INTEGRATING MICROMAGNETS AND HYBRID NANOWIRES IN MAJORANA FERMION EXPERIMENTS

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INTRODUCTION

We propose using nanoscale magnets in solid state Majorana Fermion systems to provide a controllable magnetic field. These devices generate stray field patterns suitable for the generation of Majorana zero modes.

BACKGROUND

- Majorana zero modes could be utilized in quantum computing applications
- Majoranas appear in solid state systems as non-abelian quasiparticle states that are their own anti-particle
- They are hypothesized to be seen in semiconductor-superconductor hybrid systems under magnetic fields. Experiments use semiconductor nanowires with strong spin-orbit coupling and are coated with superconducting shells
- Much work has been done in searching for Majoranas in solid state systems, but conclusive evidence has yet to be found. Further experimental design and material advancement is required
- A magnetic field is required to drive the topological transition. Nanoscale control over the field magnitude and direction is advantageous, particularly for advanced geometries
- Micromagnets could offer nanoscale control of magnetic field and allow a topological superconducting state allowing partial Majorana separation

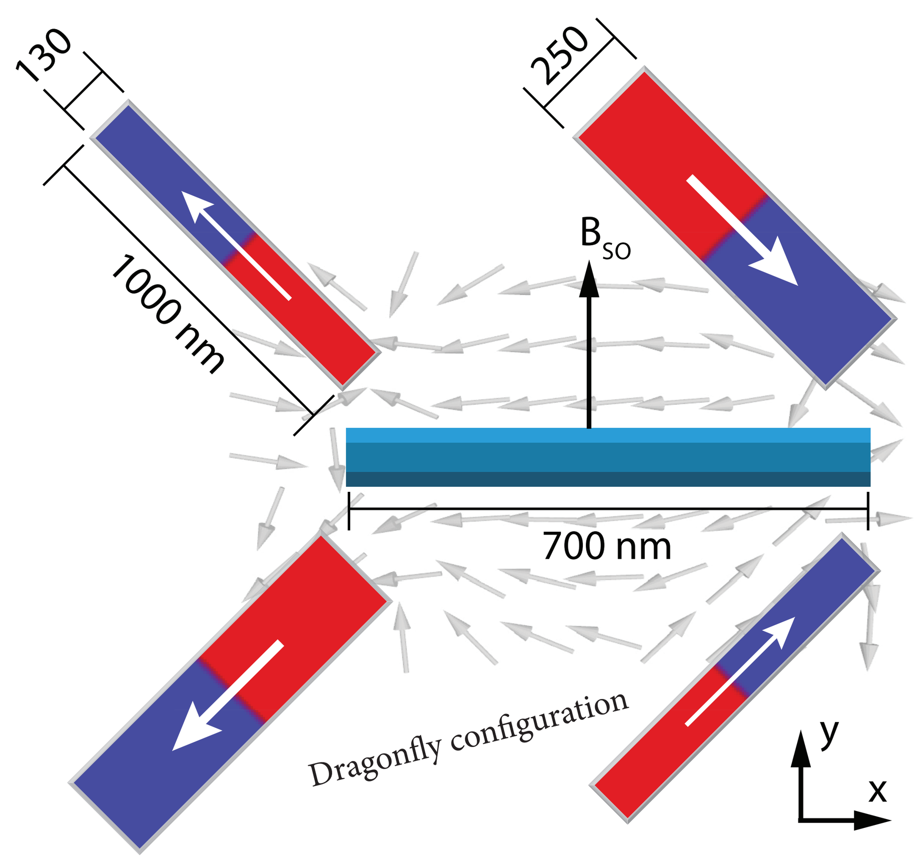
METHODS

The bespoke micromagnetic simulation software MuMax3 was used for accurate magnetic field and hysteresis calculations. The 3D magnetic field profiles were then integrated over the nanowire cross-section and input into a standard Lutchyn-Oreg Majorana model on a 1D lattice to perform Majorana simulations where the Majorana wavefunctions and spectra were extracted.

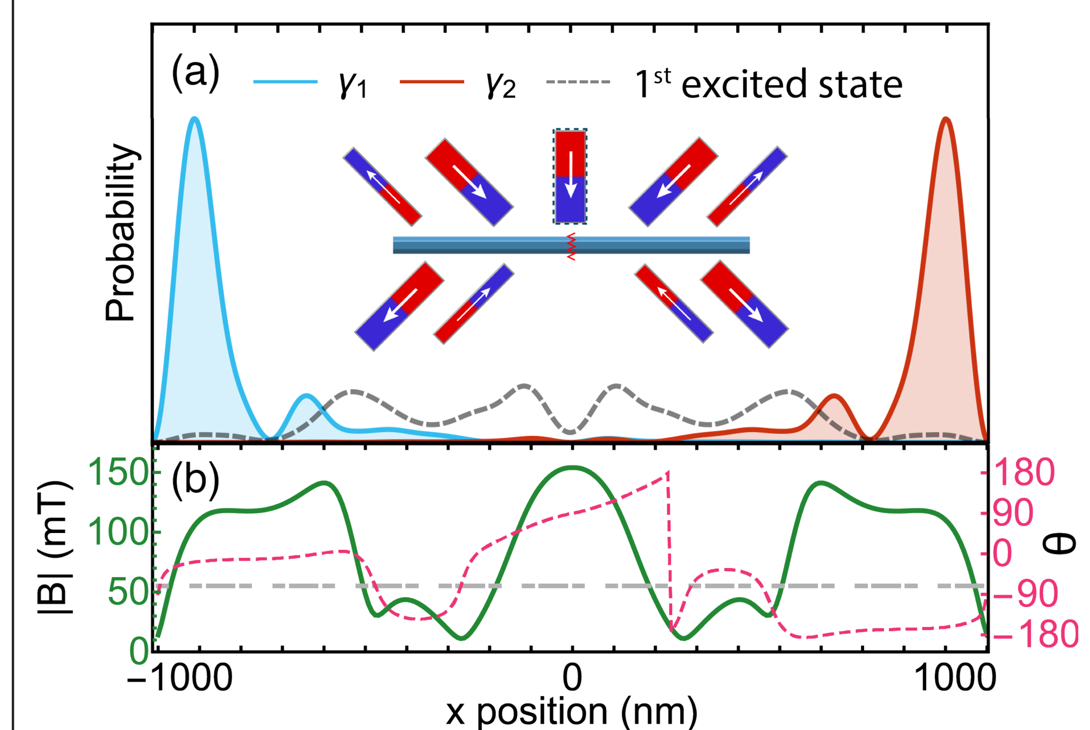
Micromagnets in Mumax3 → Majorana nanowire model → Majorana signatures

RESULTS

Micromagnets could offer novel ways to produce and control Majorana-based devices. This was shown via magnetic field simulations integrated with a 1D Majorana Schrödinger model demonstrating Majorana signatures.

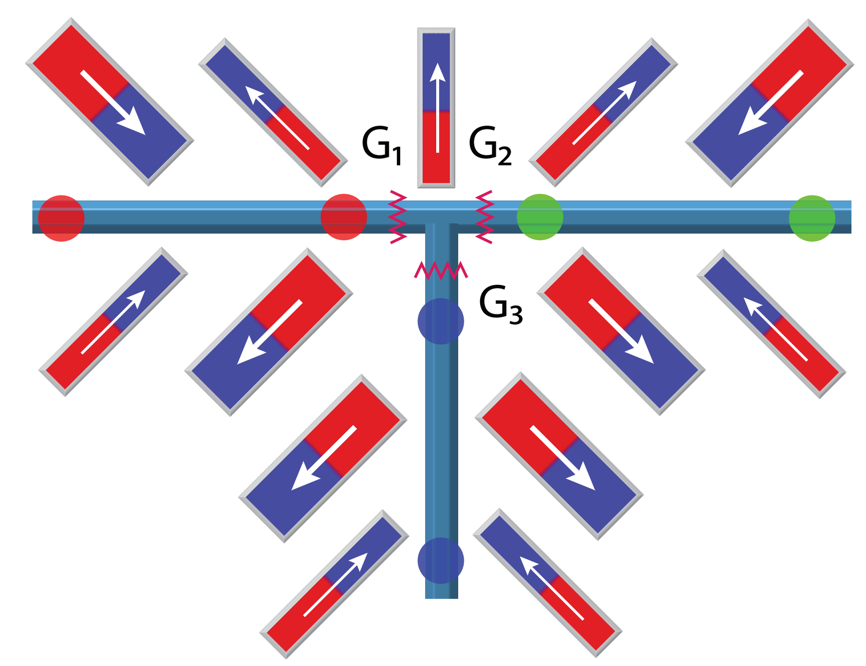


The basic building block of the Dragonfly (left) has four micromagnets arranged around the nanowire such that field lines flow along the 700 nm wire, with field lines shown as gray arrows. The spin-orbit axis is indicated by B_{so}. The magnet configuration was designed via hysteresis simulation.

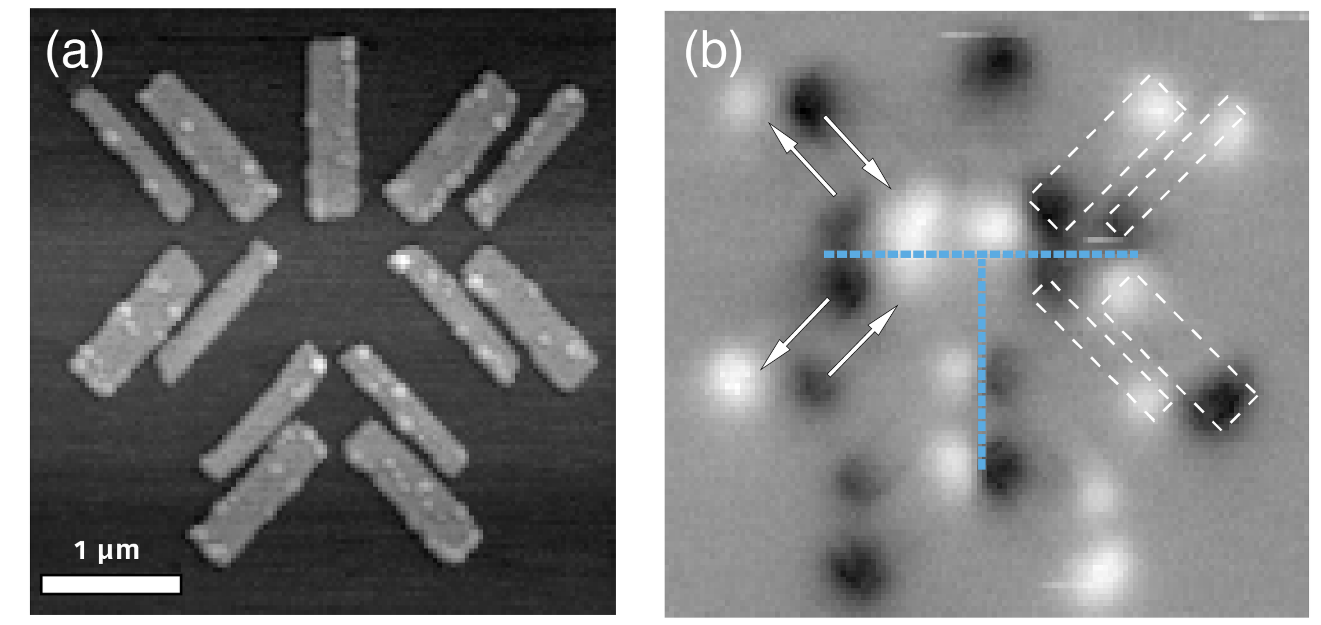


In (a) Majorana wavefunctions, γ_1 and γ_2, are at the ends of a 2000nm nanowire. These were realized using the stray field in (b) (which plots the magnitude and angle relative to wire) that was produced by the configuration in the inset. This demonstrates that combining units to form longer topological nanowire is possible.

A junction setup for braiding Majoranas is shown and a similar setup was simulated. Coloured circles represent pairs of Majorana zero modes and red zig-zags represent barriers. This design was experimentally made and tested, shown at top right of poster.



EXPERIMENTAL TEST



(a) Atomic force microscopy of a junction setup with 20 nm-thick magnets.
(b) Magnetic force microscopy data on a different device where arrows indicate the magnetization direction, white dashed lines are representative magnet dimensions, and blue dashed line is where the Majorana nanowire is envisioned.

LIMITATIONS/ FUTURE WORK

- Limited strength of stray fields from micromagnets. Previous experiments have typical stray fields ~ tens of milliTesla. Stronger magnetic materials or thicker micromagnets could help.
- Difficulty preparing all micromagnets in the appropriate relative magnetic orientation. Although basic two-Majorana experiments should be possible already, in the future better control over coercive fields, further pattern optimization, and direct magnetic writing can be deployed.
- Material of the nanowire, leads, and other components were not considered in these simulations, but the main magnetic effects are presumed to come from the magnets themselves.
- Using a Y-junction, instead of a T-junction, may require fewer micromagnets
- Rather than gate-controlled Majorana coupling, magnetic field mediated coupling can be investigated by flipping micromagnets at the junctions.
- The implementation of the Poisson-Schrödinger equation for the 3D geometry of a single nanowire could be integrated with 3D stray field profiles.

CONCLUSION

We considered device concepts in which micromagnets generate stray field patterns suitable for the generation of Majorana zero modes.

Micromagnets could offer novel ways to control Majorana-based devices, particularly for advanced geometries where some nanowire segments may run perpendicular to others.

Link to accompanying paper
https://arxiv.org/abs/2104.05130