Josephson Diode Effect in one dimensional Josephson junctions

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Reference - A. Soori, J. Phys.:Condens. Matter 37, 10LT02 (2025)

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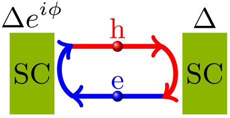
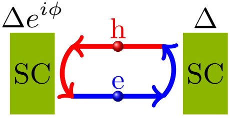
Josephson Effect and Current-Phase Relation (CPR)

- When phases of the pairing amplitudes of two superconductors are different, a junction between the two carries current - Josephson effect.
- The current depends on the phase difference between the SCs, defined by the **Current-Phase Relation (CPR)**.
- Consider SNS junctions.



(a)



(b)

- Weights of processes carrying currents in forward and backward directions are different under a phase bias $\rightarrow$ Josephson effect.

Josephson Diode Effect (JDE)

- The **Josephson Diode Effect (JDE)** refers to unequal magnitudes of the maximum and minimum supercurrents in CPR.
- Time reversal and inversion need to be broken.
- Band asymmetry can result in JDE [JPCM 36, 335303 (2024)].
- JDE is rooted in **magnetochiral anisotropy**, in systems with SOC and Zeeman fields.
- Studies have mostly focused on two-dimensional systems with SOC and an applied Zeeman field.
- In purely 1D, SNS junctions do not show JDE unless (singlet) superconductor also has SOC.

Triplet Pairing

- Josephson junctions involving **triplet superconductors** with ferromagnetic materials exhibit the **anomalous Josephson effect (AJE)**.
- Does JDE show up in 1D Josephson junctions with SCs having triplet pairing along with singlet pairing?
- We find that in SCs with mixed singlet-triplet pairing, both JDE and AJE are observed, which would otherwise be absent in purely singlet SCs.
- The system is mixed SC-quantum wire-mixed SC, where quantum wire has SOC and Zeeman field parallel to one another.

Current-Phase Relationship (CPR)

- Parameters: $\mu_s = \mu_0 = -1.875t$, $\alpha = 0.05t$, $\Delta_s = 0.0125t$, $b = 0.015t$, $\theta = 0$, $L_s = L_q = 20$.
- The diode effect is driven by the triplet pairing amplitude, Δ_t.
- JDE always accompanies the anomalous Josephson effect.

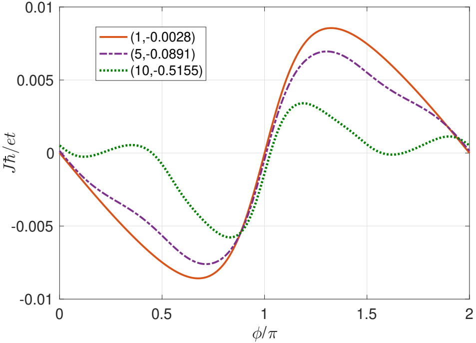


Figure: CPR for different values of Δ_t/Δ_s. The legend shows $(\Delta_t/\Delta_s, \gamma)$ for each curve. $\gamma = \Delta J_c/J_{c,av}$

Absence of Diode Effect in Singlet Pairing

- Josephson current is carried by pairs of electron and hole states.
- The dynamical phases accumulated by electron-hole pairs are identical in forward and backward directions when SC is singlet.

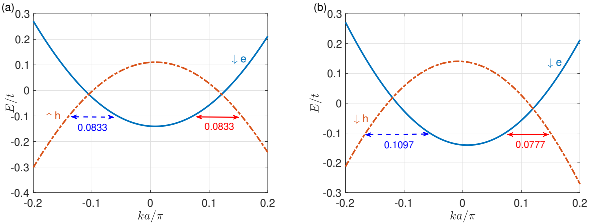


Figure: (a) Singlet phase: ↓-electron, ↑-hole. (b) Triplet phase: ↓-electron, ↓-hole.

Dependence of γ on Triplet Pairing Amplitude

- $|\gamma|$ increases with Δ_t, peaks, and then decreases.
- Competing mechanisms explain the behavior of γ.

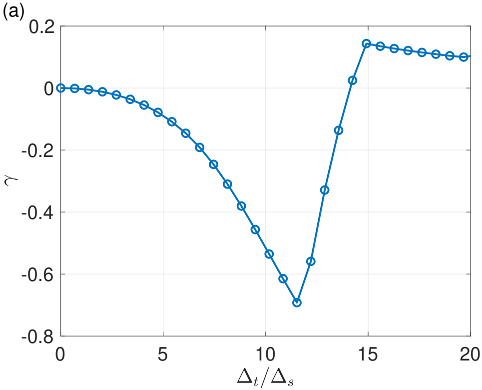
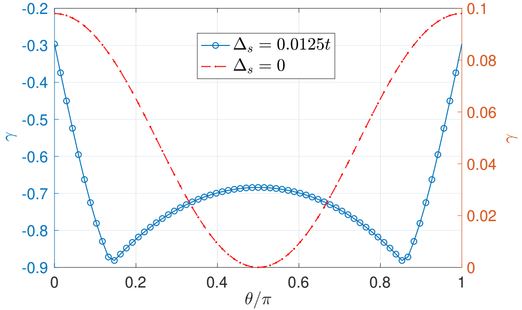


Figure: Diode effect coefficient γ versus Δ_t/Δ_s.

Diode Effect Coefficient γ vs. θ

- The diode effect coefficient γ is influenced by the angle θ between the direction of triplet pairing and SOC in the quantum wire.
- We plot γ versus θ for two cases:
  - $\Delta_s = 0$
  - $\Delta_s = 0.0125t$
- Other parameters: $\Delta_t = 0.1t$, $\mu_s = \mu_0 = -1.875t$, $\alpha = 0.05t$, $b = 0.015t$, and $L_s = L_q = 20$.



Absence of Diode Effect at $\theta = \pi/2$ (For $\Delta_s = 0$)

- For $\Delta_s = 0$, the diode effect is absent when $\theta = \pi/2$.
- At $\theta = \pi/2$, the triplet pairing becomes $(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$.
- In this case, pairing occurs between electrons and holes with opposite spins.
- The electron-hole pairs of opposite spins acquire identical dynamical phases for states carrying current in both directions.
- This symmetry causes the diode effect to vanish for $\Delta_s = 0$.

Dependence of γ on Chemical Potential

- Tuning the chemical potential in the central quantum wire affects γ.
- Oscillations in γ arise due to Fabry-Pérot interference.

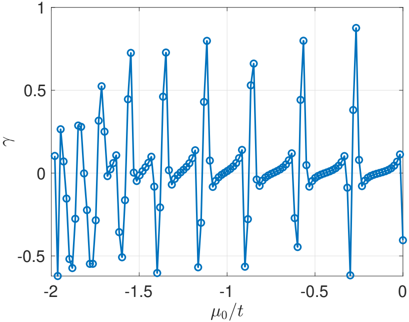


Figure: Diode effect coefficient γ versus μ_0.

Summary

- JDE is absent in 1D setups when the superconductivity is purely singlet.
- In the presence of both SOC and a Zeeman field, JDE shows up when the SC has triplet pairing.
- The chemical potential in the quantum wire causes oscillations in the diode effect coefficient due to Fabry-Pérot interference.
- Quantum wires can probe triplet pairings in superconductors by observing JDE, and this effect is accompanied by the anomalous Josephson effect.

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Thank you for your attention.