Probing Synthetic CdGM States Through Critical Current in Full-Shell Nanowire Josephson Junctions

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TL;DR

A full-shell nanowire in an axial field is a synthetic Abrikosov vortex. Microscopic theory predicts that its CdGM analogs, bound at a radius smaller than the shell's, skew the critical current within every non-zero fluxoid lobe. We observe that effect experimentally.

The experiment — arXiv:2607.18371

The theory — PRB **111**, 235420 (2025)

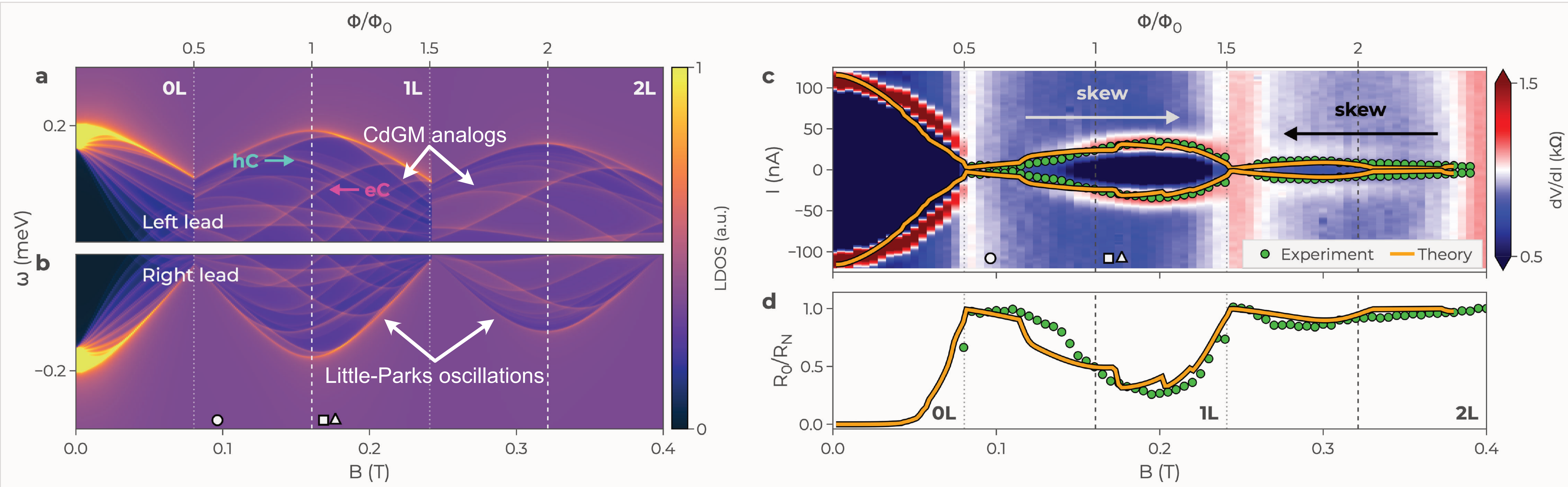

Fig. 1 — **Critical current skewness caused by CdGM analogs.** Local density of states (LDOS) at the end of a semi-infinite full-shell nanowire on the (a) left and (b) right side of the junction, versus magnetic field B (normalized flux Φ/Φ_0) and energy ω. The shell gap edge is modulated into LP lobes; inside, CdGM analogs disperse with flux, exhibiting a distinct skewness. Depending on their dominant character, they are either electron-like (eC), with a generally positive slope, or hole-like (hC), with a generally negative slope. (c) Differential resistance dV/dI versus applied current and axial field, showing a traceable LP modulation and skewness in the n ≠ 0 lobes. Green dots are the extracted critical current, the orange line the value simulated with the wires in (a, b). (d) Zero-current resistance R_0 normalized to the normal resistance R_N, same device following the same skewness pattern, in accordance with the simulation (orange line). These results are qualitatively reproduced across different devices.

1 A vortex you can actually resolve

Caroli-de Gennes-Matricon (CdGM) states fill the core of an Abrikosov vortex in a type-II superconductor. Their level spacing is a tiny fraction of the gap, so in a bulk superconductor they blur into a continuum, rendering them notoriously difficult to resolve and only in a few materials.

A full-shell nanowire (semiconductor nanowire fully wrapped in a superconductor) in an axial magnetic field is a synthetic vortex whose CdGM analogs are spaced on the order of the gap. Tunneling spectroscopy has already seen them [2]. A characteristic fingerprint has been predicted in the critical current of a Josephson junction [3].

2 CdGM analogs enclose less flux than the shell

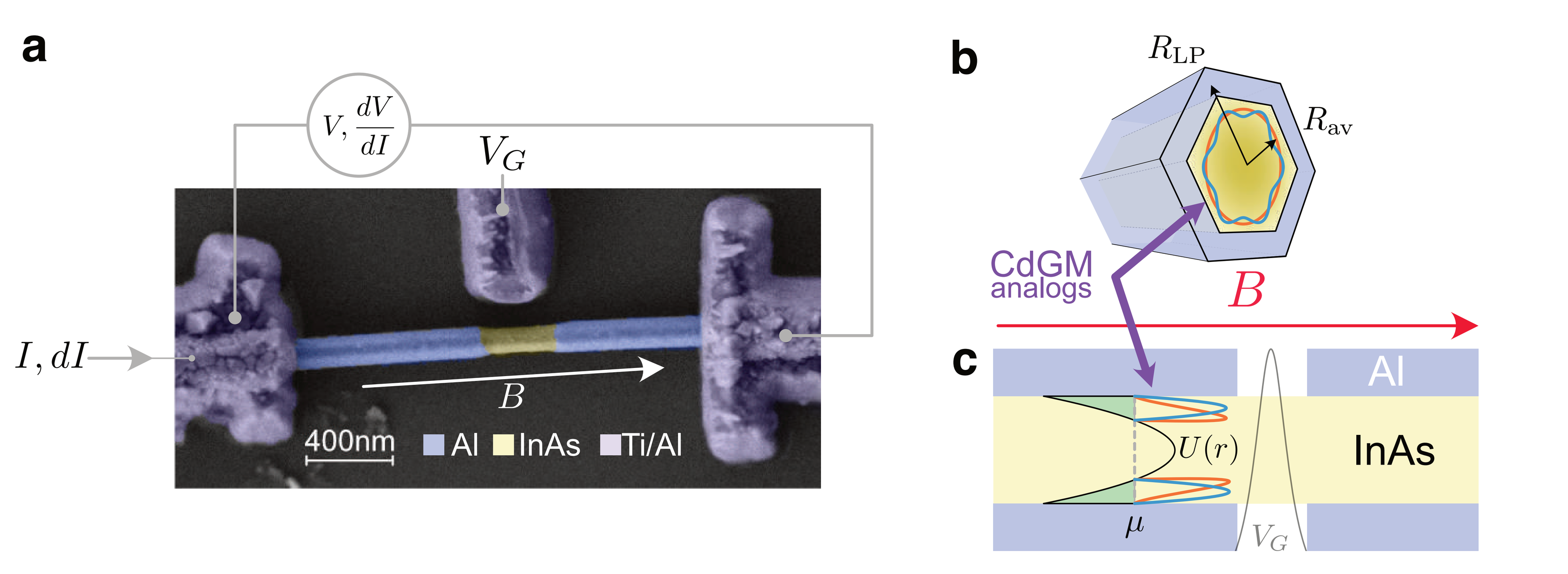

Fig. 2 — **Full-shell nanowire Josephson junction.** (a) Micrograph of the device and schematic of the measurement circuit; V_G controls the transparency of the junction. (b) Cross-section of a full-shell nanowire, with CdGM analogs localized at a radius R_{av} smaller than the shell radius, R_{av}~0.6 R_{LP}. (c) Schematic of the Josephson junction.

- Doubly-connected shell: quantized fluxoid + Little-Parks gap modulation with magnetic flux.
- Material mismatch: radial potential U(r) confines CdGM analogs close to the InAs/Al interface => different flux enclosed => mismatch in the Little-Parks period.
- The junction is overdamped, so dV/dI peaks at the critical current and zero-current resistance follows it.

3 0- and π-junctions from CdGM analogs

- Except for 0L (protected by symmetry), the critical current is skewed towards high fields (1L) or low fields (2L). Same behavior reproduced by zero-current resistance.
- CdGMs with negative mass (hC) => 0-junctions. Possitive mass (eC) => π-junctions.
- Zero-energy crossing => character switch => 0- to π-junction.
- This way, the skewness of the CdGMs, each with its own Little-Parks period, is transmitted to the critical current.

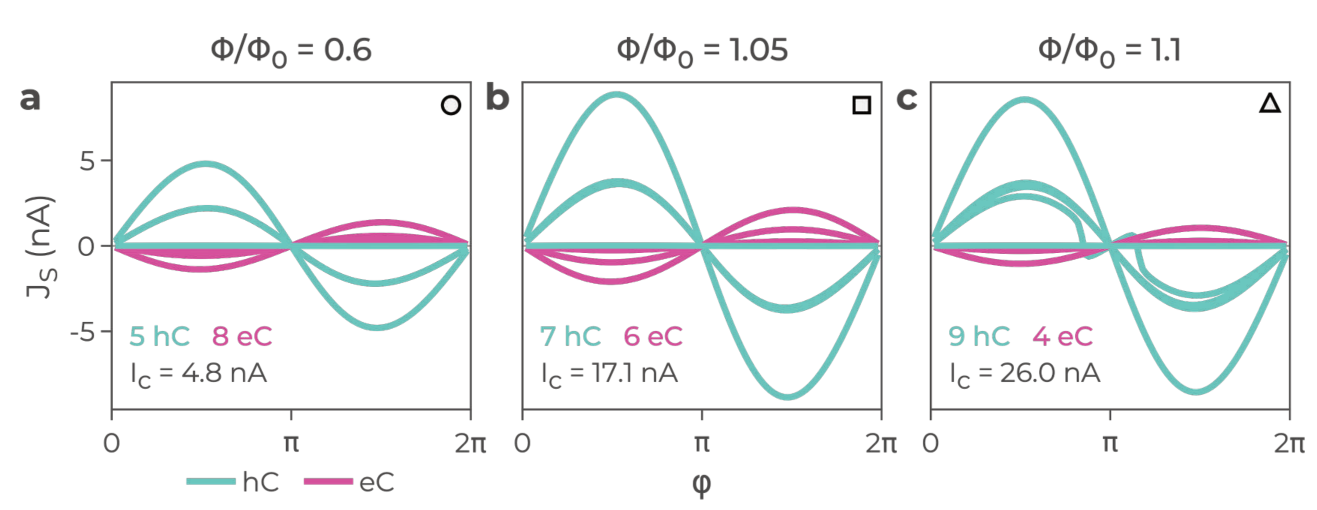

Fig. 3 — **Skewness from the current-phase relation (CPR).** Josephson current J_S vs phase difference between the leads of the junction for the three fluxes indicated in Fig. 1 for each CdGM channel. The contribution of 0-junction (arising from hC CdGMs) and π-junction (arising from eC CdGMs) CPRs determines the flux-dependent critical current. The number of involved hC and eC CdGMS is indicated in each panel. (b,c) bracket a CdGM crossing zero energy.

4 Learning about the core from the current

- A single set of parameters fits the full field range.
- The skewness depends on the filling of CdGMs and their radial localization.
- Microscopic details of the core are revealed in the structure of the critical current.

KEY TAKEAWAY

The critical current reflects the number and character of CdGM analogs. Each one that crosses zero energy flips a 0-junction into a π-junction. The running total is what skews the supercurrent, reading the interior of the nanowire core.

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References. [1] C. Payá *et al.*, arXiv:2607.18371 (2026). [2] M. Deng *et al.*, *Phys. Rev. Lett.* **134**, 206302 (2025). [3] C. Payá *et al.*, *Physical Review B* **111**, 235420 (2025).

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