Majorana Bound States in 3D-TI Josephson Junctions

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What are Majorana Bound States?

- Majorana Bound States (MBS) are non-abelian quasi-particles.
- MBSs form in three-dimensional topological insulator (3D-TI) nanowire Josephson Junctions (JJ).
- Formed from superposing particle and hole wave functions with zero energy.

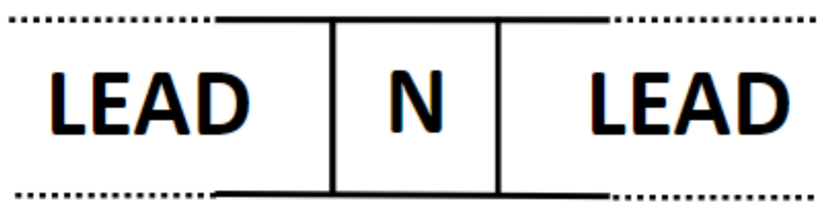

Fig 1. Nanowire setup, where N represents the normal region composed of 3D-TI. Leads are superconductors [1].

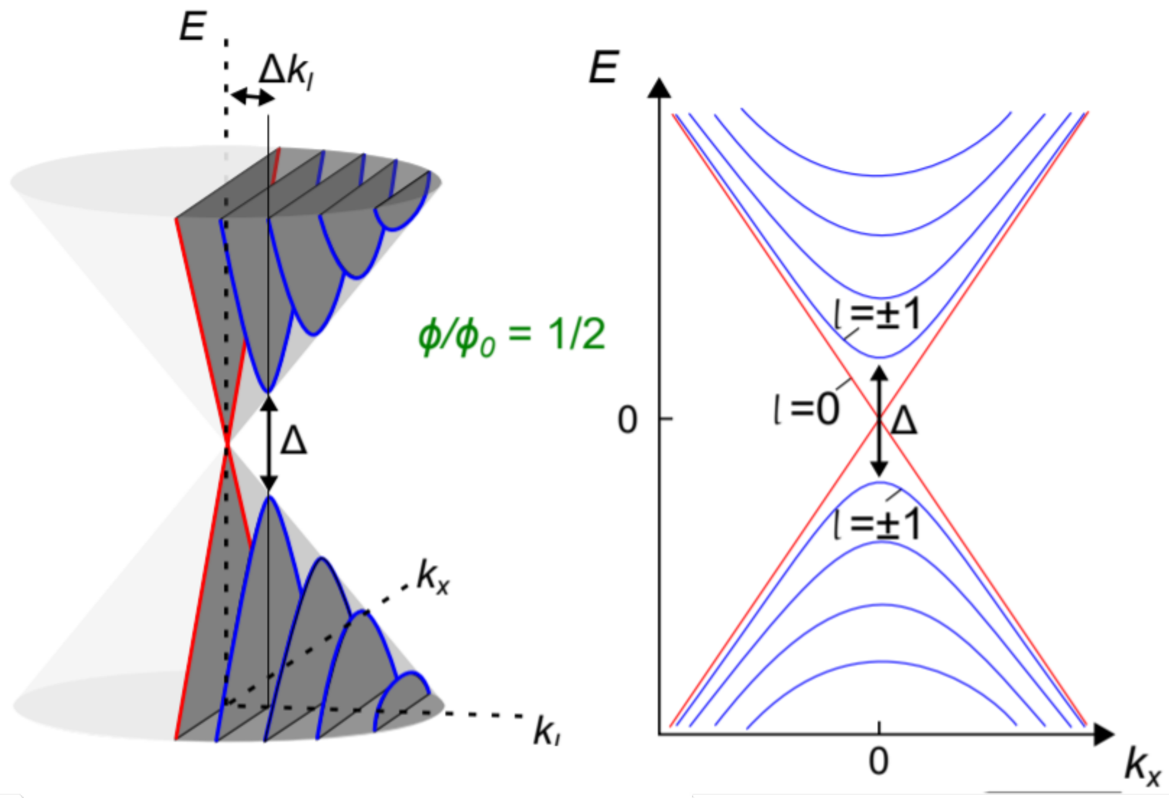

Fig 2. Left - Diagram of the Dirac cone showing the dispersion relation in the TI nanowire. Right – overlap of all possible bands [1].

Methodology

Scattering matrix formalism

We represent the scattering of N incident (I) and N emitted (E) modes with an $S_{N\times N}$ matrix:

$$\psi^{(E)} = S_{N\times N}(E)\psi^{(I)},$$

where S is a function of the energy of the incoming modes [2].

Calibration of matrix

Time reversal symmetry (TRS) must be maintained, the scattering matrix must also be unitary. This leads to:

$$S + S^T = 0,$$

Calibration ensures this condition is followed.

Beenakker equation

We denote the scattering matrix due to reflection and scattering region as S_A and S_N.

At the interface, the continuity condition leads to:

$$\det[I - S_A S_N] = 0.$$

This can be solved for the energies of the bound states [2].

Results

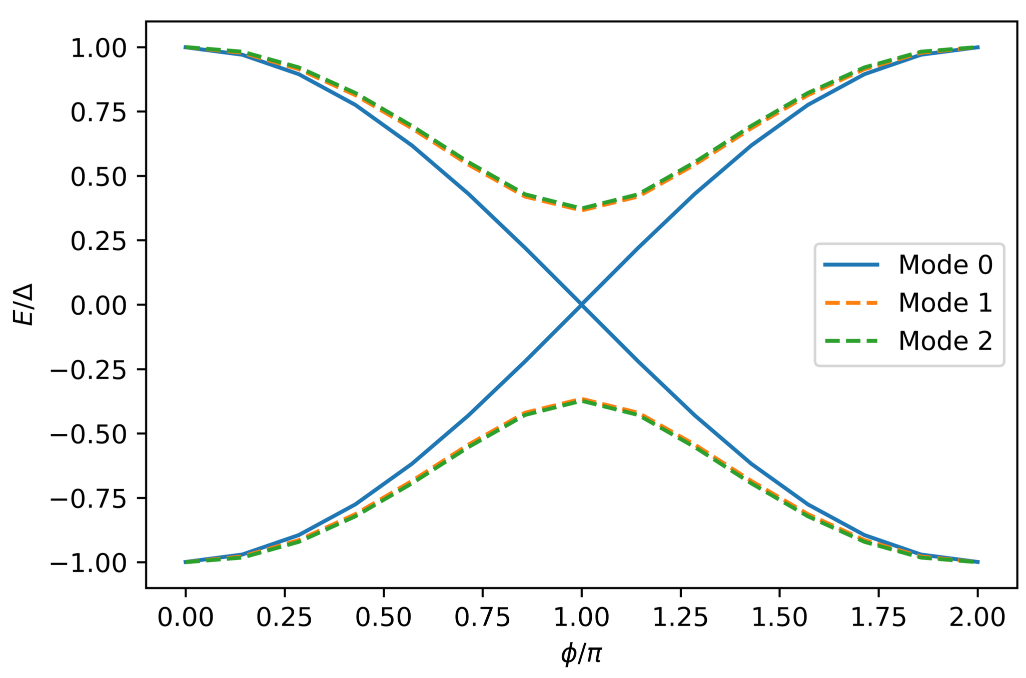

Fig. 3. Andreev bound states spectrum with disorder applied, plotting energy as a function of phase difference.

- As expected, adding disorder to the system causes bound state modes to gap out.
- The Majorana mode is topologically protected and is not affected by the disorder.

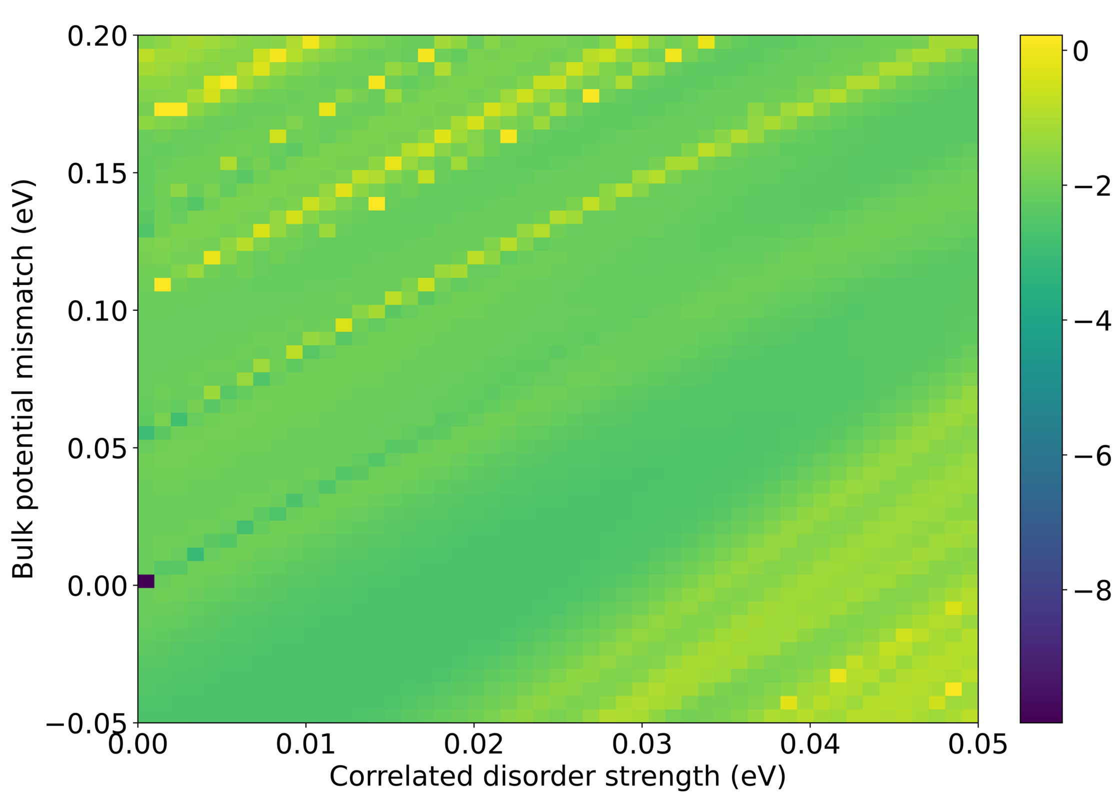

Fig. 4. Displaying log of maximum value of $S + S^T$ for varying disorders and mismatches.

- Deviations from TRS equation generally of order of magnitude of 10^{-3}.
- We observe patterns of anomalous points, breaking TRS condition by order of magnitude of 1.

Conclusion and Further Work

So far, we concluded:

- We can calibrate the scattering matrix to maintain TRS.
- Anomalous points appear for certain disorders and mismatches where TRS is not well preserved.

Next steps...

- Investigate the energy transitions between different bound states.
- Explore anomalous TRS breaking points.
- Optimise parameters of the system to ensure TRS is maintained.

References

[1] D. Rosenbach, K. Moors, A. R. Jalil, J. Kölzer, E. Zimmermann, J. Schubert, S. Karimzadah, G. Mussler, P. Schüffelgen, D. Grützmacher, H. Lüth, and T. Schäpers, "Gate-induced decoupling of surface and bulk state properties in selectively-deposited bi2te3 nanoribbons," 2022

[2] C. W. J. Beenakker, "Universal limit of critical-current fluctuations in mesoscopic josephson junctions," Phys. Rev. Lett., vol. 67, pp. 3836–3839, Dec 1991. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.67.3836