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	Carlos Pay
	Instituto de Ciencia de Materiales de
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Engeniering topologically protected edge states Signals in the LDOS: CdGM analogs Full 2D simulation: band bending and the solid-core model Disorder-induced mode-mixing: a new mechanism for topology Conclusions

Full-shell Majorana nanowires A theoretical description

Carlos Payá

Instituto de Ciencia de Materiales de Madrid (ICMM), CSIC

January 10, 2024





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Full-shell Majorana nanowires

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Outline

Engeniering topologically protected edge states

⊖ Signals in the LDOS: CdGM analogs

⊕ Full 2D simulation: band bending and the solid-core model

O Disorder-induced mode-mixing: a new mechanism for topology

Ø Conclusions

① Engeniering topologically protected edge states

② Signals in the LDOS: CdGM analogs

③ Full 2D simulation: band bending and the solid-core model

() Disorder-induced mode-mixing: a new mechanism for topology

Conclusions

Outline

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A toy model The Lutchyn-Oreg model The full-shell nanowire

The Kitaev chain

• Chain of *N* spin-less fermions (*p*-wave superconductivity):

$$=-\mu\sum_{j=1}^{N}\left(c_{j}^{\dagger}c_{j}-\frac{1}{2}\right)+\sum_{j=1}^{N-1}\left[-t\left(c_{j}^{\dagger}c_{j+1}+c_{j+1}^{\dagger}c_{j}\right)+\Delta\left(c_{j}c_{j+1}+c_{j+1}^{\dagger}c_{j}^{\dagger}\right)\right]$$

(a) $c_1 - \cdots - c_j - c_{j+1} - \cdots - c_N$

R. Aguado 2017, Rivista del Nuovo Cimento.
E. Prada et al. 2020, Nature Reviews Physics.
A. Y. Kitaev 2001, Physics-Uspekhi.

Carlos Payá Full-shell Majorana nanowires

Full-shell Majorana nanowires Full-shell Majorana nanowires Engeniering topologically protected edge states A toy model The Kitaev chain

The simplest topological model.

- 1. Chain of fermions. Chem pot + hopping + superconducting pairing.
- 2. Majorana representation. $\gamma^{\rm A}$ and $\gamma^{\rm B}$ are Majorana operators.
- 3. Hamiltonian in terms of Majorana operators. Cases:
 - $\Delta = t = 0$: trivial. Just a chain of decoupled fermions.
 - $t = \Delta$, $\mu = 0$. Long-range coupling. Same site decoupled. Edge states disappear from the hamiltonian!
- **4.** Unpaired Majorana follow non-Abelian statistics. When two MBS interact, the final state of the system depends on the order of the exchanges.

The Kitaey chain Chain of N spin-less fermions (p-wave superconductivity) $H = -\mu \sum_{i=1}^{N} \left(r_i^{\dagger} r_j - \frac{1}{\tau} \right) + \sum_{i=1}^{N-1} \left[-i \left(r_i^{\dagger} r_{j+1} + r_{j+1}^{\dagger} r_j \right) + \Delta \left(r_j r_{j+1} + r_{j+1}^{\dagger} r_j^{\dagger} \right) \right]$ 0------

A toy model The Lutchyn-Oreg model The full-shell nanowire

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(a)

Majorana representation:

$$c_1 - \cdots - c_j - c_{j+1} - \cdots - c_N$$

 $c_j = \frac{1}{2} \left(\gamma_j^{\mathcal{A}} + i \gamma_j^{\mathcal{B}} \right), \quad c_j^{\dagger} = \frac{1}{2} \left(\gamma_j^{\mathcal{A}} - i \gamma_j^{\mathcal{B}} \right)$

(b)			
• - • - • •			
$\gamma_1^A \gamma_1^B$	$\gamma_j^A \gamma_j^B$	$\gamma^A_{j+1} \ \gamma^B_{j+1}$	$\gamma^A_N \gamma^B_N$

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$\label{eq:characteristic} \begin{array}{c} \hline \mbox{The Kitaev chain} \\ \hline & \mbox{Characteristic} \\ & \mbox{-} e_{-r} \frac{p_{1}^{2}}{2} \left(\gamma_{1} \frac{1}{2} \right) \frac{p_{1}^{2}}{2} \left[+ \left(\gamma_{1} + \gamma_{1}^{2} \right) + \left(\gamma_{1} + \gamma_{1}^{2} \right) + \left(\gamma_{1} + \gamma_{1}^{2} \right) \right] \\ & \mbox{Majoran approximation:} \\ & \mbox{-} e_{1} \left(\gamma_{1} + \gamma_{1}^{2} - \frac{\gamma_{1}^{2}}{2} + \frac{\gamma_{1}^{2}}{2} \right) \\ & \mbox{Majoran approximation:} \\ & \mbox{-} e_{1} \left(\gamma_{1} + \gamma_{1}^{2} - \frac{\gamma_{1}^{2}}{2} + \frac{\gamma_{1}^{2}}{2} \right) \\ & \mbox{Majoran approximation:} \\ & \mbox{-} e_{1} \left(\gamma_{1}^{2} - \frac{\gamma_{1}^{2}}{2} + \frac{\gamma_{1}^{2}}{2} + \frac{\gamma_{1}^{2}}{2} \right) \\ & \mbox{Majoran approximation:} \\ & \mbox{-} e_{1} \left(\gamma_{1}^{2} - \frac{\gamma_{1}^{2}}{2} + \frac{\gamma_{1}^{2}}{2} +$

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A toy model

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► Hamiltonian in terms of Maiorana operators:

 $c_1 - \cdots - c_j - c_{j+1} - \cdots - c_N$

 $H = -\frac{i\mu}{2}\sum_{j=1}^{N}\gamma_{j}^{A}\gamma_{j}^{B} + \frac{i}{2}\sum_{j=1}^{N-1}\left[(\Delta+t)\gamma_{j}^{B}\gamma_{j+1}^{A} + (\Delta-t)\gamma_{j}^{A}\gamma_{j+1}^{B}\right] \qquad (c)$

 $\gamma_{A}^{A} \sim_{A}^{B} \gamma_{i}^{A} \gamma_{i}^{B} \gamma_{i+1}^{A} \gamma_{i+1}^{B} \gamma_{i+1}^{A} \gamma_{N}^{A} \gamma_{N}^{B}$

Full-shell Majorana nanowires -Engeniering topologically protected edge states ⊢A toy model 2024 └─The Kitaev chain

The Kitaey chain Chain of N snin-less fermions (n-wave superconductivity): $H = -\mu \sum_{i=1}^{M} \left(q_i^{2} q_{i}^{2} - \frac{1}{q} \right) + \sum_{i=1}^{M-1} \left[-i \left(q_i^{2} q_{i+1} + q_{i+1}^{2} q_{i} \right) + \Delta \left(q_i q_{i+1} + q_{i+1}^{2} q_{i}^{2} \right) \right]$ Majorana representation $r_i = \frac{1}{2} \left(\gamma_i^A + \nu \gamma_i^B \right), \quad r_i^\dagger = \frac{1}{2} \left(\gamma_i^A - \nu \gamma_i^B \right)$ Hamiltonian in terms of Majorana ······ $H = -\frac{2\pi}{2}\sum_{j=1}^{N} y_{j}^{0} y_{j}^{0} + \frac{2}{2}\sum_{j=1}^{N-1} \left[(\Delta + i) y_{j}^{0} y_{j+1}^{0} + (\Delta - i) y_{j}^{0} y_{j+1}^{0} \right] \qquad (1)$

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Kitaev chain energy dispersion

Let's consider periodic boundary conditions and solve the eigenvalue problem in momentum space:



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- We distinguish two regimes separated by a gap closing.
- In the open boundary conditions, they correspond to the presence or absence of MZM.
- It is an example of BDI topology.

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Majoranas for qubits



- ► MZM are non-Abelian anyons.
- Gap closing/reopening \Rightarrow topological protection.

R. Aguado 2017, *Rivista del Nuovo Cimento*.
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 $\overset{4}{\smile}$ Majoranas for qubits

-Engeniering topologically protected edge states

Full-shell Majorana nanowires

A toy model



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We need a *p*-wave superconductor!

Full-shell Majorana nanowires Engeniering topologically protected edge states The Lutchyn-Oreg model We need a p-wave superconductor!

• Fu-Kane did it for 3D topological insulators.

We need a p-wave superconductor!

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A toy model **The Lutchyn-Oreg model** The full-shell nanowire

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Full-shell Majorana nanowires Engeniering topologically protected edge states The Lutchyn-Oreg model We need a p-wave superconductor!

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Signals in the LDOS: CdGM analogs Full 2D simulation: band bending and the solid-core model Disorder-induced mode-mixing: a new mechanism for topology Conclusions A toy model The Lutchyn-Oreg model The full-shell nanowire

Rashba, Zeeman and helical bands



Full-shell Majorana nanowires Engeniering topologically protected edge states The Lutchyn-Oreg model Rashba, Zeeman and helical bands



- SOC breaks spin degeneracy and shifts bands in energy and k-space.
- Zeeman field breaks time-reversal symmetry and splits bands in energy.
- When μ in the Zeeman gap, there is only one band with spin locked to momentum, i.e. helical.
- Add SC \Rightarrow two gaps. One of them, $\Delta_1,$ can close and induce a topological transition.

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Topological phase transition



$$V_{Zc}=\sqrt{\Delta^2+\mu^2}$$

R. M. Lutchyn, J. D. Sau, and S. Das Sarma 2010, *Phys. Rev. Lett.* R. Aguado 2017, *Rivista del Nuovo Cimento.*

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Full-shell Majorana nanowires Engeniering topologically protected edge states The Lutchyn-Oreg model Topological phase transition

- Δ_1 closes at k = 0 for $V_Z = V_{Zc}$.
- Disadvantage: need high magnetic fields and high g.
- High magnetic fields kill SC.

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Searching for Majoranas

Full-shell Majorana nanowires Engeniering topologically protected edge states The Lutchyn-Oreg model Searching for Majoranas



Strong experimental interest.

Zero-bias anomalies in tunneling spectroscopy experiments

device 1

Mourik 2012, Albrecht 2016, Deng 2016



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Claims: V. Mourik et al. 2012, Science. S. M. Albrecht et al. 2016, Nature. M. T. Deng et al. 2016, Science. Trivial explanations: E. J. H. Lee et al. 2012, Phys. Rev. Lett. M. Valentini, F. Peñaranda, et al. 2021, Science. M. Valentini, M. Borovkov, et al. 2022, Nature.

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- Strong experimental interest.
- Zero-bias anomalies detected with non-topological explanations.





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Searching for Majoranas

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Searching for Majoranas

Drawbacks:

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A toy model The Lutchyn-Oreg model The full-shell nanowire

Searching for Majoranas

Full-shell Majorana nanowires Engeniering topologically protected edge states The Lutchyn-Oreg model Searching for Majoranas

Searching for Majoranas

Drawbacks:
 Multimode effects.

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	Drawbacks:
	 Multimode effects.
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· High magnetic fields.

Orbital effects.

 Strong experimental interest.
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Searching for Majoranas

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The Lutchyn-Oreg model

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Full-shell Majorana nanowires -10 -Engeniering topologically protected edge states 5 The Lutchyn-Oreg model 2024 Searching for Majoranas

Searching for	Majoranas

 Drawbacks Multimade effects · Electrostatic environment Strong experimental interest Renormalized parameter Zero, bias anomalies detected with · High magnetic fields. Orbital effects. non-topological explanations Charge and pairing inhomogeneities

- Drawbacks:
 - Multimode effects.
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Full-shell Majorana nanowires

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Searching for	Majoranas	
		Drawbacks

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- Drawbacks:
 - Multimode effects.
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Searching for	Majoranas

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 Constraint detected with
 Non-topological explanations.
 Constraint

- Drawbacks:
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 - Electrostatic environment.
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Engeniering topologically protected edge states

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Engeniering topologically protected edge states

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The Little-Parks effect



- Cylinder \Leftrightarrow vortex.
- ► Too thin for full Meissner.
- Quantized winding of the order parameter: $\Delta = |\Delta|e^{in\varphi}$.
- $n \in \mathbb{Z}$ and jumps every flux quantum Φ_0 .
- ► Quasi-quantization of flux ⇒ pairing presents LP lobes.
- Depends on *R*, SC thickness *d* and ξ_d, the SC coherence length.

W. A. Little and R. D. Parks 1962, *Phys. Rev. Lett.* R. D. Parks and W. A. Little 1964, *Phys. Rev.* Full-shell Majorana nanowires Full-shell Majorana nanowires Engeniering topologically protected edge states The full-shell nanowire The Little-Parks effect



A toy model The Lutchyn-Oreg model The full-shell nanowire

The full-shell nanowire: analytical hollow-core model



• **Effective** Zeeman field:

$$V_Z = \phi \left(\frac{1}{4mR^2} + \frac{\alpha}{2R} \right)$$

- $\phi = n \frac{\Phi}{\Phi_0}$, magnetic flux.
- ► *n* number of fluxoids.
- ► No need for g-factor. $\Phi \sim \Phi_0$.

S. Vaitiekėnas *et al.* 2020, *Science*. P. San-Jose *et al.* 2023, *Phys. Rev. B.* **C. Payá** *et al.* **2023,** *arXiv.*

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Full-shell Majorana nanowires Engeniering topologically protected edge states The full-shell nanowire The full-shell nanowire: analytical hollow-core model



The full-shell nanowire: analytical hollow-core more

- Zeeman field for the hollow-core model.
- *n* integer part of flux.

A toy model The Lutchyn-Oreg model The full-shell nanowire

► Good generalized angular momentum

 $m_J = \begin{cases} \mathbb{Z} + 1/2, & \text{if } n \text{ even} \\ \mathbb{Z}, & \text{if } n \text{ odd} \end{cases}$

 $J_z = -i\partial_{\varphi} + \frac{1}{2}\sigma_z + \frac{1}{2}n\tau_z$

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The full-shell nanowire: analytical hollow-core more

► Effective Zeeman field:

φ = n − Φ/Φ₀, magnetic flux.
 n number of fluxoids.
 No need for σ−factor. Φ ~ Φ₀

 $V_Z = \phi \left(\frac{1}{4mR^2} + \frac{\alpha}{2R} \right)$

Good generalized angular momentum J₂ = −i∂_x + ½σ₂ + ½πτ₂:

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 \blacktriangleright \Rightarrow Computationally affordable.

The full-shell nanowire: analytical hollow-core model



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The full-shell nanowire: analytical hollow-core more

► Effective Zeeman field:

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Full-shell Majorana nanowires

The full-shell nanowire: analytical hollow-core model

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- Easier to understand physics.

S. Vaitiekėnas *et al.* 2020, *Science*. P. San-Jose *et al.* 2023, *Phys. Rev. B*. **C. Payá** *et al.* **2023,** *arXiv***.** Full-shell Majorana nanowires Engeniering topologically protected edge states The full-shell nanowire The full-shell nanowire: analytical hollow-core model

The full-shell nanowire: analytical hollow-core more

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Earlier to undustand aburio

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- Easier to understand physics.
- SOC and chemical potential non-tunable.

S. Vaitiekėnas *et al.* 2020, *Science.* P. San-Jose *et al.* 2023, *Phys. Rev. B.* **C. Payá** *et al.* **2023,** *arXiv.* Full-shell Majorana nanowires Engeniering topologically protected edge states The full-shell nanowire The full-shell nanowire: analytical hollow-core model

The full-shell nanowire: analytical hollow-core more

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Earlier to undurstand aburies

SOC and chamical notantial

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More than just MBS Towards a realistic model

The CdGM analog states







- Each minimum in the bands corresponds to a van Hove peak in the LDOS.
- These Van Hove peaks are CdGM analogs.
- LP switched off for clarity.
- Turn on and see LDOS against flux.





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2024

The CdGM analog states

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Full-shell Majorana nanowires

—More than just MBS

Turn on and see LDOS against flux.

-Signals in the LDOS: CdGM analogs

└─The CdGM analog states





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• LP effect turned on.

- Left: LDOS cut for white line in LDOS v flux.
- Lots of states over MZM.
- Taking only $m_J = 0$, minigap is huge.





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Full-shell Majorana nanowires Signals in the LDOS: CdGM analogs More than just MBS LDOS vs. flux

• LP effect turned on.

• Left: LDOS cut for white line in LDOS v flux.

LDOS vs. flux

LDOS.

LDOS (arb. units)

- Lots of states over MZM.
- Taking only $m_J = 0$, minigap is huge.

More than just MBS Towards a realistic model

The tubular-core model





- Increase *w* and keep "equivalent" parameters.
- Notice DP. It shifts towards higher fluxes.
- Leading to a shifted gap and skewed CdGM analogs.
- Sometimes there is true topological minigap! Why? \Rightarrow competition between MBS and CdGMs.

More than just MBS Towards a realistic model

The tubular-core model



- ▶ Phase Diagram just shifts when increasing *w*.
- ► True topological protection only for small islands.

Phase Diagram just shifts when increasing w.
 True topological protection only for small islands

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C. Payá et al. 2023, arXiv.

More than just MBS Towards a realistic model

The modified hollow-core model



• $w \leq 0.5R \Rightarrow$ all physics can be recuperated just with R_{av}

Full-shell Majorana nanowires Signals in the LDOS: CdGM analogs Towards a realistic model The modified hollow-core model



• PD have the same shape for all w.

• Up to w = 0.5R, they can be fitted to a $w \to 0$ model (orange in w = 20 nm).

C. Payá et al. 2023, arXiv.

Role of the radial modes Phase Diagram

A solid core simulation: first radial mode



- Solid-core: boundary conditions change.
- Realistic simulation: conduction band-bending.
- If all states in first radial mode, similar to tubular-core.



A solid core simulation: first radial mode

C. Payá et al. 2023, arXiv.

Role of the radial modes Phase Diagram

A solid core simulation: first radial mode



A solid core simulation: first radial mode

Conduction band bends close to the interface.

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Role of the radial modes Phase Diagram

A solid core simulation: first radial mode



• Different boundary conditions: WF can extend to r = 0.

Full-shell Majorana nanowires Full-Shell Majorana nanowires Full 2D simulation: band bending and the solid-core model Role of the radial modes A solid core simulation: first radial mode

A solid core simulation: first radial mode

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Role of the radial modes Phase Diagram

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Full-shell Majorana nanowires -Full 2D simulation: band bending and the solid-core model -Role of the radial modes -A solid core simulation: first radial mode

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- If all states in first radial mode, similar to tubular-core.



Role of the radial modes Phase Diagram

A solid core simulation: second radial mode





- MBS second radial mode is the first to enter \Rightarrow extends through all first lobe.
- But all *m_J* in first radial mode enter before.
- LDOS is covered with CdGM.
- No true topological protection anywhere.
- Intuition: larger radial modes have smaller average radius.

C. Payá et al. 2023, arXiv.

Role of the radial modes Phase Diagram

A solid core simulation: second radial mode



When the second radial mode is occupied, the ZEP expands over the full lobe, but CdGMs cover it.

C. Payá et al. 2023, arXiv.

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C. Pavá et al. 2023. arXiv.



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Role of the radial mode Phase Diagram

More radial modes in the Phase Diagram



- Notice axis are mean α and U_{min} , the minimum of the dome-profile.
- ▶ One wedge per radial mode. No islands outside the first radial mode.

C. Payá et al. 2023, arXiv.

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Full-shell Majorana nanowires -Full 2D simulation: band bending and the solid-core model -Phase Diagram -More radial modes in the Phase Diagram

▶ Notice axis are mean α and U_{min} , the minimum of the dome-profile. ▶ One wedge per radial mode. No islands outside the first radial mode.

More radial modes in the Phase Diagram

- At $\langle \alpha \rangle = 0$, singularity. No topology possible.
- Begins at $U_{min} = -1$ meV bc. mean α is not well defined at $U_{min} = 0$.

Role of the radial mode Phase Diagram

Topological invariant



• N_M is the number of MBS.



- N_M calculated with Pfaffian.
- Pfaffian is a generalization of the determinant for antisymmetric matrices.

Topological invariant

Nu is the number of MBS.

C. Payá et al. 2023, arXiv.

The topological transition mechanism A nanowire with generic disorder Phase Diagram with disorder

Where is topology in the Hamiltonian?

Hamiltonian

 $\langle m_J | H | m_J \rangle = H_{K,m_J} \tau_z + V_Z \sigma_z + A_{m_J} + C_{m_J} \sigma_z \tau_z + \alpha k_z \sigma_y \tau_z$

- σ_i, τ_i Pauli matrices in spin and electron-hole space.
- H_{K,m_J} is the kinetic term (+ effective chemical potential).
- ► V_Z is the effective Zeeman term.
- A_{m_J} and C_{mJ} is the coupling of J_z with the magnetic field and the spin.
- $\alpha k_z \sigma_y \tau_z$ allows topological transitions when $m_J = 0$.

S. Vaitiekėnas *et al.* 2020, *Science*. **C. Payá** *et al.* **2023,** *arXiv***.**

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- This hamiltonain is for the MHC, but the structure is valid for the SCM.
- H_K contains μ , the effective chemical potential renormalized by α .
- *V_Z* is the effective Zeeman term shown before.
- $\alpha k_z \sigma_y \tau_z$ is the term that provides helical bands.

Where is topology in the Hamiltonian

$\langle m_J | H | m_J \rangle = H_{K,m,\tau_2} + V_Z \sigma_Z + A_{m_1} + C_{m,\sigma_2} \tau_Z + \alpha k_Z \sigma_z \tau_Z$

- σ_i, τ_i Pauli matrices in spin and electron-hole space.
 H is the binstic term (1) effective chemical meteorist)
- ► V_Z is the effective Zeeman term.
- ► A_m, and C_{mJ} is the coupling of J₂ with the magnetic field and the spin.
 ► A_m = 0

The topological transition mechanism A nanowire with generic disorder Phase Diagram with disorder

Topology through mode-mixing

- A $\pm m_J$ crossing is parabolic $\epsilon \sim k_z^2$.
- ▶ It can be shown that any mode-mixing term $M \sim \mathbb{I}, \sigma_z, \tau_z$:

 $\langle m_J | M | - m_J \rangle \sim \alpha k_z.$

▶ ⇒ mode-mixing acts as *p*-wave pairing between $m_J \leftrightarrow -m_J$ states.

Full-shell Majorana nanowires Disorder-induced mode-mixing: a new mechanism for topology The topological transition mechanism Topology through mode-mixing

- Bands have to cross at $k_z = 0$.
- Demonstration only requires diagonality in spin and electron-hole space.
- Actual size of the minigaps depend on the model.

Topology through mode-mixing

 A ±m_J crossing is parabolic ε ~ k_J².
 It can be shown that any mode-mixing term M ~ 1, σ₂, τ_j: (m_J/M|−m_j) ~ αk_j.
 ⇒ mode-mixing between m_J ↔ −m_J state

C. Payá et al. 2023, arXiv.

The topological transition mechanism A nanowire with generic disorder Phase Diagram with disorder

Shaping the wave-function with radial harmonics



Full-shell Majorana nanowires

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2024

- Disorder-induced mode-mixing: a new mechanism for topology
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Full-shell Majorana nanowires

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The topological transition mechan A nanowire with generic disorder Phase Diagram with disorder

Effects on the LDOS



- ► Unperturbated cylinder.
- ► No topological protection.

Full-shell Majorana nanowires Disorder-induced mode-mixing: a new mechanism for topology A nanowire with generic disorder Effects on the LDOS



Unperturbated cylinder.
 No topological protection

- m_J is tracked even if it's not well defined just by continuity of the CdGMs.
- Smooth model ensures non-divergent second derivative.
- Non-smooth model ensures only non-divergent first derivative.

C. Payá et al. 2023, arXiv.

The topological transition mechan A nanowire with generic disorder Phase Diagram with disorder

Effects on the LDOS



- \blacktriangleright Smooth distortion \sim defects in the nanowire profile.
- All m_J modes interact with each other, opening gaps at 0 energy or creating new MZM.
- ► Topology is now possible in all lobes, as it can origin from any *m*_J mode.

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> Topology is now possible in all lobes, as it can origin from any m, mod

- Smooth distortion external with such other scores in the numwire profile.
 All m. modes interact with such other scores interact of energy or crustion new
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The topological transition mechar A nanowire with generic disorder Phase Diagram with disorder

Effects on the LDOS



- \blacktriangleright Non-smooth distortion \sim defects in the nanowire profile + atomic size defects.
- ► Topological minigaps are larger because harmonic pre-factors can be larger.

C. Payá et al. 2023, arXiv.

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Full-shell Majorana nanowires Disorder-induced mode-mixing: a new mechanism for topology A nanowire with generic disorder Effects on the LDOS



Non-smooth distortion ~ defects in the nanowire profile + atomic size defects.
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The topological transition mechan A nanowire with generic disorder Phase Diagram with disorder

Effects on the LDOS



Full-shell Majorana nanowires Disorder-induced mode-mixing: a new mechanism for topology A nanowire with generic disorder Effects on the LDOS

• Remind MZM thickness is artificial.





The topological transition mechanis: A nanowire with generic disorder Phase Diagram with disorder

Tubular-core



$$(\mu_{m_J}-\mathcal{C}_{m_J})^2-(\mathcal{A}_{m_J}+V_Z)^2+\Delta^2=0 \xrightarrow[m_J=0]{} V_Z=\sqrt{\Delta^2+\mu_0^2}$$

► Valid for any disorder model.

C. Payá et al. 2023, arXiv.

Full-shell Majorana nanowires Disorder-induced mode-mixing: a new mechanism for topology Phase Diagram with disorder Tubular-core



Tubular-core

> Follows a simple distribution

Valid for any disorder model.

 $(\mu_{m_j} - C_{m_j})^2 - (A_{m_j} + V_Z)^2 + \Delta^2 = 0 \longrightarrow V_Z = \sqrt{\Delta^2 + \mu_0^2}$

- No need for islands. All CdGM crossings are now gapped.
- However, minigaps depend on the disorder model.

The topological transition mechanism A nanowire with generic disorder Phase Diagram with disorder

Solid-core



Full-shell Majorana nanowires Disorder-induced mode-mixing: a new mechanism for topology Phase Diagram with disorder Solid-core

- Even if there is topology in the second lobe, minigaps there are probably quite small.
- Advantage of mode-mixing: topology is not confined to a region of the phase-diagram.

Solid-core

Independent of the discutor mo

Disorder-induced mode-mixing: a new mechanism for topology Conclusions

Summary

Summary



8 88 8

Summary

$\gamma_1^A \gamma_1^B \gamma_j^A \gamma_j^B \gamma_{j+1}^A \gamma_{j+1}^B \gamma_N^A \gamma_N^B$

Summary

Summary



Full-shell Majorana nanowires 2024-01-10 -Conclusions —Summary



Summary

Summary



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Summary

Summary







Disorder-induced mode-mixing: a new mechanism for topology Conclusions

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Disorder-induced mode-mixing: a new mechanism for topology Conclusions

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Signals in the LDOS: CdGM analogs Disorder-induced mode-mixing: a new mechanism for topology Conclusions

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Full-shell Majorana nanowires 2024-01-10 -Conclusions -Summary L_Summary



Signals in the LDOS: CdGM analogs Disorder-induced mode-mixing: a new mechanism for topology Conclusions

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Full-shell Majorana nanowires 2024-01-10 -Conclusions -Summary L_Summary



Engeniering topologically protected edge states Signals in the LDOS: CdGM analogs Disorder-induced mode-mixing: a new mechanism for topology Conclusions

Summary

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Summary

Summary



Full-shell Majorana nanowires 2024-01-10 -Conclusions —Summary Summary



Summary Messages

Conclusions

- ► In pristine full-shell hybrid nanowires:
 - 1. Majorana zero modes appear at odd LP lobes coexist with CdGM analog states.

Full-shell Majorana nanowires

In pristine full-shell hybrid nanowires:
 I. Majorana zero modes appear at odd LP lobes consist with CdGM analog states

Conclusions

- 1. Majorana zero modes appear at odd LP lobes along CdGM analog states.
- 2. MZMs are generally topologically unprotected except for small islands in parameter space.
- 3. Tubular-core nanowires are a good experimental proposal for MZMs.
- 4. The solid-core phenomenology is more complex and depends on the radial modes.
- **5.** Mode-mixing induced by disorder behaves as an effective p-wave pairing.
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Full-shell Majorana nanowires

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Full-shell Majorana nanowires

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Full-shell Majorana nanowires

Conclusions

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Full-shell Majorana nanowires

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Full-shell Majorana nanowires Conclusions Messages Conclusions

- Conclusions

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Summary Messages

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Take home message

Majorana physics of full-shell nanowires is very rich. For pristine configurations, the tubular-core model is the optimal candidate but, in the presence of mode-mixing, half of the parameter space is suitable for topologically protected Majorana bound states.

Full-shell Majorana nanowires

home message ana physics of full-shall nanowires is very rich. For pristine configur

Conclusions

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Summary Messages Full-shell Majorana nanowires Conclusions Messages

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Full-shell Majorana nanowires

A theoretical description

Carlos Payá

Instituto de Ciencia de Materiales de Madrid (ICMM), CSIC

January 10, 2024





Cylindrical nanowire Mode-mixing

Hollow-core results



Full-shell Majorana nanowires Cylindrical nanowire Hollow-core Hollow-core results



Cylindrical nanowire Modified hollow-core

Modified hollow-core results



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Modified hollow-core results



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Cylindrical nanowire Mode-mixing Tubular-core

Destructive Litle-Parks

Full-shell Majorana nanowires Cylindrical nanowire Cylindrical nanowire Tubular-core Destructive Litle-Parks

Destructive Litle-Parks





C. Payá et al. 2023, arXiv.

Mode-mixing A hexagonal nanowire

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Hexagonal wave-function



- New red stripes. Hexagon has $\ell = 6$.
- Upper stripe: $m_J = 0$ mixes with $m_J = \pm 6$.
- Lower stripe: $m_J = 3$ mixes with $m_J = -3$.
- ► The MZM coming from m_J = ±3 cannot interact with m_J = 0 ⇒ they overlap.
- The $m_J = \pm 6$ MZM annihilates the $m_J = 0$ MZM.
 - C. Payá et al. 2023, arXiv.

• $m_J \neq 0$ stripes are just a continuation of $m_J = 0$ (difficult to see in just one slide).

Hexagonal wave-function

New red stripes. Hexagon has l =
 Upper stripe: m_l = 0 mixes with

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The $m_J = \pm 6$ MZM annihilates the $m_J = 0$ MZM.

 $m_J = \pm 6.$

• In blue, original $m_J = 0$ PD border.

Hexagonal wave-function

Full-shell Majorana nanowires

A hexagonal nanowire

-Mode-mixing

10

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2024



Hexagonal wave-function



Except for the new topological stripes and a region where the MZM splits, the system is equivalent to the cylinder.

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Carlos Payá Full-shell Majorana nanowires

Full-shell Majorana nanowires Hode-mixing A hexagonal nanowire Hexagonal wave-function



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Full-shell Majorana nanowires ⁰⁷ - Mode-mixing ¹⁰ - A hexagonal nanowire



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