Multiple-Nanowire Superconducting Quantum Interference Devices: Symmetries, Vorticity Stability Regions, and Diode Effect

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INTRODUCTION

- Traditional Superconducting Quantum Interference Devices (SQUIDs) use 2 parallel Josephson Junctions (sinusoidal CPR)
- We generalize to Multiple-Wire SQUIDs (MW-SQUIDs) with N parallel nanowires (linear CPR)
- We define and study Vorticity Stability Regions (VSR) geometries
- Result: Identify symmetries, superconducting diode effects, generalized Little-Parks, and Disjoint VSRs

DEVICE

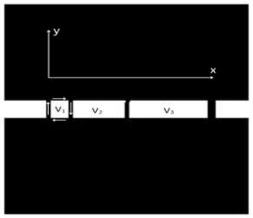


Fig. 1. Example 4 superconducting nanowire device with vorticity state v_i

THEORY

Phase Difference

$$\phi_i = \phi_j + 2\pi b\left(x_i - x_j\right) - 2\pi v_{i,j} \quad (1)$$

b: normalized magnetic field
$v_{i,j}$: # of vortices between i-th & j-th nanowire

1-D Weak link Current-Phase relationship

$$j_i = j_{c,i}\frac{\phi_i}{\phi_{c,i}} \quad (2)$$

ϕ_i = phase difference on i-th nanowire
$\phi_{c,i}$ = critical phase difference for i-th nanowire

WHAT IS A VORTICITY STABILITY REGION?

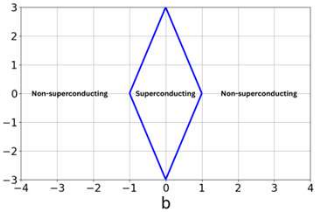


Fig. 2. Example VSR for 3 identical nanowire SQUID

EXAMPLE VORTICITY STABILITY REGIONS (VSR)

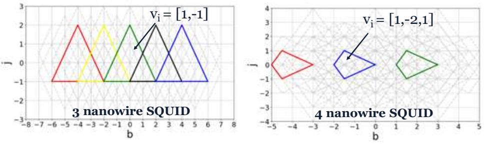


Fig. 3. Non-zero vortex distributions produce complicated VSRs

PARITY AND TIME SYMMETRIES

Parity-Symmetric Device
→ Current-Symmetric VSR

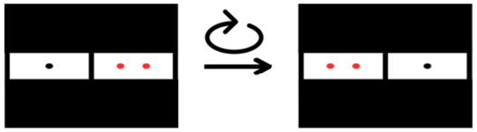


Fig. 4. Parity (P) Transformation

Parity-Time-Symmetric Device
→ Magnetic-Symmetric VSR

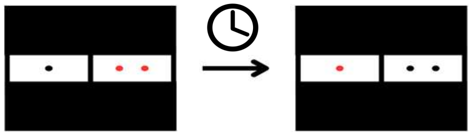


Fig. 5. Time (T) Inversion

DEVICE SYMMETRY

Device's Intrinsic Symmetry
≅ Charge-Parity-Time (CPT) Symmetry

Or:

The device's symmetry is mathematically equivalent to CPT symmetry

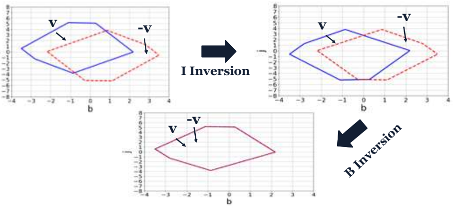


Fig. 6. IBV Symmetry ←→ Device's Intrinsic Symmetry

SUPERCONDUCTING DIODE EFFECT (SDE)

Breaking Time & Parity Symmetry
→ Superconducting Diode Effect

This means…
1.) Vortices must be present
2.) Vorticity array cannot be parity-symmetric

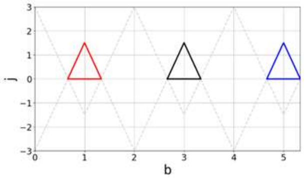
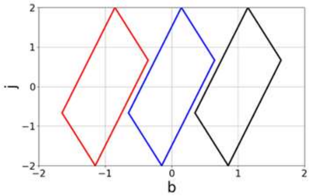


Fig. 7. SDE Ex 1: Perfect Superconducting Diode

Fig. 8. SDE Ex 2: Supercurrent Range Controller



OTHER RESULTS

Different Sized Vorticity Loops
→ Device Periodicity Change

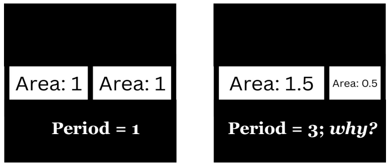


Fig. 9. "Generalized Little Parks Effect"
←→ Synchronized Meissner Currents

Short Nanowires
→ Topologically Disjoint VSRs

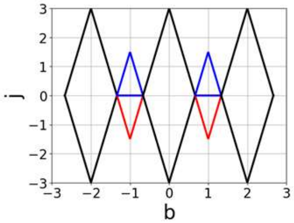


Fig. 10. Disjoint VSRs with 3 nanowire SQUID

Note: can observe quantum phase transitions

KEY TAKEAWAYS

- Realized new Vorticity Stability Region (VSR) geometries
- Connected device parity-time & parity symmetries to current & magnetic symmetries
- Derived Superconducting Diode Effect (SDE) via broken time & parity symmetry
- Found application in perfect diodes and supercurrent range controllers
- Identified topologically disjoint VSRs
  → quantum phase transitions
- Analytically generalized Little Parks Effect to the case of more than 2 weak links
- Proved device intrinsic symmetry is isomorphic to Charge-Parity-Time symmetry

FUTURE WORK

On-going work to develop nanowire qubits and symmetry-protected superconducting memory elements

PUBLICATIONS

[1] Sun C., Bezryadin A. (2025) Multiple Nanowire Superconducting Quantum Interference Devices: Critical Currents, Symmetries, and Vorticity Stability Regions, Nano Express

[2] Sun C., Zhao Z., Bezryadin A. (2025) Perfect Superconducting Diode and Supercurrent Range Controller, Physics Letters A

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