Title: Self-organized topological state with Majorana fermions

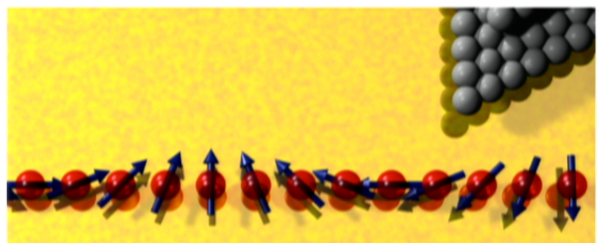
Date: Sep 17, 2013 03:30 PM

URL: http://pirsa.org/13090071

Abstract: Topological phases, quite generally, are difficult to come by. They either occur under rather extreme conditions (e.g. the quantum Hall liquids, which require high sample purity, strong magnetic fields and low temperatures) or demand fine tuning of system parameters, as in the majority of known topological insulators. Many perfectly sensible topological phases, such as the Weyl semimetals and topological superconductors, remain experimentally undiscovered. In this talk I will introduce a system in which a key dynamical parameter adjusts itself in response to the changing external conditions so that the ground state naturally favors the topological phase. The system consists of a quantum wire formed of individual magnetic atoms placed on the surface of an ordinary s-wave superconductor. It realizes the Kitaev paradigm of topological superconductivity when the wavevector characterizing the emergent spin helix dynamically self-tunes to support the topological phase.

Self-organized Topological State with Majorana Fermions

M. Franz and M.M. Vazifeh
University of British Columbia
arXiv:1307.2279



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CIFAR
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Antimatter

Ettore Majorana 1938

Matter = Antimatter

Antimatter

Ettore Majorana 1938

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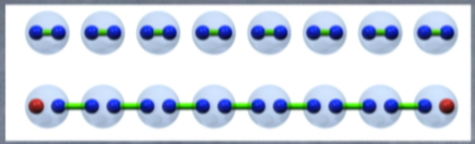
"Antimatter"
by Salvador Dalí (1958)

Overview:

Majorana fermions in topological superconductors



- Majorana fermions - particles that are identical to their antiparticles
- Can occur as collective excitations in solids with unconventional SC pairing.
- Obey non-abelian exchange statistics, can serve as a platform for fault-tolerant quantum computation.

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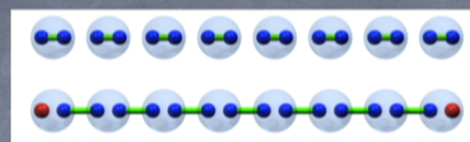

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NATURE PHYSICS | VOL 5 | SEPTEMBER 2009 | www.nature.com/naturephysics

perspective

Majorana returns

Frank Wilczek

In his short career, Ettore Majorana made several profound contributions. One of them, his concept of 'Majorana fermions' — particles that are their own antiparticle — is finding ever wider relevance in modern physics.

Enrico Fermi had to cajole his friend Ettore Majorana into publishing his big idea: a modification of the Dirac equation that would have profound ramifications for particle physics. Shortly afterwards, in 1938, Majorana mysteriously disappeared, and for 70 years his modified equation remained a rather obscure footnote in theoretical physics (Box 1). Now suddenly, it seems, Majorana's concept is ubiquitous, and his equation is central to recent work not only in neutrino physics, supersymmetry and dark matter, but also on some exotic states of ordinary matter.

Indeed, when, in 1928, Paul Dirac discovered[1] the theoretical framework for describing spin-½ particles, it seemed that complex numbers were unavoidable (Box 2). Dirac's original equation contained both real and imaginary numbers, and therefore it can only pertain to complex fields. For Dirac, who was concerned with describing electrons, this feature posed no problem, and even came to seem an advantage because it 'explained' why positrons, the antiparticles of electrons, exist.

Enter Ettore Majorana. In his 1937 paper[2], Majorana posed, and answered, the number of electrons minus the number of antielectrons, plus the number of electron neutrinos minus the number of antielectron neutrinos is a constant (call it L_e). These laws lead to many successful selection rules. For example, the particles (muon neutrinos, ν_μ) emitted in positive pion (π) decay, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, will induce neutron-to-proton conversion $\nu_\mu + n \rightarrow \mu^- + p$, but not proton-to-neutron conversion $\nu_\mu + p \rightarrow \mu^+ + n$; the particles (muon antineutrinos, $\bar{\nu}_\mu$) emitted in the negative pion decay $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ obey the opposite pattern. Indeed, it was through studies of this kind that the existence of different

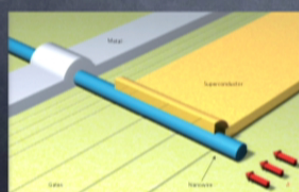
NATURE|Vol 464|11 March 2010|doi:10.1038/nature08915

REVIEW INSIGHT

Non-Abelian states of matter

Ady Stern[1]

Quantum mechanics classifies all elementary particles as either fermions or bosons, and this classification is crucial to the understanding of a variety of physical systems, such as lasers, metals and superconductors. In certain two-dimensional systems, interactions between electrons or atoms lead to the formation of quasiparticles that break the fermion–boson dichotomy. A particularly interesting alternative is offered by 'non-Abelian' states of matter, in which the presence of quasiparticles makes the ground state degenerate, and interchanges of identical quasiparticles shift the system between different ground states. Present experimental studies attempt to identify non-Abelian states in systems that manifest the fractional quantum Hall effect. If such states can be identified, they may become useful for quantum computation.



NATURE NANOTECHNOLOGY | VOL 8 | MARCH 2013 | www.nature.com/naturenanotechnology 149

commentary

Majorana's wires

Marcel Franz

Experiments on nanowires have shown evidence of solid-state analogues of the particles predicted by Ettore Majorana more than 70 years ago. Although stronger confirmation is still to come, these first observations have already fuelled expectations of fundamental results and potential applications in quantum information technology.

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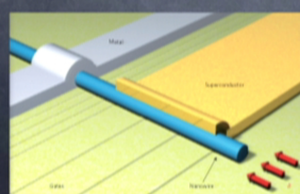

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Majorana fermions

Ordinary fermions $\{c_i^\dagger, c_j\} = \delta_{ij}$

Write in terms of Majorana fermions: $c_j = (\gamma_{j1} + i\gamma_{j2})/2$

$$\{\gamma_{i\alpha}, \gamma_{j\beta}\} = \delta_{ij}\delta_{\alpha\beta}, \quad \gamma_{i\alpha}^\dagger = \gamma_{i\alpha}$$

Canonical transformation: can be used to recast ANY fermionic Hamiltonian in terms of Majorana operators

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Certain Hamiltonians can support solutions with isolated localized Majorana fermions

Example: `Kitaev 1D model' [Phys. Usp. 44, 131 (2001)]

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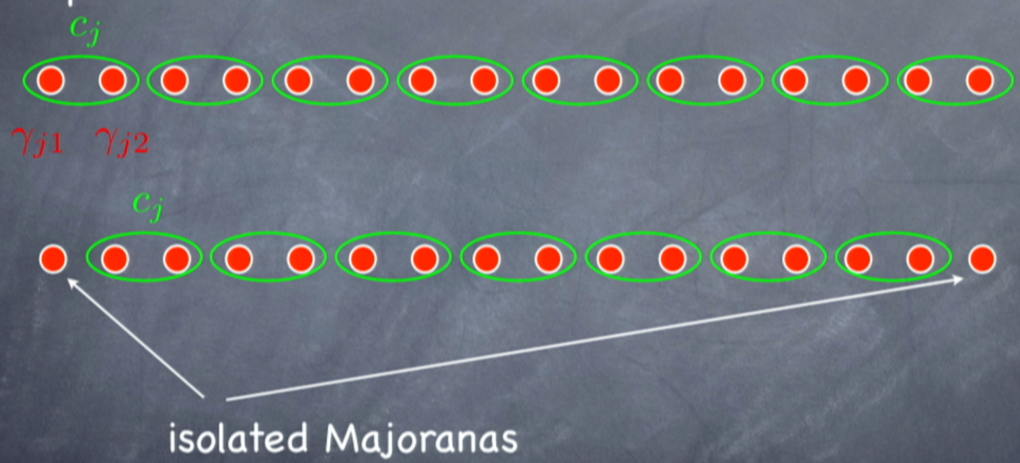

- Proposed realizations:
  a. Moore-Read FQHE
  b. Spin-polarized p+ip superconductor
  c. TI/SC interface
  d. Rashba-coupled semicond. + SC + magnetic insulator
  e. 1D quantum wires

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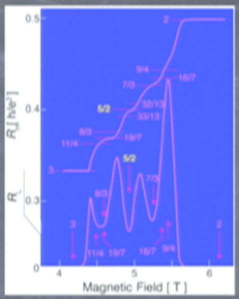

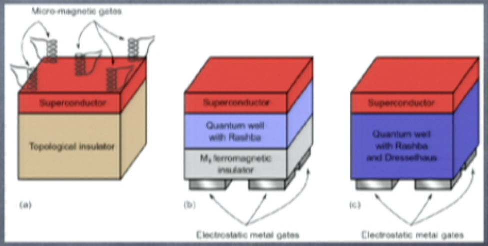

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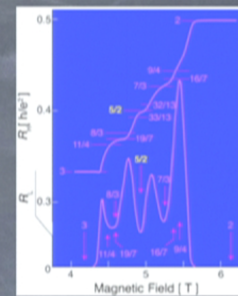
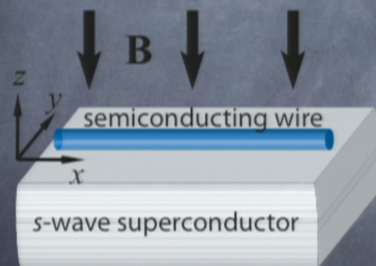
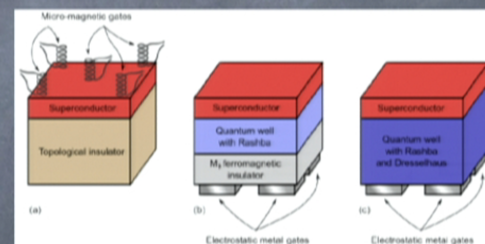


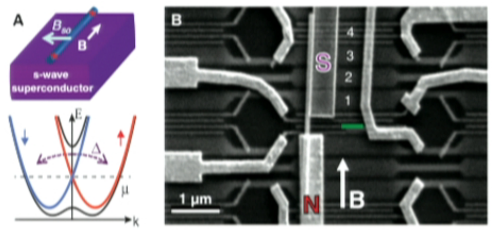


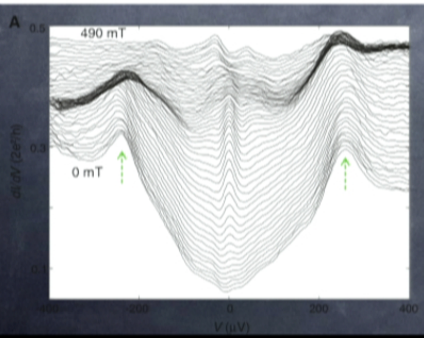


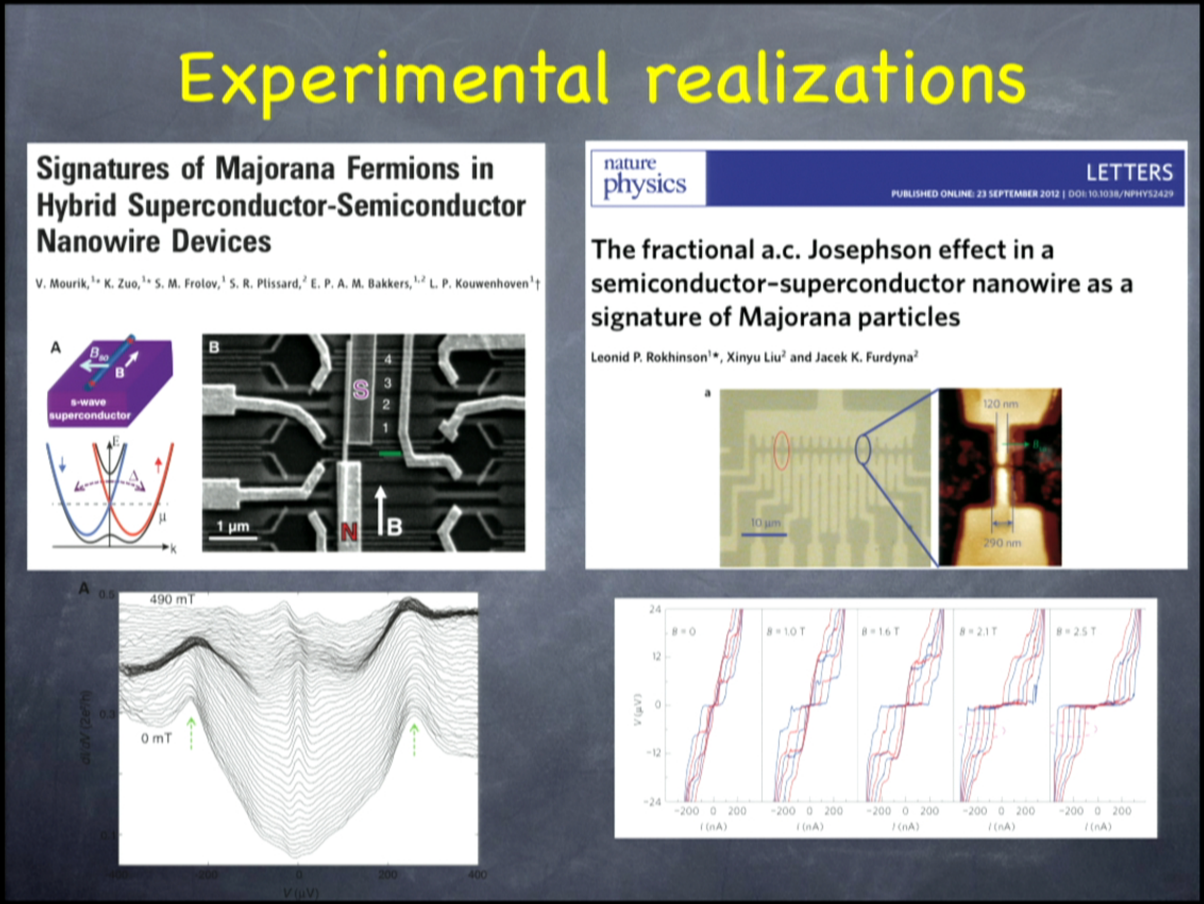
Experimental realizations

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1*] K. Zuo,[1*] S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†



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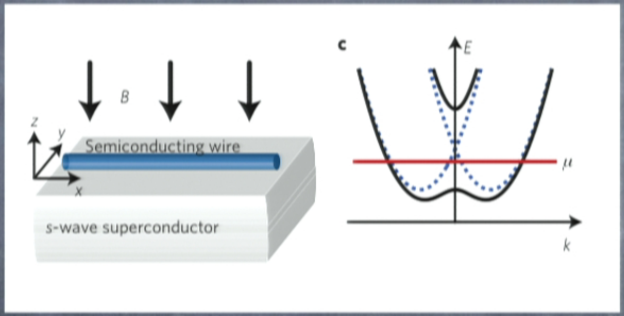
V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, L. P. Kouwenhoven
s-wave superconductor
1 µm
S
N
B
490 mT
0 mT
nature physics
LETTERS
The fractional a.c. Josephson effect in a semiconductor–superconductor nanowire as a signature of Majorana particles
Leonid P. Rokhinson, Xinyu Liu and Jacek K. Furdyna
120 nm
10 µm
290 nm
B = 0
B = 1.0 T
B = 1.6 T
B = 2.1 T
B = 2.5 T
I (nA)
V (µV)

Rashba-coupled semiconductor quantum wire

(a brief review)

Lutchyn et al. PRL 2010, Oreg et al. PRL 2010

$$H_0 = \int_{-\infty}^{\infty} dx \psi_\sigma^\dagger(x) \left(-\frac{\partial_x^2}{2m^*} - \mu + i\alpha\sigma_y\partial_x + V_x\sigma_x \right)_{\sigma\sigma'} \psi_{\sigma'}(x),$$



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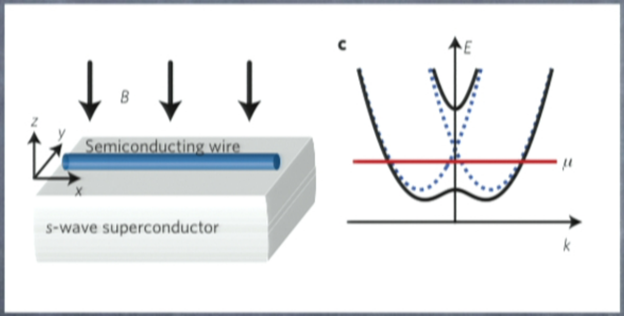
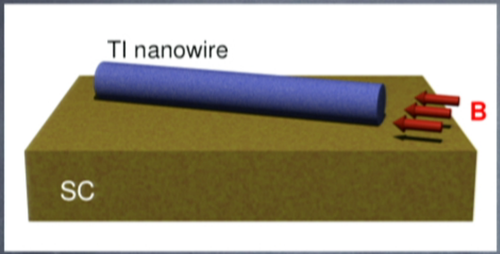


Another proposal

[A. Cook and M. Franz, Phys. Rev. B 84, 201105R (2011)]



TI nanowire placed on top of ordinary s-wave SC in longitudinal applied magnetic field.

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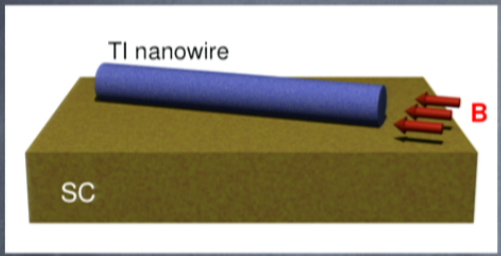

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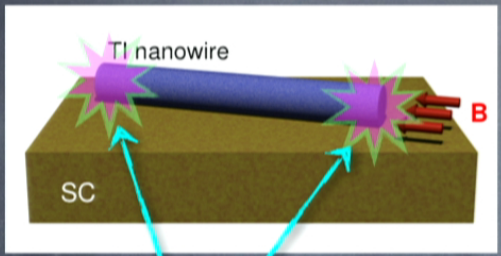


Majorana fermions

TI nanowire placed on top of ordinary s-wave SC in longitudinal applied magnetic field.

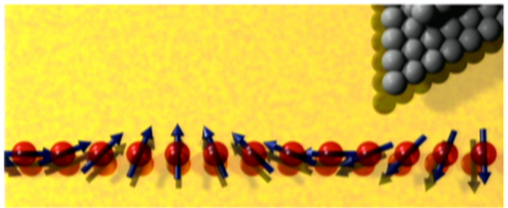
No fine tuning:

1. Chemical potential inside the bulk gap (~300meV in Bi_2Se_3).

2. Flux close to 1/2 flux quantum.

3. Robust against non-magnetic disorder.

Motivation for the present work



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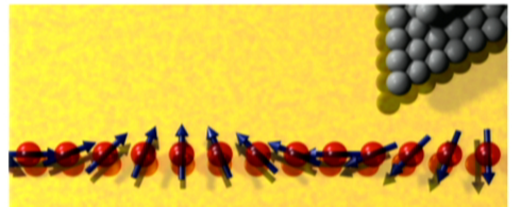


• Topological states of matter often occur under extreme conditions or require fine tuning:

- QHE: high-purity samples, strong fields, low T
- TI: must tune chemical composition,doping, strain
- TSC, Weyl semimetals: experimentally undiscovered

What we desire:
A system that wants to be topological,
a.k.a. 'self-organized' topological state

Bulletin of the American Physical Society

APS March Meeting 2013
Volume 58, Number 1

Monday–Friday, March 18–22, 2013; Baltimore, Maryland

Session M12: Topological Insulators: Topological States in Superconductors
8:00 AM–11:00 AM, Wednesday, March 20, 2013
Room: 314

Sponsoring Unit: DCMP
Chair: Andrew Wray, Lawrence Berkeley National Laboratory

Abstract ID: BAPS.2013.MAR.M12.8

Abstract: M12.00008 : Majorana end modes in STM Fabricated Atomic Chains on the Surface of a Superconductor: Theory \& Experiment
9:24 AM–9:36 AM

Preview Abstract

MathJax **On** | Off ← Abstract →

Authors:
Stevan Nadj-Perge
(Princeton University)

Ilya Drozdov
(Princeton University)

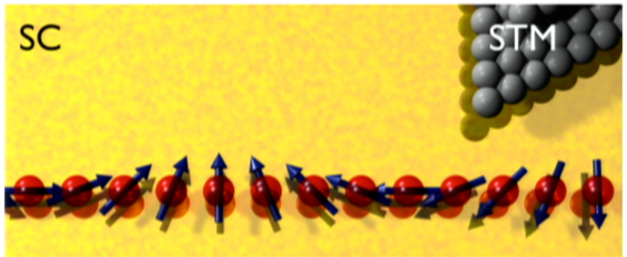
Jungpil Seo
(Princeton University)

Andrei Bernevig
(Princeton University)

Ali Yazdani

Proposed system

A chain of magnetic atoms deposited on the surface of an ordinary s-wave superconductor



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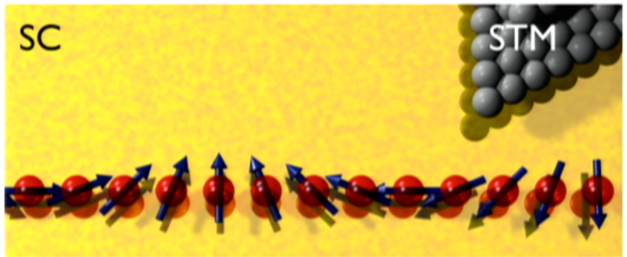


It is known that if the adatom moments form a spiral with the correct pitch then the wire is in the topological phase with Majorana fermions localized near its ends.

T.-P. Choy, J. M. Edge, A. R. Akhmerov, and C. W. J. Beenakker, PRB 84, 195442 (2011)
I. Martin and A.F. Morpurgo, PRB 85, 144505 (2012).
S. Nadj-Perge, I. K. Drozdov, B. A. Bernevig, and Ali Yazdani, arXiv:1303.6363

The Hamiltonian

$$\mathcal{H}_0 = -\sum_{ij\sigma} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} - \mu \sum_{i\sigma} c^\dagger_{i\sigma} c_{i\sigma} + J \sum_i \boldsymbol{S}_i \cdot (c^\dagger_{i\sigma} \boldsymbol{\sigma}_{\sigma\sigma'} c_{i\sigma'})$$

$$\mathcal{H} = \mathcal{H}_0 + \sum_j (\Delta c^\dagger_{j\uparrow} c^\dagger_{j\downarrow} + \text{h.c.}).$$

with adatom spins forming a coplanar spiral

$$\boldsymbol{S}_j = S[\cos(Gx_j), \sin(Gx_j), 0]$$

A spin-dependent gauge transformation

$$c_{j\uparrow} \to c_{j\uparrow} e^{\frac{i}{2} G z_j}, \qquad c_{j\downarrow} \to c_{j\downarrow} e^{-\frac{i}{2} G z_j},$$

brings it to a translation-invariant form.

effective SOC

$$\mathcal{H} \;=\; \sum\big[\xi(q)c^{\dagger}_{q\sigma}c_{q\sigma} + b(q)c^{\dagger}_{q\sigma}\sigma^{z}_{\sigma\sigma'}c_{q\sigma'} \;+\; JSc^{\dagger}_{q\sigma}\sigma^{x}_{\sigma\sigma'}c_{q\sigma'} + (\Delta c^{\dagger}_{q\uparrow}c^{\dagger}_{-q\downarrow} + \mathrm{h.c.})\big]$$

with

$$\xi(q) \;=\; \tfrac{1}{2}[\epsilon_0(q - G/2) + \epsilon_0(q + G/2)] - \mu,$$

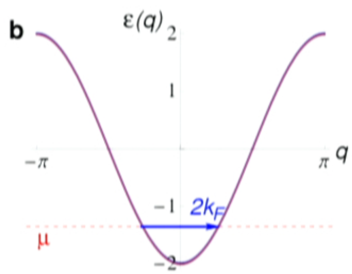
$$b(q) \;=\; \tfrac{1}{2}[\epsilon_0(q - \bar{G}/2) - \epsilon_0(q + G/2)]$$

$$\epsilon_0(q) = -\textstyle\sum_j t_{0j}e^{iqz_j}$$

Normal state spectra

No exchange coupling
(J=0):

$$\epsilon_0(q) = -2t\cos q$$



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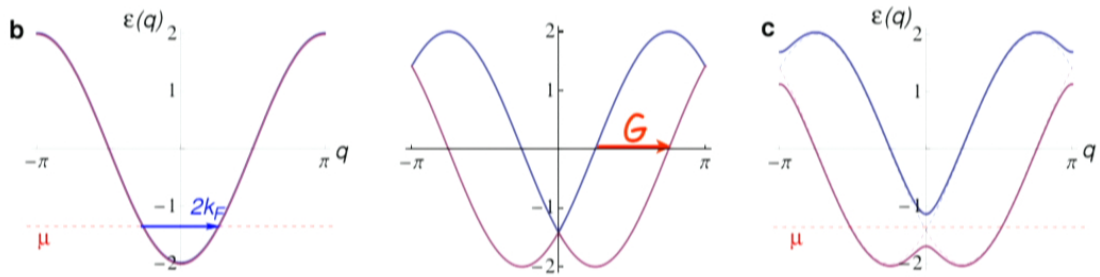

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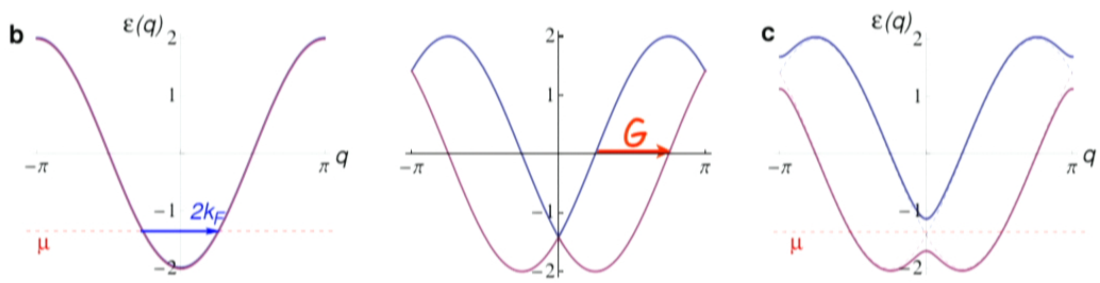

When μ lies inside the Zeeman gap the system becomes a 1D topological superconductor with Majorana zero modes.

The wavevector G of the spiral is a dynamical parameter: it will assume a value that minimizes the system free energy.

$$\chi_0(q) = \frac{L}{\pi}\frac{2m}{\hbar^2 q}\ln\left|\frac{2k_F - q}{2k_F + q}\right|$$

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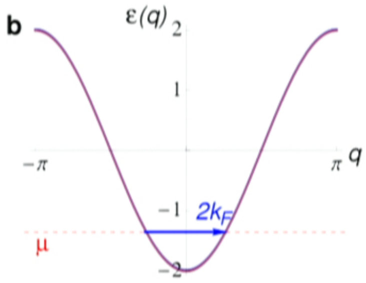

The static spin susceptibility $\chi(q)$ of 1D electron gas has a peak at $2k_F$ so we expect

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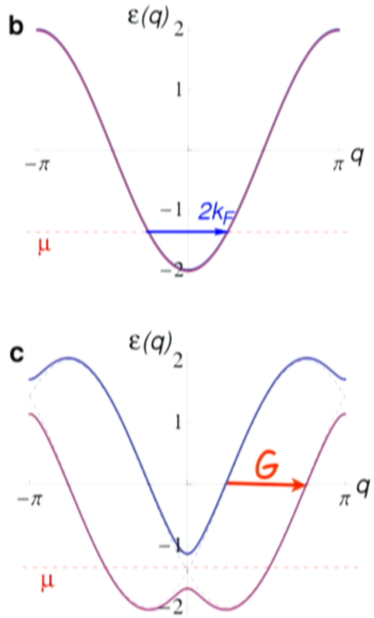

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But this is exactly the pitch required for the topological phase to emerge!

PHYSICAL REVIEW B **80**, 165119 (2009)

Nuclear magnetism and electron order in interacting one-dimensional conductors

Bernd Braunecker,[1] Pascal Simon,[2] and Daniel Loss[1]
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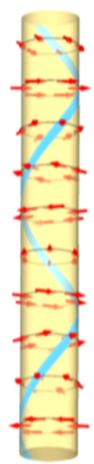
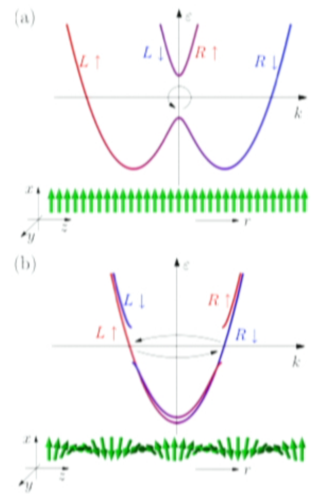
[2]*Laboratoire de Physique des Solides, CNRS UMR-8502, Université de Paris Sud, 91405 Orsay Cedex, France*

(Received 6 August 2009; revised manuscript received 25 September 2009; published 16 October 2009)





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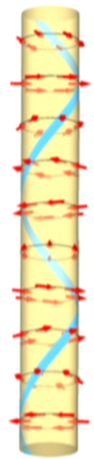

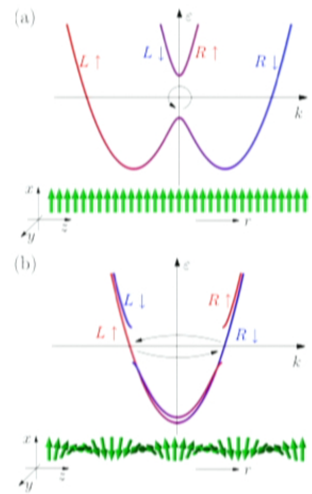

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To address this question we minimize the ground state energy $E_g(G)$ of the system and find $G_{min}(\mu)$.

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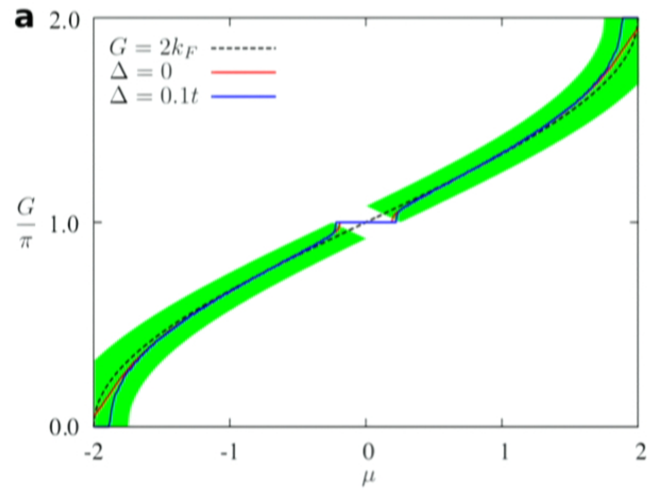

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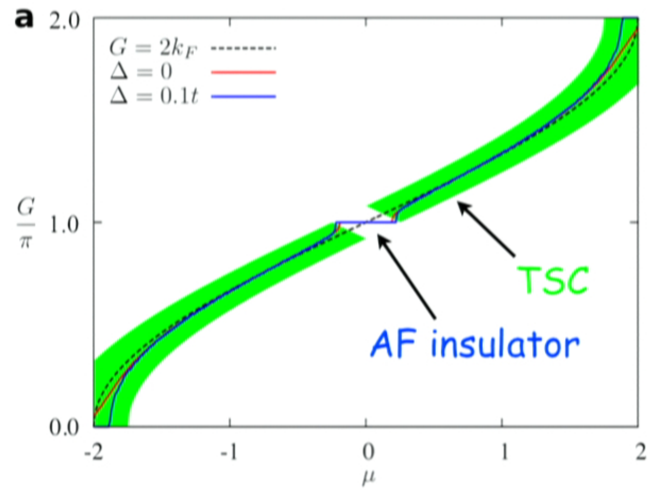

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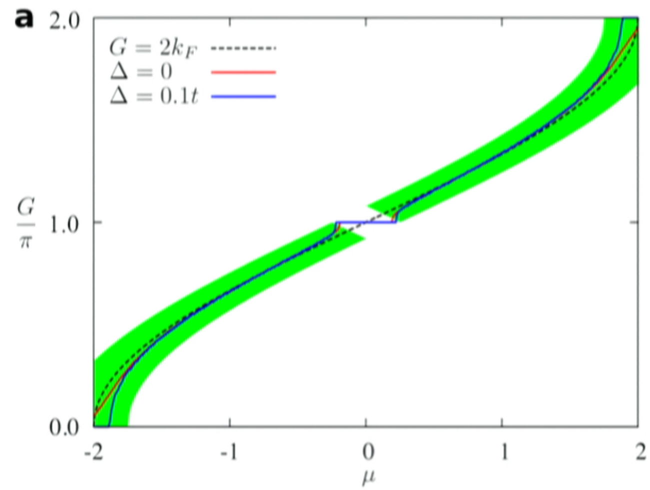
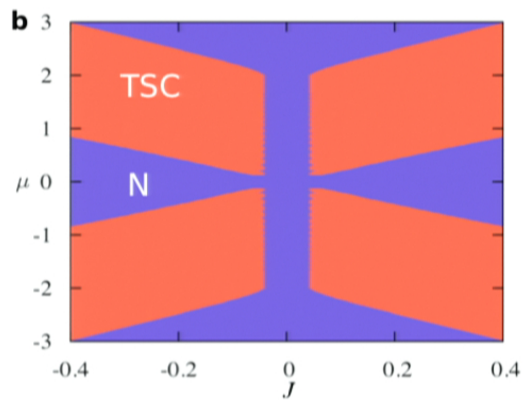


Topological phase diagram

Compute Kitaev's Majorana number

$$\mathcal{M}(H) = \mathrm{sgn}[\mathrm{Pf}(\tilde{H}(k=0))\mathrm{Pf}(\tilde{H}(k=\pi))]$$



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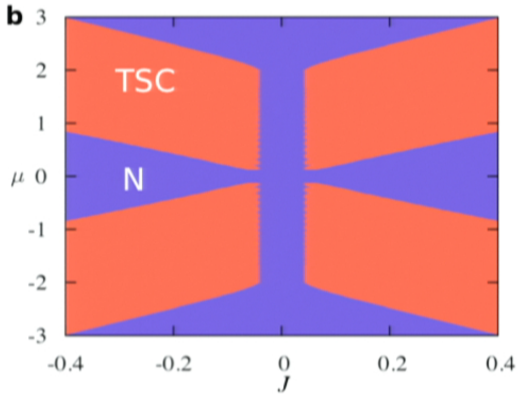

More elaborate model

- Capture chain-substrate proximity effect

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{\rm SC} + \mathcal{H}_{cd}$$

$$\mathcal{H}_{\rm SC} = \sum_{\boldsymbol{k}} \left[\xi_0(\boldsymbol{k}) d^\dagger_{\boldsymbol{k}\sigma} d_{\boldsymbol{k}\sigma} + (\Delta_0 d^\dagger_{\boldsymbol{k}\uparrow} d^\dagger_{-\boldsymbol{k}\downarrow} + \text{h.c.}) \right]$$

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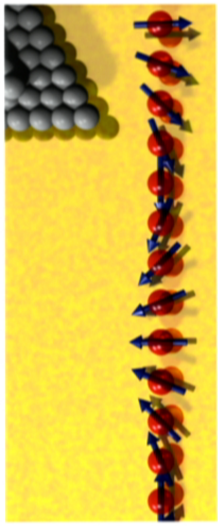

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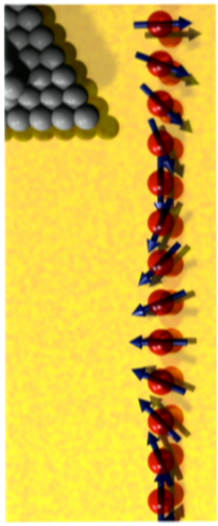

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- Fluctuations in the SC phase - pinned to 3D bulk
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- Magnons
  - Assume SOC will select a particular plane for the spiral

Selected for a Viewpoint in *Physics*
PRL **108,** 197204 (2012) PHYSICAL REVIEW LETTERS week ending 11 MAY 2012

Information Transfer by Vector Spin Chirality in Finite Magnetic Chains

Matthias Menzel,[1] Yuriy Mokrousov,[2] Robert Wieser,[1] Jessica E. Bickel,[1] Elena Vedmedenko,[1] Stefan Blügel,[2] Stefan Heinze,[3] Kirsten von Bergmann,[1] André Kubetzka,[1] and Roland Wiesendanger[1]
[1]*Institut für Angewandte Physik, Universität Hamburg, Jungiusstr. 11, 20355 Hamburg, Germany*
[2]*Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich, D-52425 Jülich, Germany*
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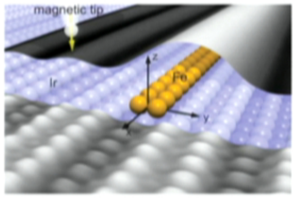

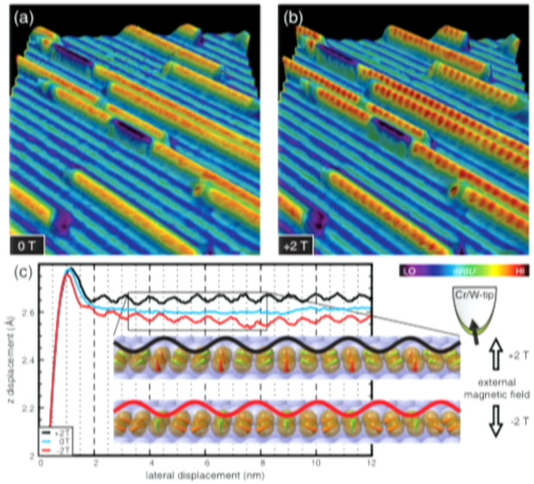

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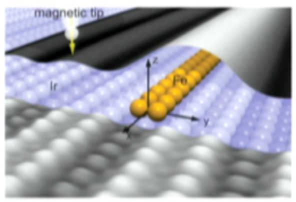
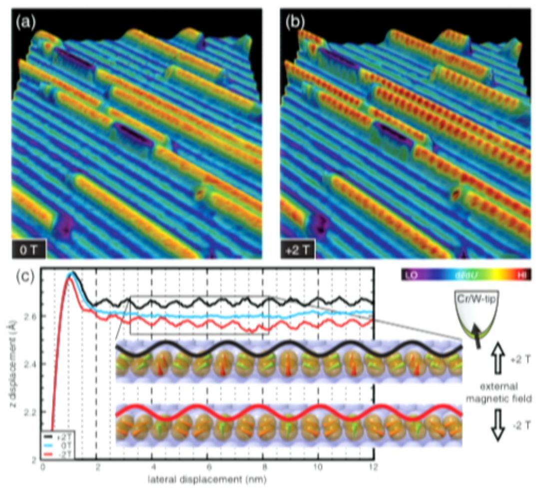


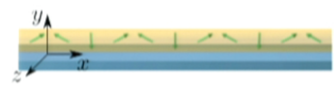


How do we know this prediction is correct?

Topological Superconductivity and Majorana Fermions in RKKY Systems

Jelena Klinovaja,[1] Peter Stano,[1,2] Ali Yazdani,[3] and Daniel Loss[1]
[1]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2]*Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia*
[3]*Joseph Henry Laboratories and Department of Physics, Princeton University, Princeton, New Jersey 08544*
(Dated: July 5, 2013)

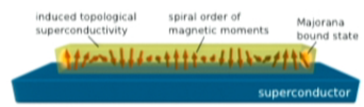
arXiv:1307.1442v1



Interplay between classical magnetic moments and superconductivity in quantum one-dimensional conductors: toward a self-sustained topological Majorana phase

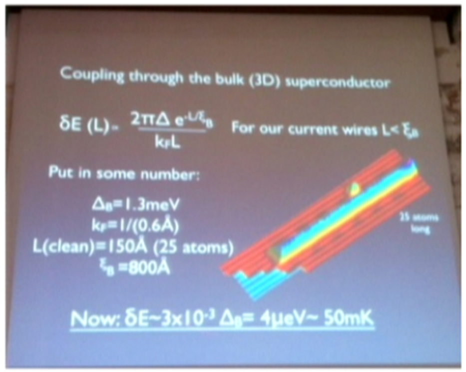
Bernd Braunecker[1] and Pascal Simon[2]
[1]*Departamento de Física Teórica de la Materia Condensada, Centro de Investigación de Física de la Materia Condensada, and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[2]*Laboratoire de Physique des Solides, CNRS UMR-8502, Université de Paris Sud, 91405 Orsay Cedex, France*
(Dated: July 10, 2013)

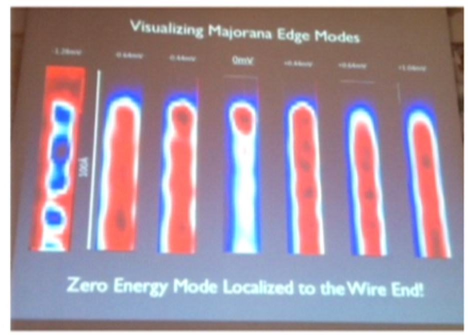
arXiv:1307.2431v1



Possible signatures of Majorana end modes in Gd wires self-assembled on (110) surface of crystalline Pb.

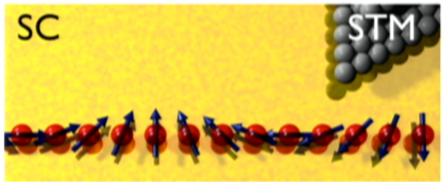
A. Yazdani, Erice talk July 16, 2013



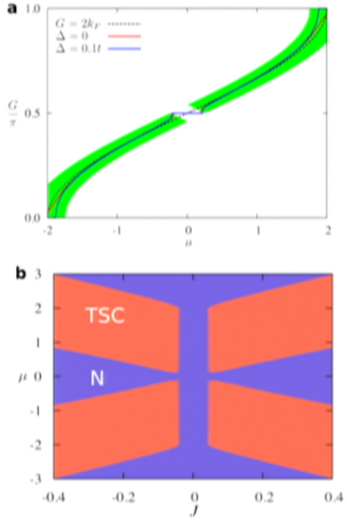


Conclusions

[arXiv:1307.2279]



- Majorana fermions are expected to occur in a chain of magnetic adatoms on a SC substrate
- This requires spiral magnetic order with a correct pitch $G \simeq 2k_F$
- Under a wide range of physical conditions the spiral pitch G spontaneously adjusts to produce the topological phase.



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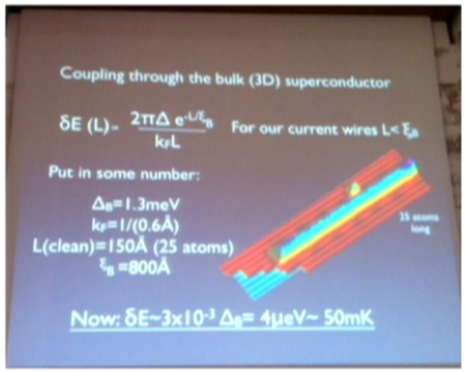

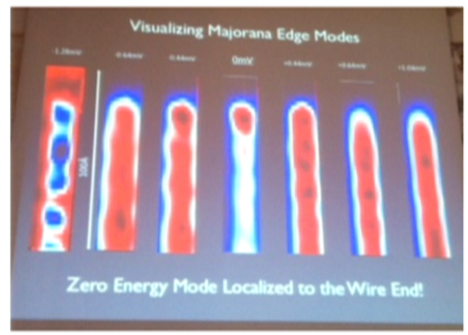

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