CNR-NANO (PISA)
NEST Laboratory
Scuola Normale Superiore

HYBRID JOSEPHSON-JUNCTION FOR TOPOLOGICAL APPLICATIONS

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Outline

- Topological states of matter
- Anyons and fractional quantum Hall effect
- Majorana fermions in condensed matter
- Coexistence of Quantum Hall and superconductivity
- Outlook and perspectives

Quantum Technology

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ROADMAP

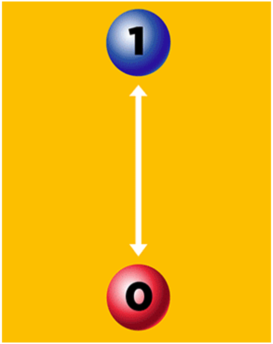
The quantum technologies roadmap: a European community view

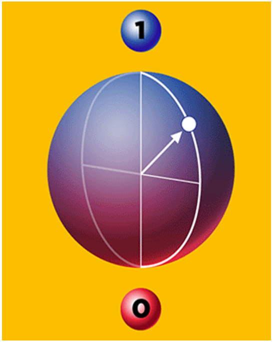
Antonio Acín[1,2], Immanuel Bloch[3,4], Harry Buhrman[5], Tommaso Calarco[6], Christopher Eichler[7], Jens Eisert[8], Daniel Esteve[9], Nicolas Gisin[10], Steffen J Glaser[11], Fedor Jelezko[6], Stefan Kuhr[12], Maciej Lewenstein[1,2], Max F Riedel[6], Piet O Schmidt[13,14], Rob Thew[10], Andreas Wallraff[7], Ian Walmsley[15] and Frank K Wilhelm[16]

Quantum computing

Towards a Quantum Computer Era

- Classical Bit
- Qu-Bit





Need for protection against errors and decoherence!

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**

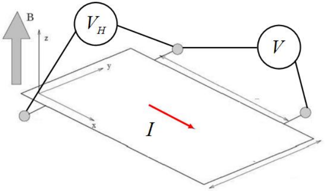
Intrinsic robustness $\leftrightarrow$ Topological protection

Quantum Hall effect

Büttiker'88

Hall 1879, Von Klitzing'80

$$R_H = \frac{V_H}{I} = \frac{B}{n_e ec}$$



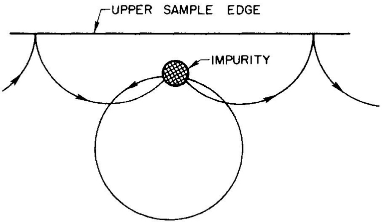


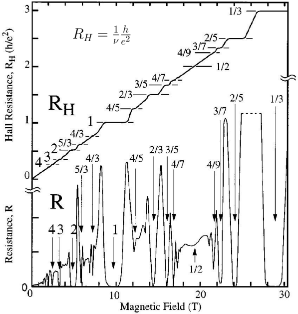
FIG. 4. Quasiclassical skipping orbits along the upper edge of the sample in presence of a localized impurity. In a high magnetic field backscattering over distances large compared to the cyclotron radius is suppressed.

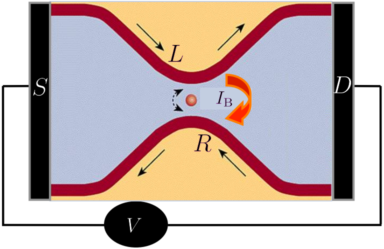
Metrological standard of resistance

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

FQHE

Quasiparticles with fractional charge and statistics !





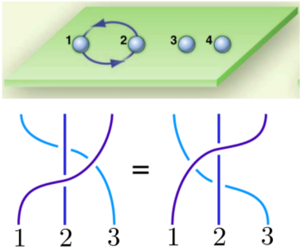
Shot noise experiments → effective fractional charges

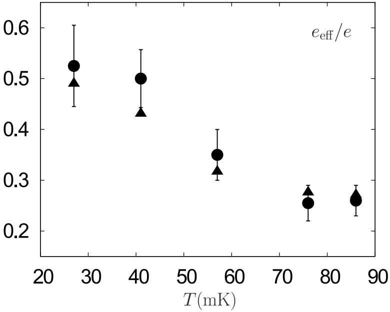
Laughlin state $\langle S \rangle = 2e^* \langle I \rangle$ $e^* = \nu e = e/m$

Laughlin'83, De Picciotto'97, Tsui'99

Anyons in FQHE

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





Non abelian anyons with effective charge $e/4$

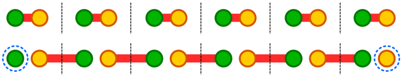
chiral Majorana modes on the edge

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

Kitaev chain

Majorana modes in condensed matter

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



Majorana operators $\gamma_{A/B,x}$ with $c_x = (\gamma_{B,x} + i\gamma_{A,x})/2$

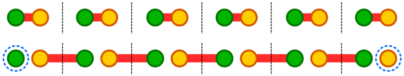
Different phases depending on μ and T

Kitaev'01, Oreg'10, Lutchin'10, Alicea'14

Kitaev chain

Majorana modes in condensed matter

$$H = -\frac{i}{2}\sum_x(-\mu\gamma_{A,x}\gamma_{B,x} + T\gamma_{B,x}\gamma_{A,x+1}).$$

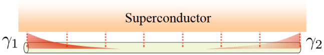


Majorana operators $\gamma_{A/B,x}$ with $c_x = (\gamma_{B,x} + i\gamma_{A,x})/2$

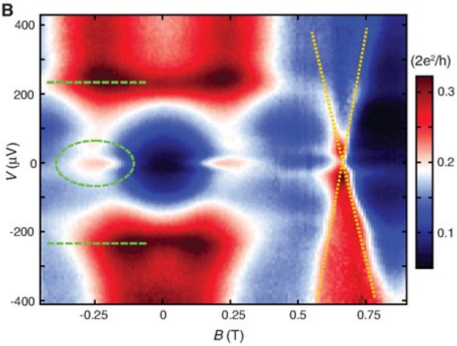
Topological phase when $|\mu| < T$

Kitaev'01, Oreg'10, Lutchin'10, Alicea'14

Majorana nanowire



- superconducting proximity effect (Al contacts at low T);
- breaking time-reversal symmetry (finite B field);
- strong spin-orbit coupling ($InAs/InSb$ nanowire)



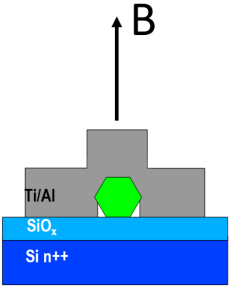
First evidence: zero bias peak $G_0 \sim 2e^2/h$

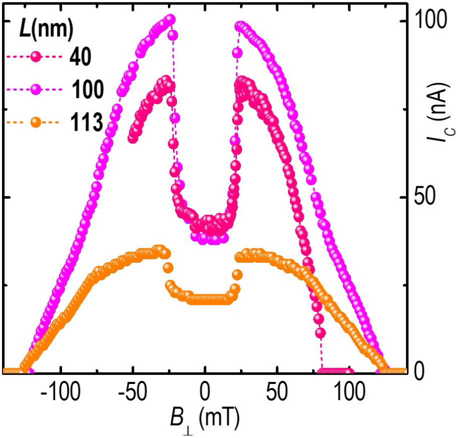
Oreg'10, Mourik'12, Zang'18

Majorana nanowire

Different experimental evidences

- 4π-periodicity of Josephson current Lutchin'16, Bocquillon'16
- Coulomb blockade and charge noise Higginbotham'15, Albrecht'16
- Giant enhancement of critical current I_C San Jose'14, Paajaste'17



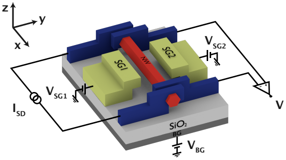


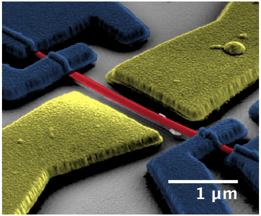
Smoking gun is still lacking!

Spin-orbit coupling

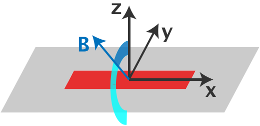
Quantum transport in suspended *InAs* nanowire

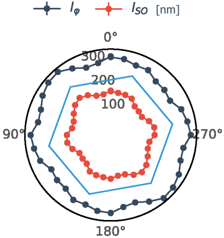
- Weak Anti-localization → spin-orbit length





vectorial dependence of L_{SO} and L_{Φ} reflecting structural symmetry of the nw





Tuning of L_{SO} with gate voltages

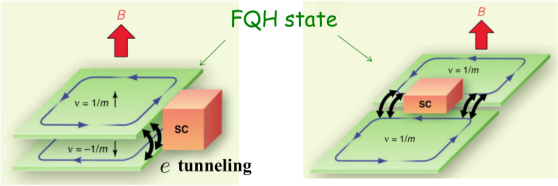
Iorio et al., ArXiv:1807.04344 2018

Quantum Hall/Superconductor

other platforms hosting anyons with non-trivial braiding

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

$N = 2$ Majorana modes $\qquad$ $N > 2$ Parafermions



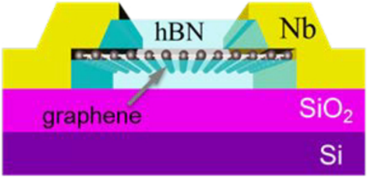
integer/fractional quantum Hall with superconducting proximity effect!

Alicea'12, Lindner'12, Alicea'15

QH/SC experiment

Coexistence of superconductivity and quantum Hall regime

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



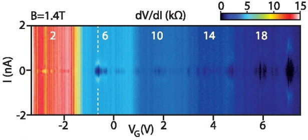
JJ supercurrent mediated by QH edge states

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

QH/SC experiment

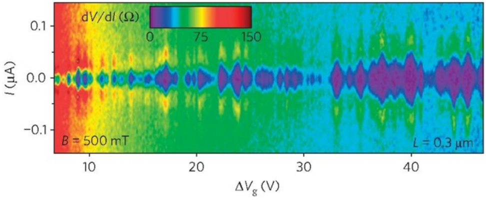
graphene Josephson-junction with *MoRe* or *Nb* contacts

- random pockets indicating supercurrent flow



- $B_C \sim 8$T Amet'17
- $l = 0.3\mu$m
- $r_c = \frac{\hbar k_F}{eB} < l/2$
- $r_c(B = 1T) \sim 25$nm

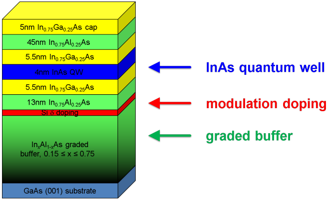
hybrid $e - h$ states on opposite edge coupled by Andreev processes

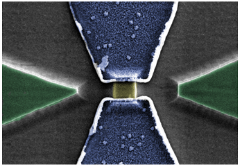


Ben Shahlom'16, Lee'16, Amet'17

Hybrid 2DEG/SC

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





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

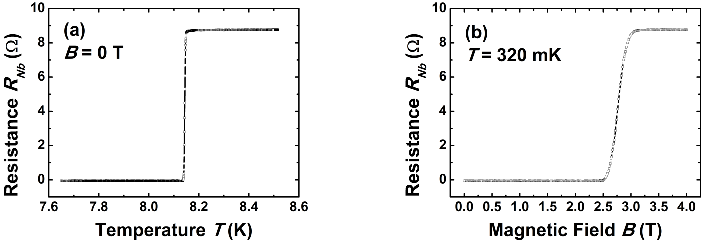
$l_{MFP} = 2.16\ \mu\mathrm{m}$

Hybrid 2DEG JJ with patterned side gates

Guiducci et al., PSS (RRL) 1800222 2018

Superconductivity

critical temperature $T_C = 8.1$ K $\rightarrow \Delta_{Nb} = 1.235$ meV
critical field $B_C = 2.77$ T at $T = 320$ mK



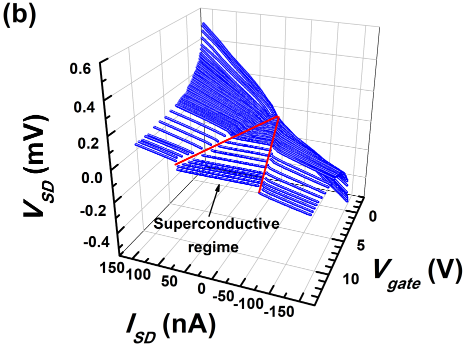
coherence length $\xi_0 = \frac{\hbar v_F}{\pi \Delta_{Nb}} = 230$ nm $< l \sim 1\mu$m

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

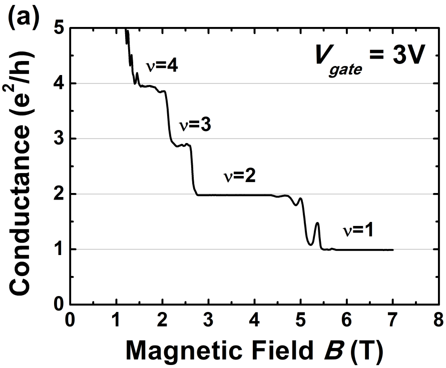
Side gates make it a **Jo-FET**

Guiducci et al., PSS(RRL) 1800222 2018

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

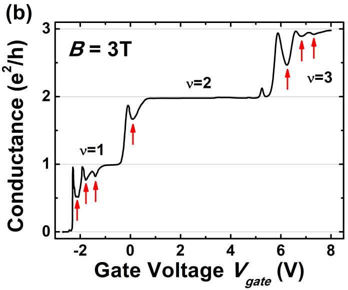


$B_C \sim 3$ T for Nb $\rightarrow$ allows for **coexistence of QH and SC correlations!**

Guiducci et al., PSS(RRL) 1800222 2018

Gate voltage

Side gates control channel width and electron density of the 2DEG



- $\Delta E = \hbar\Omega_c \pm g\mu_{\rm B}B = \alpha e V_{gate}$
- $\hbar\omega_c = \frac{eB}{m^* c} = 11.6\mathrm{meV}$
  $g\mu_{\rm B}B = 2.7\mathrm{meV}$
- $\alpha = 13.2 \cdot 10^{-4}$ lever arm

Fabri-Perot resonances due to electrostatic potential profile

$1D$ model for the junction with V_0 barrier high in the 2DEG $\rightarrow$ energy dependent transmission

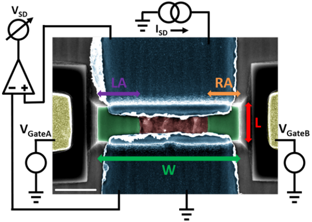
$$T(E) = \frac{h}{e^2} G_{SD}(E) = \frac{h}{e^2} G_{SD}(\alpha e V_{gate})$$

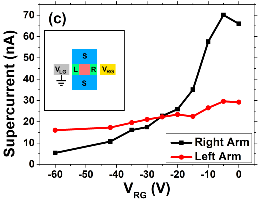
Guiducci et al., PSS(RRL) 1800222 2018

Perspectives

Coexistence of superconductivity and quantum Hall regime

- local tuning of electrostatic potential (SGM)
- fractional QH in hybrid JJ
- control of supercurrent by external side gates



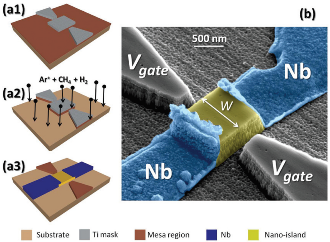


Fully tunable **tandem** Josephson junction

Guiducci et al., to be submitted

Conclusions

- New topological states of matter
- Hybrid superconductor/semiconductor devices
- Majorana (**and parafermions?**) in condensed matter
- Coexistence of quantum Hall and superconducting correlations



S. Guiducci et al., **Towards quantum Hall effect in a Josephson junction** (2018);
S. Guiducci et al., **Fully tunable tandem Josephson junction** (2018);
A. Iorio et al., **Vectorial control of the spin-orbit interaction in suspended *InAs* nanowires** (2018)