



M1 OR M2 RESEARCH INTERNSHIP, PREDOCTORAL PLACEMENT, PHD

Mathematics of Majorana fermions

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Fields : mathematical physics, functional analysis, spectral theory, numerical simulations, condensed matter, topological physics. Theoretical and/or numerical approach

Dates : second semester of the 2026/2027 academic year; PhD starting in September 2027 or September 2028

Location : Analysis, Geometry and Modelling mathematics laboratory, CY Cergy Paris Université, 2 avenue Adolphe Chauvin, 95300 Pontoise, France. Remote work is possible

Project : how can quantum information be preserved in a system with thermal excitations? In certain fermionic chains, Majorana modes localized at the ends provide boundary degrees of freedom that can retain information for very long times. The internship will investigate the mathematical mechanisms underlying this dynamical stability at nonzero temperature, through the study of strong zero modes and their prethermal counterparts [1, 2].

For a Hamiltonian H of a chain of length L , with fermion parity P , a strong zero mode is an operator Γ localized near a boundary and satisfying

$$\Gamma^* = \Gamma, \quad \Gamma^2 = 1, \quad \Gamma P + P\Gamma = 0, \quad \|[H, \Gamma]\| \leq C e^{-L/\xi},$$

where C and ξ are independent of L . These relations imply a pairing of the spectra in opposite parity sectors and the approximate conservation of Γ over times exponentially long in L , including for excited states [1]. Such a bound is not automatic in the presence of perturbations. A prethermal regime may nevertheless persist: a sufficient separation of energy scales then allows one to construct a boundary operator that is approximately conserved for a very long time, controlled by the ratio of these scales [2]. These mechanisms have recently been studied at interfaces between chains [3] and illustrated by simulations on quantum processors [4].

The starting point will be the explicit construction of a boundary mode in the Kitaev chain, followed by the introduction of a weak nearest-neighbour interaction preserving fermion parity. The goal will be to correct the boundary operator using a perturbative expansion, estimate the norm of the residual commutator, and identify resonances that may limit its conservation. For an approximate operator Γ_{app} , a bound $\|[H, \Gamma_{\text{app}}]\| \leq \varepsilon$ directly yields $\|\Gamma_{\text{app}}(t) - \Gamma_{\text{app}}\| \leq |t|\varepsilon$ (in units with $\hbar = 1$), providing a link between

the spectral construction and dynamical stability. Depending on progress, boundary autocorrelations at nonzero temperature, including infinite temperature, will also be studied.

The internship will combine reading research papers, the algebra of fermionic operators, perturbation theory and operator norm estimates. Numerical calculations on small chains may complement the analysis. The research objective is to obtain, for a specified perturbation and parameter regime, a controlled construction of an approximate boundary mode and a bound on its conservation time. The study will focus on isolated systems; conservation of a boundary observable alone does not guarantee complete protection of a qubit coupled to an environment.

Mathematical physics : mathematical physics is a branch of mathematics whose primary aim is to make results from the physics literature mathematically rigorous, in the form of proved theorems. Generalization and rigor also regularly lead to new results. Articles are written in the form of definitions, theorems and proofs, and are most often published in mathematics journals.

PhD : a PhD could be started after the internship.

REFERENCES

- [1] P. Fendley, Strong zero modes and eigenstate phase transitions in the XYZ/interacting Majorana chain, *Journal of Physics A: Mathematical and Theoretical* **49**, 30LT01 (2016). doi:10.1088/1751-8113/49/30/30LT01.
- [2] D. V. Else, P. Fendley, J. Kemp and C. Nayak, Prethermal Strong Zero Modes and Topological Qubits, *Physical Review X* **7**, 041062 (2017). doi:10.1103/PhysRevX.7.041062.
- [3] C. T. Olund, N. Y. Yao and J. Kemp, Boundary strong zero modes, *Physical Review B* **111**, L201114 (2025). doi:10.1103/PhysRevB.111.L201114.
- [4] F. Jin, S. Jiang, X. Zhu et al., Topological prethermal strong zero modes on superconducting processors, *Nature* **645**, 626–632 (2025). doi:10.1038/s41586-025-09476-z.