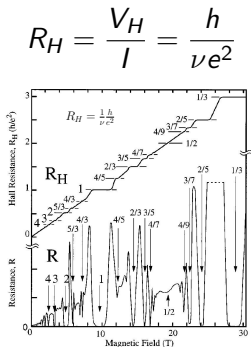
NOBEL 2016



Intrinsic robustness ↔ Topological protection

Quantum Hall effect

Von Klitzing'80, Laughlin'83,
Tsui'99



Fractional charge and statistics

Büttiker'88, Stern'08

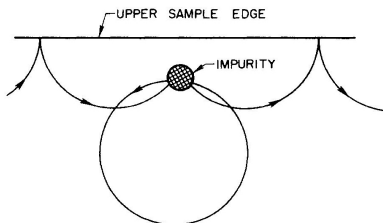
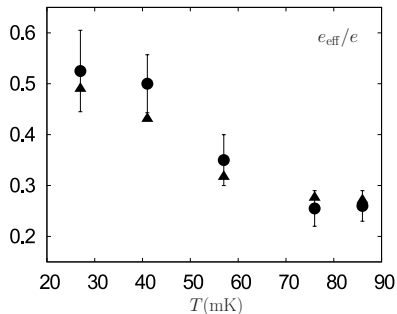
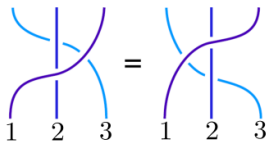
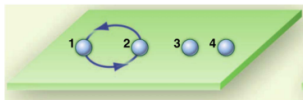


FIG. 4. Quasiclassical skipping orbits along the upper edge of the sample in presence of a localized impurity. In a high magnetic field backscattering over distances large compared to the cyclotron radius is suppressed.

- ▶ first topological state of matter
- ▶ chiral edge states

Anyons in FQHE

Exotic filling factors $\nu = \frac{5}{2}$



Non abelian anyons with effective charge $e/4$

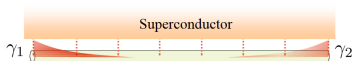
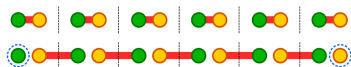
chiral Majorana modes on the edge

Stern'08, Dolev'10, Carrega et al., PRL'11

Kitaev chain

Majorana modes in condensed matter

$$H = \sum_x \left[-\mu c_x^\dagger c_x - \frac{1}{2} \left(T c_x^\dagger c_{x+1} + \Delta c_x c_{x+1} + \text{H.c.} \right) \right],$$



Smoking gun evidence still lacking

Kitaev'01, Lutchin'10, Alicea'14, Stanescu'18, Woods'19

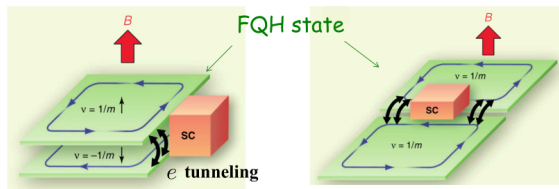
Quantum Hall/Superconductor

other platforms hosting anyons with non-trivial braiding

$$\gamma_x \gamma_{x'} = \gamma_{x'} \gamma_x e^{i \frac{2\pi}{N} \text{sgn}(x' - x)}$$

$N = 2$ Majorana modes

$N > 2$ Parafermions

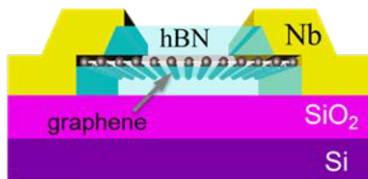


integer/fractional quantum Hall with superconducting proximity effect!

Alicea'12, Lindner'12, Alicea'15, Schmidt'19

Coexistence of superconductivity and quantum Hall regime

- Superconductors with high critical field B_C
- quantum Hall plateau at relatively low B field

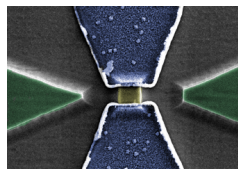
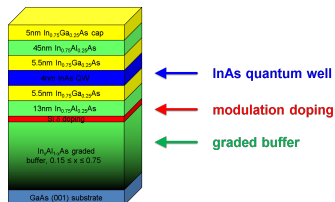


JJ supercurrent mediated by QH edge states

Ben Shalom'16, Lee'16, Amet'17, Wu'18

Hybrid 2DEG/SC

Josephson junction with *InAs* quantum well and *Nb* contacts



$$n_{2D} = 6.2 \cdot 10^{11} \text{ cm}^{-2} \quad \mu = 1.6 \cdot 10^5 \text{ cm}^2/(\text{V s})$$

$$l_{MFP} = 2.16 \text{ } \mu\text{m}$$

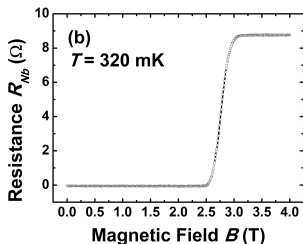
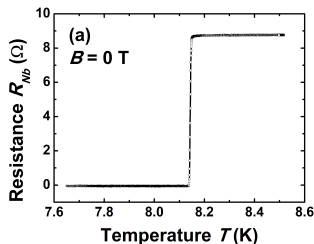
Hybrid 2DEG JJ with patterned side gates

Guiducci et al., PSS (RRL) 1800222 2018

Superconductivity

critical temperature $T_C = 8.1 \text{ K} \rightarrow \Delta_{Nb} = 1.235 \text{ meV}$

critical field $B_C = 2.77 \text{ T}$ at $T = 320 \text{ mK}$



coherence length $\xi_0 = \frac{\hbar v_F}{\pi \Delta_{Nb}} = 230 \text{ nm} < l \sim 1 \mu\text{m}$

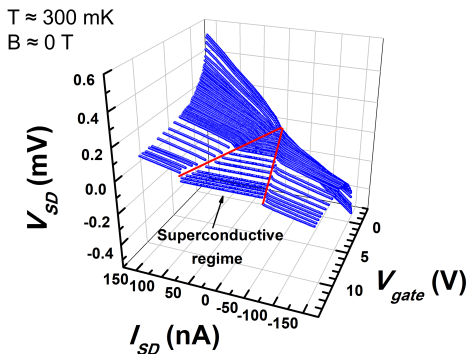
clean and ballistic regime $\xi_0 < l < l_{MFP}$

Guiducci et al., PSS(RRL) 1800222 2018

Josephson supercurrent

supercurrent flow monitored by $V_{SD}(I_{SD})$

Typical hysteretic behaviour of Josephson device $\rightarrow I_C = 170$ nA



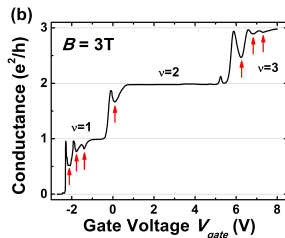
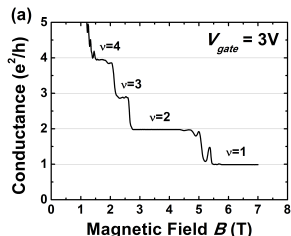
Manipulation of I_C and R_n by changing 2D electron density

Side gates make it a **Jo-FET**

Quantum Hall regime

Quantum Hall plateau develop at $B \geq 1.5$ T

Filling factor $\nu = 2$ at $B = 3$ T and $V_{gate} = 3$ V

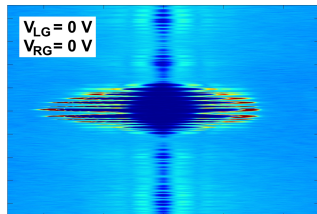
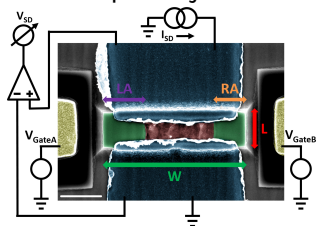


Side gates control channel width and carrier density

Guiducci et al., PSS(RRL) 1800222 2018

New hybrid device

Hybrid Josephson junction with **removed central region**



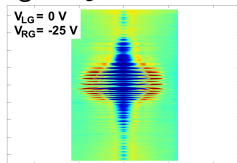
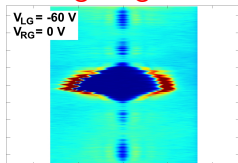
Supercurrent with fast and slow oscillations

Fast oscillations caused by the hole (with no gate dependence)

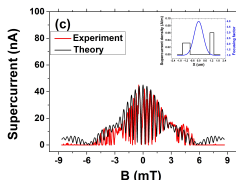
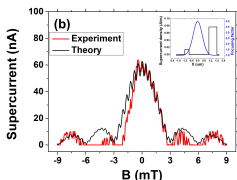
Guiducci et al., PRB 99, 235419 2019

Tuning quantum interference

asymmetric gating \rightarrow independent tuning of I_c in each arm



From Fraunhofer pattern to SQUID behaviour

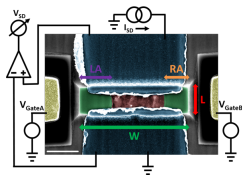
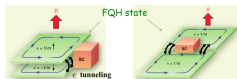


Extended JJ $\Delta B_{fast} = 0.34 \text{ mT}$ $\Delta B_{slow} = 2.9 \text{ mT}$
 \rightarrow effective width of the arms and supercurrent densities

Guiducci et al., PRB 99, 235419 2019

Conclusions and outlook

- ▶ New topological states of matter
- ▶ Coexistence of quantum Hall and superconducting correlations
- ▶ Electrostatic control of quantum interference in JJ devices



S. Guiducci et al., **Towards quantum Hall effect in a Josephson junction** PSS:RRL (2018);

S. Guiducci et al., **Full electrostatic control of quantum interference in an extended trenched JJ** PRB (2019);

D. Rossini et al., **Anyonic tight-binding models of parafermions and of fractionalized fermions** PRB (2019).

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