



M2 internship proposal

Chiral Majorana modes in graphene and TMD multilayers

Context:

Topological quantum matter hosts exotic excitations, ranging from fractionally charged anyons to Majorana modes with non-Abelian exchange statistics [1-4]. The latter allow to store and manipulate quantum information non-locally, in a way that is inherently protected against local sources of noise and decoherence.

This idea has motivated numerous theoretical proposals for creating, manipulating, and detecting Majorana zero modes in hybrid nanowires [5-7], and experiments have reported signatures across a variety of platforms [8-13]. However, interpreting the experimental data remains subtle and controversial, as most observations admit alternative explanations [14-18]. Moreover, most current approaches rely on zero-dimensional (0D) Majorana modes localized at the ends of topological superconducting wires, which act as stationary qubits. Consequently, this architecture faces major challenges for scalable quantum operations based on Majorana manipulation.

Meanwhile, an emerging class of atomically thin, layered materials offers the prospect of one-dimensional (1D) chiral Majorana modes that can be manipulated dynamically. This opens new possibilities for engineering topological quantum phases and studying the special electronic states that emerge at their boundaries.

Graphene multilayers are a particularly interesting example. Depending on the layer stacking and charge-carrier density, they can display quantum anomalous Hall (QAH) states [19-21], correlated insulating phases, and unconventional superconductivity. The coexistence of QAH, topological, and superconducting phases makes them a promising setting to study and control emergent non-Abelian excitations. Another interesting platform is transition-metal dichalcogenide (TMD) multilayers. Their strong spin-orbit coupling can open topological gaps [22-23] and stabilize superconductivity against in-plane magnetic fields well beyond the Pauli (paramagnetic) limit [24-26].

In this internship, motivated by recent experiments on graphene and TMD multilayers, we will theoretically investigate 2D multilayers that could host chiral Majorana modes. We will also study the creation of Majorana wave packets and their time-dependent propagation and manipulation.

The project will involve analytical modeling and numerical calculations, with the possibility of connecting theoretical predictions directly to experimentally realizable systems (in collaboration with our colleagues at SPEC/CEA). It will provide an opportunity to learn about topological phases of matter, quantum materials, using numerical and analytical methods while working on a problem at the interface of fundamental condensed matter physics and emerging quantum technologies.

Project goals:

- Develop expertise on topological phases of matter and their unique edge states.
- Understand which experimental signatures reveal their presence
- Propose experimental platforms to create and control these phases.
- Identify and analyze realistic experimental setups which might degrade their protection.

Environment: The project will take place at SPMS lab at CentraleSupélec and will be supervised by Dganit MEIDAN

Extension: There is a possibility to extend this project to a doctorate thesis ([funding secured](#)).

Contact: Interested candidates can send a CV, and motivation letter to:
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Keywords: Topological quantum matter, Quantum Hall effect, Superconductivity, Twisted bi-layer graphene.

Skills: A solid background in quantum mechanics and condensed-matter physics, including basic knowledge of band theory, tight-binding models, and second quantization. Familiarity with superconductivity, BCS/Bogoliubov–de Gennes, topological phases and bulk–boundary correspondence is desirable. Experience with numerical calculations and scientific programming in Python. Knowledge of linear-response theory and the Kubo formalism is an advantage.

References:

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| [1] N. Read et al., PRB 61, 10267 (2000). | [20] J. Xie et al., Nature Materials 24, 1042 (2025). |
| [2] D. A. Ivanov, PRL 86, 268 (2001). | [21] Y. Choi et al., Nature 639, 342 (2025). |
| [3] A. Y. Kitaev, Physics-Uspekhi 44, 131 (2001). | [22] S. Tang et al., Nat. Phys. 13, 683 (2017). |
| [4] C. Nayak et al., RMP 80, 1083 (2008). | [23] X. Qian et al., Science 346, 1344 (2014). |
| [5] L. Fu et al., PRL 100, 096407 (2008). | [24] J. M. Lu et al., Science 350, 1353 (2015). |
| [6] R. M. Lutchyn et al., PRL 105, 077001 (2010). | [25] Y. Saito et al., Nat. Phys. 12, 144 (2016). |
| [7] Y. Oreg et al., PRL 105, 177002 (2010). | [26] X. Xi et al., Nat. Phys. 12, 139 (2016). |
| [8] V. Mourik et al., Science 336, 1003 (2012). | |
| [9] A. Das et al., Nat. Phys. 8, 887(2012). | |
| [10] L. P. Rokhinson et al., Nat. Phys. 8, 795 (2012). | |
| [11] M. T. Deng et al., Nano Lett. 12, 6414 (2012). | |
| [12] S. Nadj-Perge et al., Science 346, 602 (2014). | |
| [13] T. Machida et al., Nat. Mater. 18, 811 (2019). | |
| [14] J. Liu et al., PRL 109, 267002 (2012). | |
| [15] D. I. Pikulin et al., NJP 14, 125011 (2012). | |
| [16] D. Bagrets et al., PRL 109, 227005 (2012). | |
| [17] G. Kells et al., PRB 85, 060507 (2012). | |
| [18] G. Kells et al., PRB 86, 100503 (2012). | |
| [19] Z. Lu et al., Nature 626, 759 (2024). | |