How to send current through a neutral mode

Anton Akhmerov
with Johan Nilsson and Carlo Beenakker
arXiv:0903.2196

(Related work: Fu&Kane arXiv:0903.2427)

KITP informal session, March 25 2009

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Windows

Topological
Quantum

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Freedman et al.

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(54) **QUASI-PARTICLE INTERFEROMETRY FOR LOGICAL GATES**

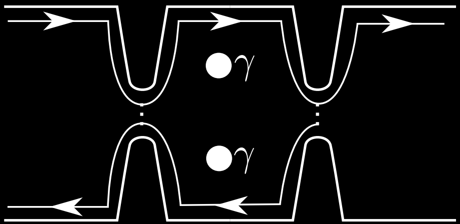
(75) Inventors: **Michael H. Freedman**, Redmond, WA (US); **Chetan V. Nayak**, Santa Monica, CA (US); **Sankar Das Sarma**, Potomac, MD (US)

(73) Assignee: **Microsoft Corporation**, Redmond, WA (US)

(57) **ABSTRACT**

A quantum computer can only function stably if it can execute gates with extreme accuracy. "Topological protection" is a road to such accuracies. Quasi-particle interferometry is a tool for constructing topologically protected gates. Assuming the corrections of the Moore-Read Model for $\nu=5/2$'s FQHE (Nucl. Phys. B 360, 362 (1991)) we show how to manipulate the collective state of two e/4-charge anti-dots in order to switch said collective state from one carrying trivial SU(2) charge, $|1\rangle$, to one carrying a fermionic SU(2) charge $|\epsilon\rangle$.

Majorana fermions & edge state interferometry



Das Sarma *et al.*, Stern & Halperin, Bonderson *et al.*

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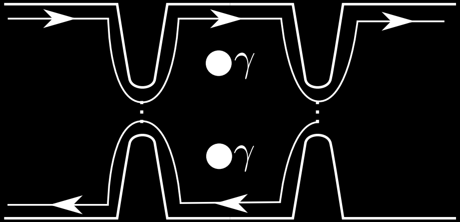

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   a particle equal to its own antiparticle $\gamma = \gamma^\dagger$

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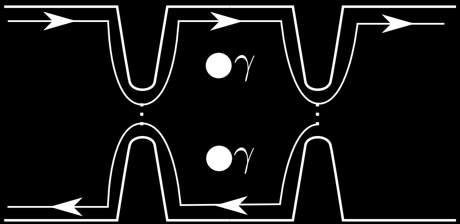

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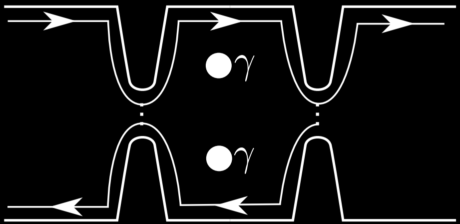

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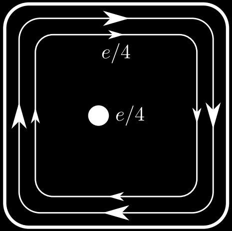
   $a = \gamma_1 + i\gamma_2, \ \ a^\dagger = \gamma_1 - i\gamma_2$
3. Nonabelian braiding statistics
   Allows readout in Fabry-Perot interferometer

Candidates

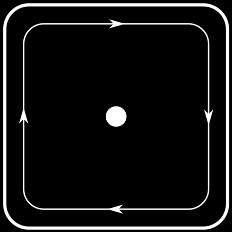
$5/2$ FQHE (Moore&Read, 1991)



- Charged bulk excitations
- Charged edge quasiparticles
- Some experimental evidence (Radu *et al.*, Dolev *et al.*, Willet *et al.*)

Candidates

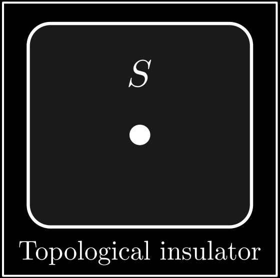
$p_x \pm ip_y$ superconductor (Greiter *et al.*, 1991; Read&Green, 2000; Ivanov, 2001)



- Everything charge-neutral $\Rightarrow$ no electric coupling
- $\mathrm{Sr_2RuO_4}$ or cold atoms
- No clear experimental signature yet

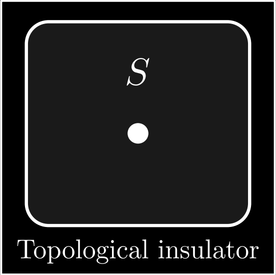
Candidates

s-wave superconductor on 3D topological insulator (Fu&Kane, 2008)



- Time reversal symmetry, no gap $\Rightarrow$ no edge state
- *e.g.* $\mathrm{Bi_2Se_3}$, huge gap
- Promising recent discovery

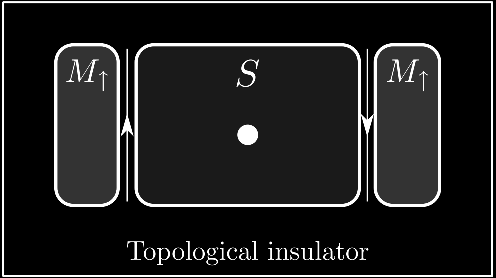
Topological insulators



Has time reversal and electron-hole symmetries

$$H = \begin{pmatrix} v\boldsymbol{\sigma}\mathbf{p} - E_F & \Delta \\ \Delta^* & E_F - v\boldsymbol{\sigma}\mathbf{p} \end{pmatrix}$$

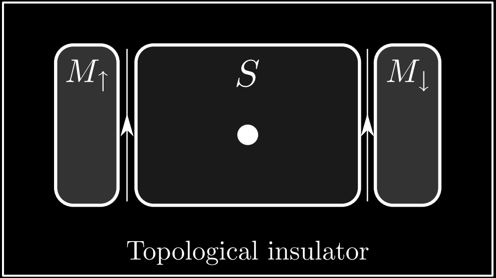
Topological insulators



Edge Majorana mode (Fu&Kane)

$$H = \begin{pmatrix} v\boldsymbol{\sigma}\mathbf{p} + m\sigma_z - E_F & \Delta \\ \Delta^* & E_F - v\boldsymbol{\sigma}\mathbf{p} + m\sigma_z \end{pmatrix}$$

Topological insulators

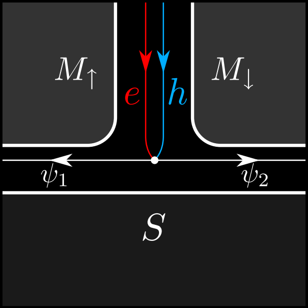


Edge Majorana mode

$$H = \begin{pmatrix} v\boldsymbol{\sigma}\mathbf{p} - m\sigma_z - E_F & \Delta \\ \Delta^* & E_F - v\boldsymbol{\sigma}\mathbf{p} - m\sigma_z \end{pmatrix}$$

with direction controlled by magnetization

Electron to Majorana converter



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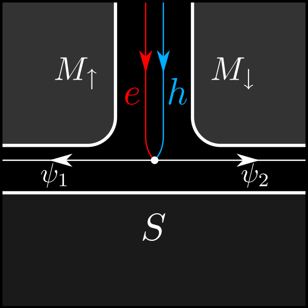
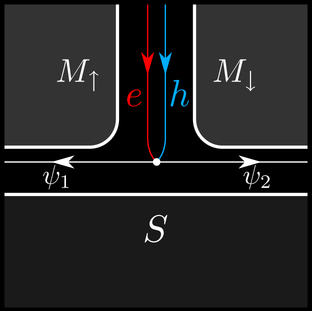


1. No backscattering

Electron to Majorana converter



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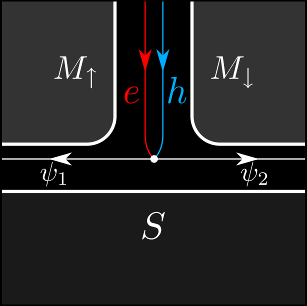

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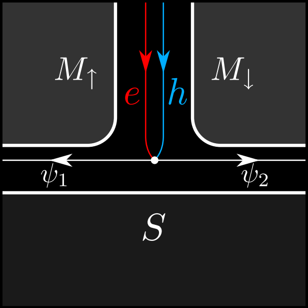

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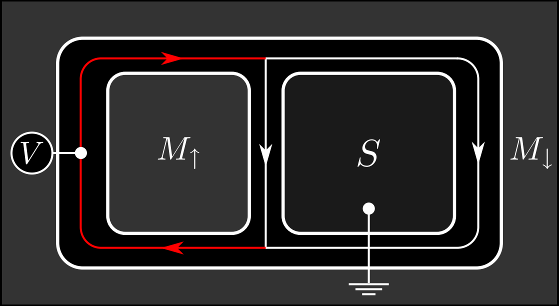
4. Symmetric, geometry-independent scattering

Setup 1: Mach-Zehnder



$$c_{in} \to \psi_1 + i\psi_2 \to c_{out}$$

$$G = 0$$

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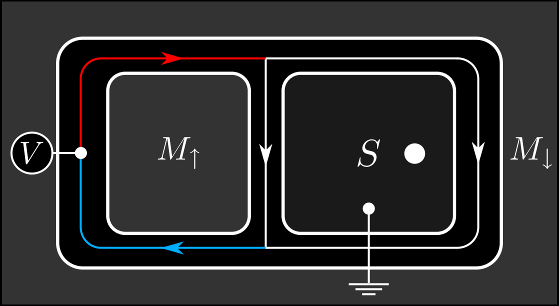

$$c_{in} \to \psi_1 + i\psi_2 \to \psi_1 - i\psi_2 \to c^\dagger_{out}$$

$$G = 2\frac{e^2}{h}$$

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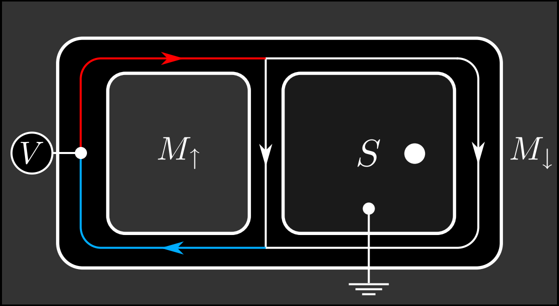
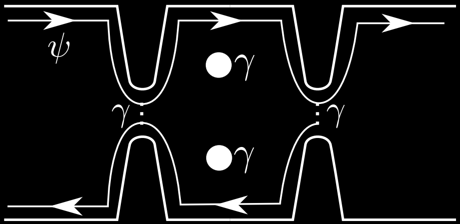


Finite V, dynamic phase

$$G(V) = 2\frac{e^2}{h}\sin^2\left(\frac{\pi N}{2} + \frac{eV\delta L}{\hbar v}\right)$$

Preparation: vortex tunneling



$$\psi \to \gamma \times \gamma$$

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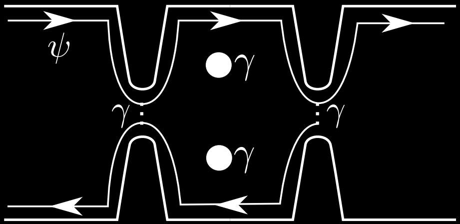

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Two vortices move one Majorana (Fendley, Fisher, Nayak 2006)

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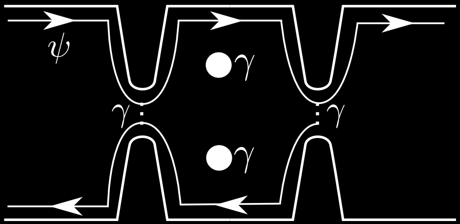

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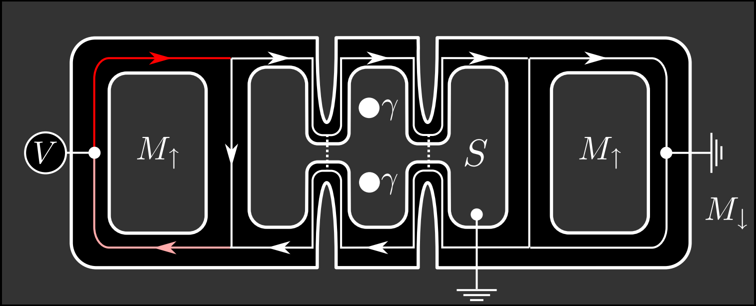
Vortex tunneling = phase slip $\quad t_\gamma \sim \exp(-\sqrt{CI_c})$

Setup 2: Fabry-Perot



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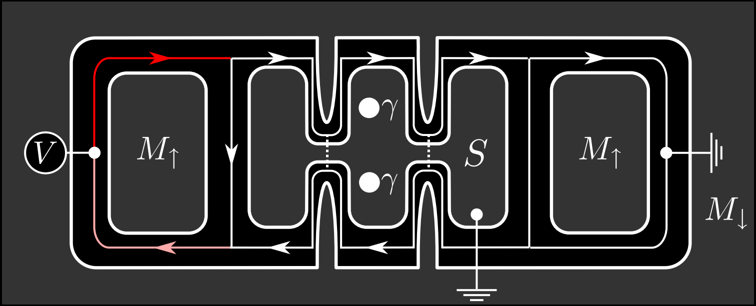

$$I = V\frac{e^2}{h}\,\mathrm{Re}(t_\psi)$$

Proportional to Majorana tunneling amplitude

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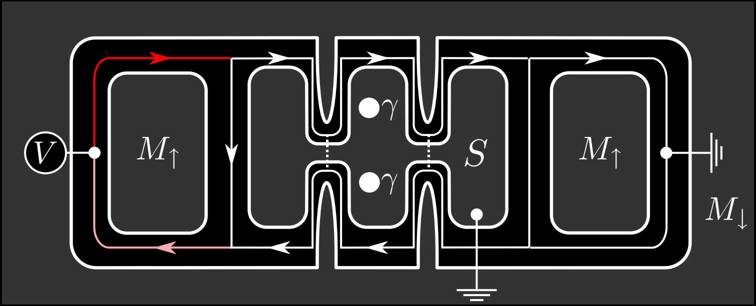

$$I \sim V \frac{e^2}{h} (t_{\gamma 1} + (-1)^{n_f} t_{\gamma 2})^2$$

Allows for the Majorana qubit readout

Conclusions

1. Deterministic conversion of an electron into a pair of Majorana fermions

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1. Deterministic conversion of an electron into a pair of Majorana fermions
2. Large conductance via a neutral mode
3. Detection of Majoranas (no experimental evidence yet!)
4. Readout of a topological qubit. (Way around MS patent :-)

Conclusions

Thank you all.
The end.