

Nonlocal Josephson diode effect in minimal Kitaev chains

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(Received 7 December 2025; accepted 9 March 2026; published 26 March 2026)

We study the emergence of the nonlocal Josephson effect in a system composed of three laterally coupled minimal Kitaev chains and exploit it to realize the nonlocal Josephson diode effect. We find that an imbalance between crossed Andreev reflections and electron cotunneling in the middle Kitaev chain gives rise to an asymmetric 2π -periodic phase-dependent Andreev spectrum, controlled by the superconducting phases across the left and right junctions. We then show that the asymmetric Andreev spectrum, formed by hybridized Andreev bound states at the left and right junctions, enables a supercurrent across one junction via the phase difference at the other junction, thereby signaling the nonlocal Josephson effect. Notably, these nonlocal Josephson supercurrents exhibit distinct positive and negative critical currents, demonstrating the realization of the nonlocal Josephson diode effect with highly tunable polarity and efficiencies exceeding 50%. The nonlocal Josephson diode effect requires breaking local time-reversal and local charge-conjugation symmetries, with the latter being unique to minimal Kitaev chains. Our results establish minimal Kitaev chains as a highly controllable platform for engineering nonlocal Josephson phenomena.

DOI: [10.1103/hf7s-f7tj](https://doi.org/10.1103/PhysRevResearch.8.013326)

I. INTRODUCTION

Nonlocality is an inherent quantum effect revealing instantaneous action at a distance, tied to the wavefunction nature, and has led to the prediction of several phenomena relevant to quantum technologies [1]. While mostly explored in relation to entanglement [2–4], the concept of nonlocality has been often studied in superconducting devices. Perhaps the simplest example is a two-terminal superconducting junction, where variations of voltages on one terminal give rise to a differential current on the second terminal, thus determining the so-called nonlocal conductance [5–9]. More recently, nonlocality was studied in multiterminal Josephson junctions (JJs), where a supercurrent flows across one part of the system due to variations in the superconducting phases elsewhere, defining what is known as the nonlocal Josephson effect (JE) [10]. Since Josephson junctions are key for superconducting circuits and computing [11–25], the nonlocal JE is directly relevant for quantum applications while offering a way to further delve the foundations of nonlocality.

The research on nonlocal JE has not only attracted theoretical efforts [10,26–37], but also its realization has already been reported in many experiments [38–44]. Most of the studies

involved conventional spin-singlet s -wave superconductors, leaving unconventional superconductors seldom explored in spite of their intrinsic nonlocal order parameters. One of the simplest systems that hosts controllable unconventional superconductivity with a p -wave order parameter can be engineered by connecting two quantum dots (QDs) via a superconductor [45,46]. This setup represents a minimal Kitaev chain, where electron cotunneling (ECT) and crossed Andreev reflections (CARs) mediate superconducting and normal processes between QDs [45,47]. Minimal Kitaev chains have lately triggered multiple efforts [48–61] and their implementation has already been shown in superconductor-semiconductor hybrids [62–65]. Despite the significant attention, the nonlocal JE and its impact on minimal Kitaev chains have not yet been studied.

In this work, we consider three laterally coupled minimal Kitaev chains (Fig. 1) and study the emergence of nonlocal Josephson phenomena. In particular, we demonstrate that, when CAR and ECT in the middle minimal Kitaev chain are distinct, an asymmetric phase-dependent Andreev spectrum appears and is controllable by the superconducting phases across the left and right junctions. We find that this asymmetric Andreev spectrum arises from hybridized Andreev bound states (ABSs) at the left and right junctions and requires breaking local time-reversal and local charge-conjugation symmetries. Notably, the asymmetric Andreev spectrum induces a finite supercurrent across one junction by tuning the superconducting phase difference across the other junction, hence unveiling the nonlocal JE. Even more interesting is that the nonlocal supercurrents develop distinct positive and negative critical currents, giving rise to a nonreciprocal Josephson transport that defines the emergence of a nonlocal Josephson

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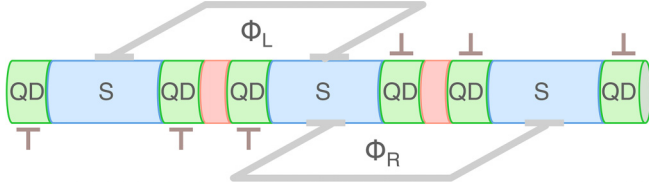


FIG. 1. Three minimal Kitaev chains laterally coupled to form a double Josephson junction, where the phase of the left (right) junction is controlled by an external magnetic flux $\Phi_{L(R)}$. Here, a minimal Kitaev chain is formed by connecting two quantum dots (green) by a superconductor (S, blue). The on-site energy of the QDs is controlled by gates (bars, brown), while the coupling between minimal Kitaev chains can be tuned by an insulating barrier (red).

diode effect. We show that this diode effect can achieve robust efficiencies surpassing 50% by controlling CAR and ECT in the middle chain and the phase difference in the second junction. Our findings put forward minimal Kitaev chains for realizing highly tunable nonlocal Josephson phenomena.

II. JJS FORMED BY THREE MINIMAL KITAEV CHAINS

We consider a Josephson system where three minimal Kitaev chains described by

$$H_\alpha(\phi_\alpha) = \varepsilon_{\alpha 1} c_{\alpha 1}^\dagger c_{\alpha 1} + \varepsilon_{\alpha 2} c_{\alpha 2}^\dagger c_{\alpha 2} + t_\alpha c_{\alpha 1}^\dagger c_{\alpha 2} + \Delta_\alpha e^{i\phi_\alpha} c_{\alpha 1}^\dagger c_{\alpha 2}^\dagger + \text{H.c.}$$

are laterally coupled (Fig. 1) and modeled by

$$H(\phi_L, \phi_R) = \sum_\alpha H_\alpha(\phi_\alpha) + \tau_L c_{L_2}^\dagger c_{M_1} + \tau_R c_{M_2}^\dagger c_{R_1} + \text{H.c.} \quad (1)$$

Here, $\alpha = L, M, R$ labels the left (L), middle (M), and right (R) minimal Kitaev chains formed by two sites $j = 1, 2$, and $c_{\alpha j}$ ($c_{\alpha j}^\dagger$) destroys (creates) an electronic state at site $j = 1, 2$ in the chain α . The first and second terms in $H_\alpha(\phi_\alpha)$ describe on-site energies $\varepsilon_{\alpha j}$ controlled by gates (brown bars in Fig. 1). The third term represents hopping between sites on the same chain, a characteristic of ECT processes. The fourth term is a spinless superconducting potential, with amplitude Δ_α and phase ϕ_α , describing CAR processes; note that the pair potential characterizes the p -wave nature of superconductivity, as in the Kitaev chain and irrespective of topology [24,66]. We model the coupling between the three chains by the second and third terms in Eq. (1) with tunneling amplitudes $\tau_{L(R)}$ across the left (right) junctions. Using a gauge symmetry, we also set the phase of the middle chain as $\phi_M = 0$, leading to the junction depending on two superconducting phases, $H(\phi_L, \phi_R)$. The phase differences ϕ_L and ϕ_R between chains can be externally controlled by magnetic fluxes (Fig. 1), as in Refs. [42,44,67]. Despite the simplicity, two-site Kitaev chains have already been experimentally realized in QDs coupled by a superconductor-semiconductor system [62–65,68], where the control of ECT and CAR was demonstrated [69,70]. As we show below, the system exhibits a unique phase dependence, enabling a nonlocal JE with nonreciprocal origin.

III. BREAKING AND PRESERVATION OF SYMMETRIES

We begin by analyzing symmetries of the Josephson system in Eq. (1). First of all, the quasiparticle energy derived by Eq. (1) forms a pair $(-E, E)$ because of particle-hole symmetry of the Bogoliubov-de Gennes Hamiltonian. While the Josephson system respects time-reversal symmetry (TRS), $\mathcal{T}H(\phi_L, \phi_R)\mathcal{T}^{-1} = H(-\phi_L, -\phi_R)$, where the time-reversal antiunitary operator $\mathcal{T}$ is given by $\mathcal{T}c_{\alpha i}\mathcal{T}^{-1} = c_{\alpha i}$, it does not have either $\mathcal{T}H(\phi_L, \phi_R)\mathcal{T}^{-1} = H(-\phi_L, \phi_R)$ or $\mathcal{T}H(\phi_L, \phi_R)\mathcal{T}^{-1} = H(\phi_L, -\phi_R)$, implying local TRS is broken across either the left or right junction, respectively. For $\tau_{L(R)} \neq 0$, the left (right) junction also explicitly breaks the local spatial inversion symmetry, even when the entire system may be spatially inversion-symmetric. Thus, each junction satisfies the standard criterion for the Josephson diode effect [71–75].

However, our system [Eq. (1)] has an additional symmetry constraint for the Josephson diode effect, which originates from a special symmetry at the “sweet spot” ($\varepsilon_\alpha = 0$, $t_\alpha = \Delta_\alpha$), where the chains support quadratically protected Majorana states [45]. In fact, for $\varepsilon_\alpha = 0$ and $t_\alpha = \Delta_\alpha$, each minimal chain has a local charge-conjugation symmetry, $C_{\alpha 1}H_\alpha(\phi_\alpha)C_{\alpha 1}^{-1} = H_\alpha(-\phi_\alpha)$, where the nontrivial action of the unitary operator $C_{\alpha 1}$ is defined by $C_{\alpha 1}c_{\alpha 1}C_{\alpha 1}^{-1} = c_{\alpha 1}^\dagger$, $C_{\alpha 1}c_{\alpha 2}C_{\alpha 1}^{-1} = -e^{i\phi_\alpha}c_{\alpha 2}$, and $C_{\alpha 1}c_{\beta i}C_{\alpha 1}^{-1} = c_{\beta i}$ ($\beta \neq \alpha$). Note that $C_{\alpha 1}$ switches only an electron at site 1 on chain α with its antiparticle. We also have a similar local charge-conjugation symmetry $C_{\alpha 2}$, switching only an electron at site 2 with its antiparticle. We can partially keep the symmetries even for the junctions in Eq. (1). For instance, by performing C_{L_2} , C_{M_1} , and an additional gauge rotation, we have $C_{LM}H(\phi_L, \phi_R)C_{LM}^{-1} = H(-\phi_L, \phi_R)$, where the unitary operator C_{LM} acts as $C_{LM}c_{L_1}C_{LM}^{-1} = e^{i\phi_L}c_{L_1}$, $C_{LM}c_{L_2}C_{LM}^{-1} = c_{L_2}^\dagger$, $C_{LM}c_{M_1}C_{LM}^{-1} = -c_{M_1}^\dagger$, $C_{LM}c_{M_2}C_{LM}^{-1} = c_{M_2}$, and $C_{LM}c_{R_i}C_{LM}^{-1} = c_{R_i}$. We also have the relation $C_{MR}H(\phi_L, \phi_R)C_{MR}^{-1} = H(\phi_L, -\phi_R)$ with a unitary operator C_{MR} constructed similarly. These relations provide the same constraint on the quasiparticle spectrum as local inversion, $E_n(\phi_L, \phi_R) = E_n(\pm\phi_L, \pm\phi_R)$, and thus, we need to break these local charge-conjugation symmetries, in addition to local TRS, to obtain the Josephson diode effect. For this purpose, we consider $\Delta_M \neq t_M$ below, which breaks both C_{LM} and C_{MR} .

IV. ANDREEV BOUND STATES AND ANDREEV MOLECULES

Having identified the role of the superconducting phase differences $\phi_{L,R}$ in the system symmetries, here we explore how they determine the behavior of the Andreev energy spectrum. This is shown in Figs. 2(a)–2(d) as a function of ϕ_L when ECT and CAR in the middle chain are the same ($t_M = \Delta_M$) for distinct values of ϕ_R at $\Delta_{L,R} = t_{L,R}$, while in Figs. 2(e)–2(h) for ECT weaker than CAR. Since $\Delta_{L,R} = t_{L,R}$, the left (right) chains host zero-energy dispersionless Majorana flat bands located in their first (second) QD, which remain robust against $\phi_{L,R}$ (Fig. 2). Depending on the ratio between CAR and ECT in the middle chain, the Andreev spectrum exhibits a strong dependence on $\phi_{L,R}$. For

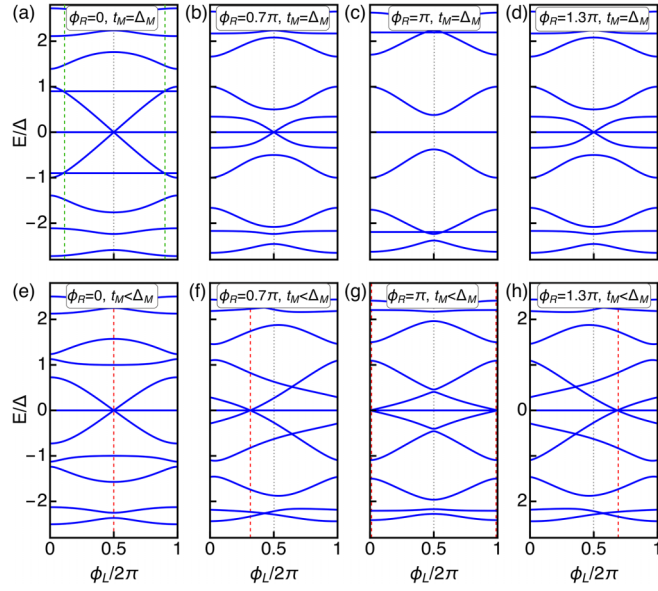


FIG. 2. Energy spectrum as a function of ϕ_L at distinct ϕ_R for $t_M = \Delta_M$ [panels (a)–(d)] and $t_M < \Delta_M$ [panels (e)–(h)]. The vertical dotted line marks $\phi_L = \pi$, while the red vertical dashed line marks ϕ_L at which the dispersing lowest ABSs reach zero energy. Parameters: $\varepsilon_\alpha = 0$, $t_{L,R} = \Delta_{L,R} \equiv \Delta = 1$, $\tau_L = 1$, and $\tau_R = 0.9$.

$t_M = \Delta_M$ at $\phi_R = 0$ [Fig. 2(a)], a pair of dispersionless Andreev bound states appear at energies close to $\pm\Delta$ and intersect a pair of dispersing ABSs near $\phi_L = 0, 2\pi$. See green vertical lines. These dispersionless ABSs originate from the right junction between the middle and right chains, and, as ϕ_R takes finite values, they hybridize with the dispersing ABSs formed in the left junction between the left and middle chains [Figs. 2(a)–2(d)]. The dispersing hybridized ABSs, which can be seen as Andreev molecules studied before in conventional superconductors [10,26,32,43,67,76–79], reach zero energy at $\phi_L = \pi$ (gray vertical line) and become flat bands with ϕ_L at $\phi_R = \pi$ [Fig. 2(c)], always maintaining a symmetric profile about $\phi_L = \pi$.

When $t_M \neq \Delta_M$, a nonzero ϕ_R modifies the phase dependence of the spectrum and, notably, it also makes the spectrum asymmetric about $\phi_L = \pi$ (vertical dashed red line), provided $\phi_R \neq 2\pi n$ with $n \in \mathbb{Z}$ (see Figs. 2(e)–2(h) and Fig. 5 in Appendix A). This asymmetry moves the zero-energy crossing of the dispersing hybridized ABSs to $\phi_L \neq \pi$, which occurs below (above) $\phi_L = \pi$ when $\phi_R < \pi$ ($\phi_R > \pi$) for $t_M < \Delta_M$ [Figs. 2(e)–2(h)]. The asymmetric spectrum turns out to be gapless over $\phi_{L,R} \in (0, 2\pi)$ and remains for $t_M > \Delta_M$ but with the zero-energy crossing at $\phi_L < \pi$ ($\phi_L > \pi$) when $\phi_R > \pi$ ($\phi_R < \pi$) in the latter case (Fig. 5). A consequence of the asymmetric spectrum under $\phi_{L,R} \neq 0$ and $\Delta_M \neq t_M$ is that the free energy develops minima away from $\phi_L = 2\pi n$, unlike conventional Josephson junctions [80,81] (See Appendix A). Thus, the imbalance between CAR and ECT in the middle Kitaev chain induces an asymmetric Andreev spectrum at nonzero superconducting phases across the left/right junctions, in line with breaking local TRS and local charge-conjugation symmetry. From an experimental point of view, we note that the ratio between Δ_M and t_M can be controlled,

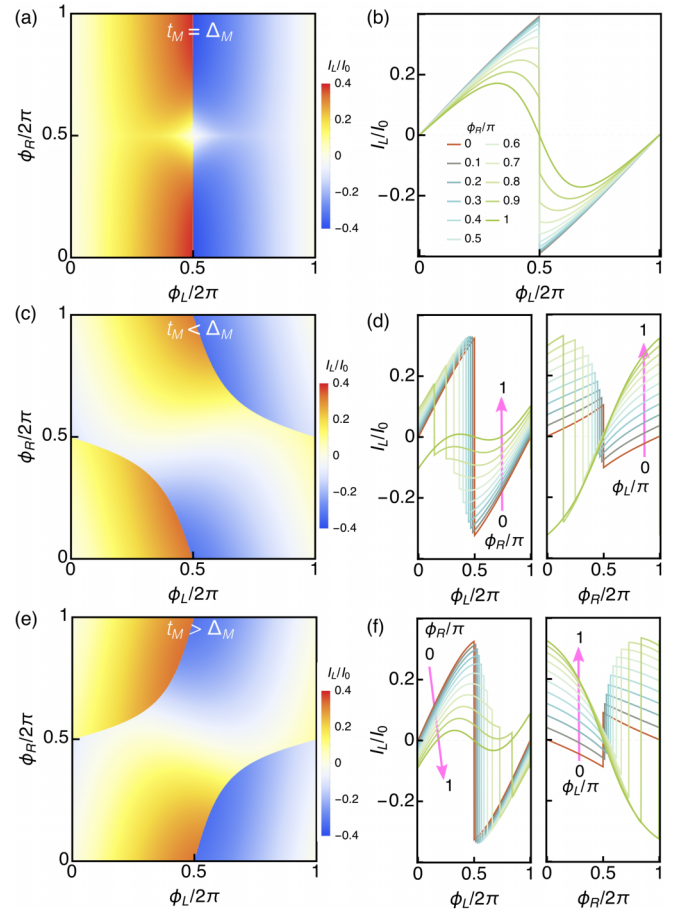


FIG. 3. Supercurrent as a function of ϕ_L and ϕ_R for $t_M < \Delta_M$ [panel (a)], $t_M = \Delta_M$ [panel (c)], and $t_M > \Delta_M$ [panel (e)]. (b), (d), (f) Line cuts as a function of $\phi_{L(R)}$ for distinct $\phi_{R(L)}$. In panels (d) and (f), the magenta arrow indicates variations of $\phi_{L,R}$ within $(0, \pi)$ in steps of 0.1π . Parameters: $I_0 = e\Delta/\hbar$, the rest as in Fig. 2.

e.g., by gating the middle chain as done in Ref. [62] for tuning CAR and ECT processes.

V. LOCAL AND NONLOCAL JOSEPHSON EFFECTS

A direct consequence of $\phi_{L,R} \neq 0$ and the imbalance between CAR and ECT in the middle chain is the phase-biased Josephson effect, which we explore here. For this purpose, we numerically obtain the phase-biased Josephson current flowing across the left junction as [24,82,83] $I_L(\phi_L, \phi_R) = (e/\hbar) \sum_{n<0} dE_n(\phi_L, \phi_R)/d\phi_L$ [84]. To visualize the supercurrent, in Figs. 3(a), 3(c), and 3(e) we show I_L as a function of ϕ_L and ϕ_R for distinct cases when CAR in the middle chain is equal [panel (a)], weaker [panel (c)], and stronger [panel (e)] than ECT in the same chain. In Figs. 3(b), 3(d), and 3(f), we show I_L as a function of ϕ_L for distinct ϕ_R , while Figs. 3(d) and 3(f) also show I_L as a function of ϕ_R for distinct ϕ_L . The first observation is that I_L in Fig. 3 strongly depends on $\phi_{L,R}$ and the ratio between ECT (t_M) and CAR (Δ_M) in the middle region, a behavior that originates from the ABSs in Fig. 2. When $\Delta_M = t_M$, the supercurrent I_L is 2π -periodic and symmetric under $\phi_R \neq 0$ [Figs. 3(a) and 3(b)], having $I_L(\phi_L = n\pi) = 0$ for any ϕ_R and equal maxima/minima

that reduce for $\phi_R \neq 0, 2\pi$; the free energy in Fig. 6(a) of Appendix B has a minimum at ϕ_L as for 0-junctions [80,85]. Also, I_L exhibits a sawtooth profile at $\phi_L = \pi$ for $\phi_R \neq \pi$ due to the zero-energy crossing of the dispersing ABSs [Figs. 2(a)–2(d)], while it smoothens out at $\phi_R = \pi$ because the dispersing ABSs become flat [Fig. 2(c)].

At $\Delta_M \neq t_M$, the supercurrent across the left junction I_L develops an intriguing anomalous behavior that varies with $\phi_{L,R} \neq 0$. See Figs. 3(c)–3(f). The most notorious feature is that $\phi_R \neq n\pi$ gives rise to $I_L(\phi_L = n\pi) \neq 0$ with $n \in \mathbb{Z}$ and it is not symmetric about $\phi_L = \pi$ anymore, which are consequences of the asymmetric Andreev spectrum shown in Figs. 2(e)–2(h). This implies that, even at $\phi_L = 0$, a supercurrent across the left junction I_L emerges and is controlled by the superconducting phase difference across the right junction ϕ_R , signaling the so-called nonlocal JE that was initially predicted in systems with conventional superconductors [10]. This nonlocal JE requires multiple terminal and does not appear in a two-terminal Josephson junction. The sawtooth profile of I_L also occurs away from $\phi_L = \pi$ [Figs. 3(d) and 3(f)] due to the shifted zero-energy crossing in the ABSs when $t_M \neq \Delta_M$. See Figs. 2(e)–2(h) and 5. It is worth noting that having $I_L(\phi_L = 0, \phi_R \neq n\pi) \neq 0$ in Figs. 3(c)–3(f) also means that a $\phi_{L,0}$ -Josephson junction is realized at $\Delta_M \neq t_M$ [80,85,86]. At $\phi_L = 0$, the current as a function of ϕ_R can develop a π shift for $t_M > \Delta_M$ [Figs. 3(e) and 3(f)], leading to a π junction [85,87]. Moreover, there are also signals of a ϕ -junction behavior [88–91], where the current I_L passes through zero neither at $\phi_L = 0, 2\pi$ nor at $\phi_L = \pi$ [Figs. 3(d) and 3(f)]. Yet another important effect of $\phi_{L,R} \neq 0$ and $t_M \neq \Delta_M$ is that the maximum positive and negative values of I_L over $\phi_L \in (0, 2\pi)$ are not the same [Figs. 3(c)–3(f)], producing a nonreciprocity between the maximum currents that can flow across the left junction. As a result, a Josephson setup with three laterally coupled minimal Kitaev chains [Eq. (1)] can realize the nonlocal Josephson effect and nonlocal nonreciprocal Josephson transport only when ECT and CAR in the middle chain are distinct.

VI. CRITICAL CURRENTS AND NONLOCAL JOSEPHSON DIODE EFFECT

To further explore the nonlocal nonreciprocal Josephson transport, we look at the critical currents across the left junction $I_{\text{CL}}^{\pm}(\phi_R) = \max_{\phi_L} [\pm I_L(\phi_L, \phi_R)]$, where $I_L(\phi_L, \phi_R)$ is the current flowing across the left junction discussed in the previous section. Figures 4(a)–4(c) show the critical currents $I_{\text{CL}}^{\pm}(\phi_R)$ as a function of ϕ_R when ECT in the middle chain is weaker than, equal to, and stronger than CAR in the same chain. At $t_M = \Delta_M$, when CAR and ECT in the middle chain are equal, the positive and negative critical currents are equal ($I_{\text{CL}}^+(\phi_R) = I_{\text{CL}}^-(\phi_R)$) and develop a minimum at $\phi_R = \pi$ [Fig. 4(b)], leading to the absence of the nonlocal Josephson diode effect. Interestingly, for $t_M < \Delta_M$, the minima of $I_{\text{CL}}^+(\phi_R)$ and $I_{\text{CL}}^-(\phi_R)$ are shifted to values below and above $\phi_R = \pi$, respectively, giving rise to nonreciprocal phase-biased Josephson currents ($I_{\text{CL}}^+(\phi_R) \neq I_{\text{CL}}^-(\phi_R)$) flowing across the left junction and fully controlled by $\phi_R \neq n\pi$. For $t_M > \Delta_M$, the shifts in the critical currents are the opposite as for $t_M < \Delta_M$ but $I_{\text{CL}}^+(\phi_R) \neq I_{\text{CL}}^-(\phi_R)$ remains. Having

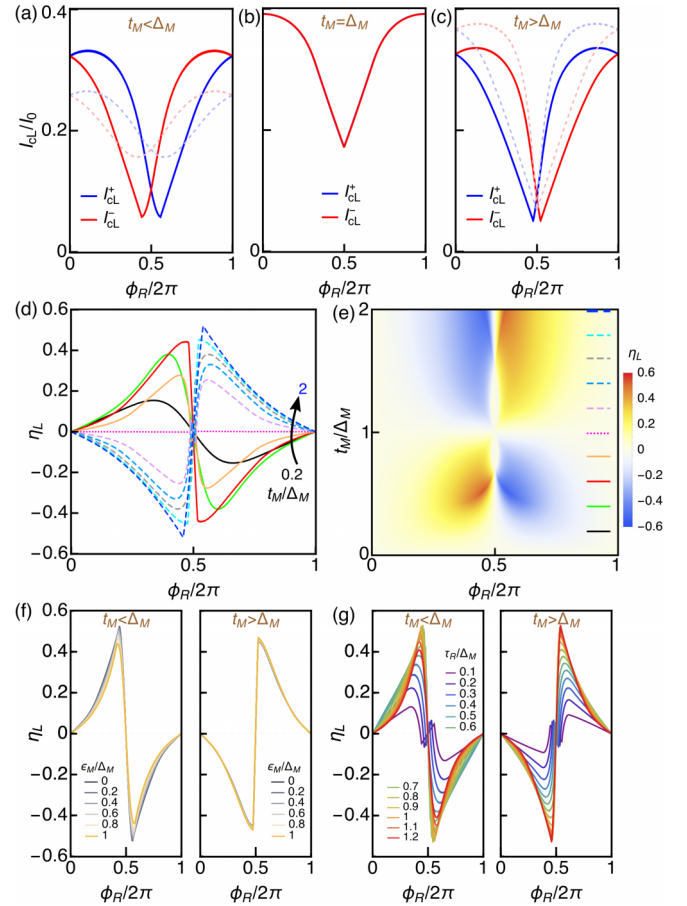


FIG. 4. Critical currents $I_{\text{CL}}^{\pm}$ as functions of ϕ_R for $t_M < \Delta_M$ [panel (a)], $t_M = \Delta_M$ [panel (b)], and $t_M > \Delta_M$ [panel (c)]. The dashed and solid lines in panel (a) correspond to $t_M = 0.2\Delta_M$ and $t_M = 0.5\Delta_M$, while to $t_M = 1.5\Delta_M$ and $t_M = 1.8\Delta_M$ in panel (c). (d), (e) Diode's quality factor η_L as a function of ϕ_R for distinct t_M in steps of $0.2\Delta_M$, marked by colored bars in panel (e). (f) η_L as a function of ϕ_R for distinct ε_M for $t_M < \Delta_M$ and $t_M > \Delta_M$. (g) The same as in panel (f) but for distinct τ_R . Parameters: $I_0 = e\Delta/\hbar$, the rest as in Fig. 2.

$I_{\text{CL}}^+(\phi_R) \neq I_{\text{CL}}^-(\phi_R)$ defines the nonlocal Josephson diode effect, which requires an imbalance between CAR and ECT in the middle chain and also $\phi_R \neq n\pi$. These conditions are consistent with the asymmetric Andreev spectrum (Fig. 2) and with the breaking of local TRS and local charge-conjugation symmetry discussed below Eq. (1), implying that they are crucial for the nonlocal Josephson diode effect in minimal Kitaev chains.

To characterize the nonlocal diode effect, we analyze its efficiency by studying the quality factor $\eta_L(\phi_R) = [I_{\text{CL}}^+(\phi_R) - I_{\text{CL}}^-(\phi_R)]/[I_{\text{CL}}^+(\phi_R) + I_{\text{CL}}^-(\phi_R)]$, where $I_{\text{CL}}^{\pm}(\phi_R)$ are the critical currents across the left junction analyzed in the previous paragraph. We show $\eta_L(\phi_R)$ in Figs. 4(d) and 4(e) as a function of ϕ_R and t_M , while in Figs. 4(f) and 4(g) we inspect the stability of the efficiencies when varying the on-site energies and tunneling across the junction since these conditions are very likely unavoidable in a realistic scenario. In Appendix C, we discuss the robustness of $\eta_L(\phi_R)$ against variations of the on-site energies ε_α (see Fig. 7). In Figs. 4(d)

and 4(e), we observe that a nonzero quality factor appears when $t_M \neq \Delta_M$ and $\phi_R \neq n\pi$, with $n \in \mathbb{Z}$, and it is enhanced just below and above $\phi_R = \pi$ achieving values above 0.5. While $t_M/\Delta_M < 1$ promotes a quality factor having a sine-line profile with ϕ_R with a fast sign change across $\phi_R = \pi$, the quality factors change sign for $t_M/\Delta_M > 1$ [see Figs. 4(d) and 4(e)]. This implies that the diode's polarity and large efficiencies can be fully controlled nonlocally by ϕ_R and are thus expected to be more tunable than regular two-terminal Josephson diodes [74,75,92–108]. By direct inspection of Fig. 4(e), one concludes that, for $t_M < \Delta_M$, the largest efficiencies are achieved for $t_M \in (0.3 - 0.7)\Delta_M$ and $0.3\pi < \phi_R < \pi$ ($\pi < \phi_R < 0.7\pi$). The large efficiencies of the nonlocal Josephson diode effect are robust against variations of the on-site energies of the middle chain, as demonstrated in Fig. 4(f). Strong variations of the on-site energies in the left and right chains, however, have a detrimental effect, while $\eta_L(\phi_R)$ remains robust against weak detuning (see Fig. 7). Moreover, having large tunneling amplitudes favors the large efficiency values of the nonlocal Josephson diode [Fig. 4(g)]. We have also verified that slight deviations from the equal CAR and ECT regime in the left /right chains weakly affect the nonlocal Josephson diode effect.

VII. CONCLUSIONS

In conclusion, we have demonstrated the nonlocal Josephson effect and the realization of a nonlocal Josephson diode in a system formed by three laterally coupled minimal Kitaev chains. In particular, we found that when the middle chain exhibits an imbalance between crossed Andreev reflections and electron cotunneling, the phase-dependent Andreev spectrum is asymmetric and can be controlled by the phase difference across the right junction. We have then shown that this asymmetric Andreev spectrum, containing hybridized Andreev bound states from both junctions, produces a supercurrent across the left junction that is controllable by the phase difference across the right junction, hence defining the nonlocal Josephson effect. Notably, we have discovered that these nonlocal Josephson effects enable distinct positive and negative critical currents, giving rise to a nonlocal Josephson diode effect whose polarity is highly tunable and can achieve efficiencies above 50%. Given the recent advances on nonlocal Josephson effect [38–44] and minimal Kitaev chains [62–65], our findings are very likely within experimental reach. In this regard, we point out that Ref. [62] has already experimentally demonstrated the control of the ratio between crossed Andreev reflections and electron cotunneling, which, applied to the middle chain in our setup, shows that the realization of the nonlocal Josephson diode effect with a highly tunable polarity in minimal Kitaev chains is a feasible idea. While our work makes us wonder about emergent effects in minimal Kitaev chains, an immediate question also involves the application of the nonlocal Josephson diode concept in longer Kitaev chains, which will be the focus of our future research.

ACKNOWLEDGMENTS

J.C. acknowledges financial support from the Swedish Research Council (Vetenskapsrådet Grant No. 2021-04121) and

from the Olle Engkvist Foundation (Grant No. 243-1026). M.S. was supported by JST CREST Grant No. JPMJCR19T2 and JSPS KAKENHI Grants No. JP24K00569 and No. JP25H01250. The computations were enabled by resources provided by the National Academic Infrastructure for Supercomputing in Sweden (NAISS), partially funded by the Swedish Research Council through Grant Agreement No. 2022-06725.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: ANDREEV BOUND STATES WHEN ECT IS STRONGER THAN CAR IN THE MIDDLE CHAIN

In Fig. 2, we looked at the Andreev spectrum when ECT is equal to or weaker than CAR in the middle chain. In this part, Fig. 5 shows the Andreev spectrum as a function of ϕ_L for distinct ϕ_R when ECT is stronger than CAR, namely, $t_M > \Delta_M$. The Andreev spectrum is symmetric when $\phi_R = 0$ [Fig. 5(a)], developing a phase dependence similar to the case with $t_M < \Delta_M$ in Fig. 2(a). Because we chose $\Delta_{L,R} = t_{L,R}$ and ε_α , the spectrum contains two dispersionless levels at zero energy, which represent the two poor man's Majorana modes located at the very outer QDs. Two extra Andreev bound states reach zero energy at $\phi = \pi$ marked by a vertical dashed red line, and those are located in the middle of the junction. However, deviations from these parameters do not change the symmetric nature of the spectrum in Fig. 5(a) unless $\phi_R \neq n\pi$. This is demonstrated in Figs. 5(b)–5(d), where a $\phi_R \neq n\pi$ makes the entire Andreev spectrum asymmetric with respect to $\phi_L = \pi$; see vertical dashed gray line. The zero-energy crossing seen at $\phi_L = 0$ in Fig. 5(a) shifts to $\phi_L > \pi$ when $\phi_R < \pi$ [Fig. 5(b)], while to $\phi_L < \pi$ for $\phi_R > \pi$ [Fig. 5(d)]; see vertical dashed red lines. At $\phi_R = \pi$, the Andreev spectrum is symmetric, the pair of dispersionless levels remain, but the first excited levels now reach zero energy at $\phi_L = 2n\pi$ while leaving a large

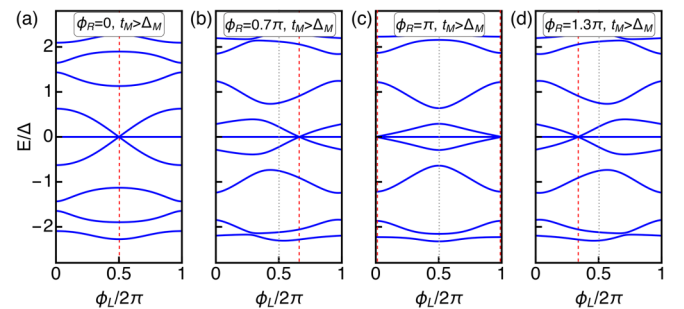


FIG. 5. Energy spectrum as a function of ϕ_L at distinct values of ϕ_R for $t_M = 1.8\Delta_M$. The vertical dotted line marks $\phi_L = \pi$, while the red vertical dashed line marks the value of ϕ_L at which the dispersing lowest ABSs reach zero energy. Parameters: $\varepsilon_\alpha = 0$, $t_{L,R} = \Delta_\alpha \equiv \Delta = 1$, $\tau_L = 1$, and $\tau_R = 0.9$.

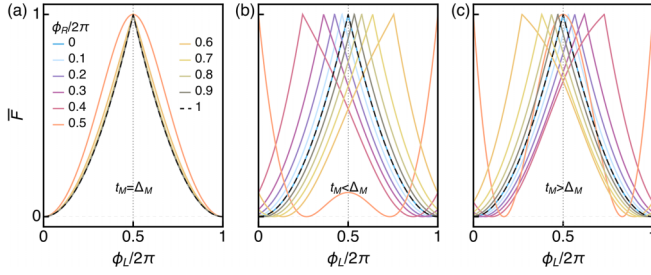


FIG. 6. Free energy $\bar{F}$ as a function of ϕ_L at distinct values of ϕ_R for $t_M = \Delta_M$, $t_M = 0.5\Delta_M$, and $t_M = 1.8\Delta_M$. Here, $\bar{F}$ is defined as $\bar{F} = (F - F_{\min})/(F_{\max} - F_{\min})$, where F is the free energy and $F_{\max(\min)}$ is the maximum (minimum) free energy value over a period of ϕ_L . Parameters: $\varepsilon_\alpha = 0$, $t_{L,R} = \Delta_\alpha \equiv \Delta = 1$, $\tau_L = 1$, and $\tau_R = 0.9$.

zero energy splitting at $\phi_L = n\pi$ [Fig. 5(c)]. In conclusion, the asymmetry in the Andreev spectrum is controlled by ϕ_R and $\Delta_M \neq t_M$, in line with the breaking local time-reversal and local charge-conjugation symmetries discussed in the main text.

APPENDIX B: FREE ENERGY OF THE JOSEPHSON SETUP

The asymmetric Andreev spectrum shown in the previous Appendix has a direct effect on the free energy, which we discuss in this Appendix. We define a normalized free energy as $\bar{F} = (F - F_{\min})/(F_{\max} - F_{\min})$, where $F_{\max} = \max_{\phi_L} [F(\phi_L, \phi_R)]$ and $F_{\min} = \min_{\phi_L} [F(\phi_L, \phi_R)]$, where the maximum and minimum are obtained over a period of 2π . In Fig. 6, we show $\bar{F}$ as a function of ϕ_L for distinct values of ϕ_R when ECT in the middle chain t_M is equal to, weaker than, and stronger than CAR in the same chain Δ_M . As anticipated, for $t_M = \Delta_M$ in Fig. 6(a), the free energy $\bar{F}$ develops minima at multiples of $2n\pi$, with $n \in \mathbb{Z}$, irrespective of the values of ϕ_R . This signals a regular Josephson junction behavior. Interestingly, for $t_M \neq \Delta_M$ and $\phi_R \neq 0$, the free energy exhibits minima away from $\phi_L = 2n\pi$ [see Figs. 6(b) and 6(c)]. For instance, for $\phi_R = \pi$ at $t_M \neq \Delta_M$, the free energy has two (double) minima away from $\phi_L = 0, \pi$, signaling the emergence of a ϕ -Josephson junction. We note that ϕ -Josephson junctions were initially predicted in Josephson junctions with alternating critical current density [88], in periodic arrays of 0- and π -Josephson junctions [89], and more recently in altermagnetic Josephson junctions [25,90,91]. Furthermore, away from $\phi_R = \pi$ at $t_M \neq \Delta_M$, the free energy is able to exhibit one minimum either close to $\phi_L = 0$ or $\phi_L = 2\pi$: on one hand, when $\pi < \phi_R < 2\pi$, the minimum is close to $\phi_L = 0$ for $t_M < \Delta_M$ but close to $\phi_L = 2n\pi$ for $t_M > \Delta_M$. On the other hand, when $0 < \phi_R < \pi$, the minimum is close to $\phi_L = 2\pi$ for $t_M < \Delta_M$ but close to $\phi_L = 0$ for $t_M > \Delta_M$. The asymmetric Andreev spectrum and nonreciprocal (diode) Josephson transport discussed in the main text are therefore tied to the free energy having a single minimum away from $\phi_L = 2n\pi$.

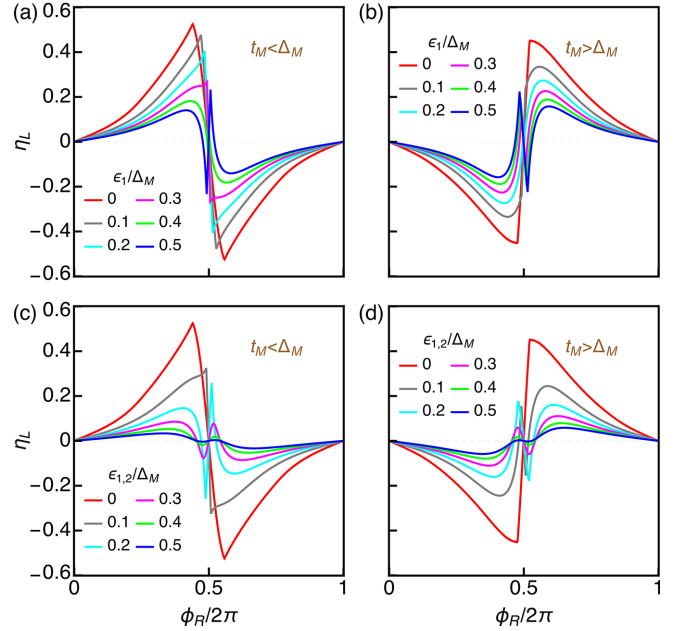


FIG. 7. Diode's efficiency as a function of ϕ_R for distinct values of the on-site energy $\varepsilon_{L_1,R_1} = \varepsilon_1$ when $t_M = 0.5\Delta_M$ [panel (a)] and $t_M = 1.8\Delta_M$ [panel (b)], in both cases at $\varepsilon_{L_2(R_2)} = 0$. (c), (d) The same as in panels (a) and (b) but both on-site energies $\varepsilon_{L_1,2} = \varepsilon_{R_1,2} = \varepsilon_{1,2}$. Parameters: $\varepsilon_M = 0$, $t_{L,R} = \Delta_\alpha \equiv \Delta = 1$, $\tau_L = 1$, and $\tau_R = 0.9$.

APPENDIX C: EFFICIENCY OF THE NONLOCAL JOSEPHSON DIODE AT FINITE ON-SITE ENERGIES

To further support the robustness of the nonlocal Josephson diode effect presented in Fig. 4, here we explore the sensitivity of the quality factor η_L under variations of the on-site energies ε_α . This is presented in Figs. 7(a) and 7(b), where we show η_L as a function of ϕ_R when the on-site energies of the first QD of the left and right chains take finite values, while in Figs. 7(b) and 7(c) we consider the case when both on-site energies of the left and right chains are nonzero and equal. The quality factors exhibit a slightly greater robustness against variations of a single on-site energy [Figs. 7(a) and 7(b)], achieving values close to 20% for detuning values of $\varepsilon_1/\Delta = 0.5$. When both QD energies of the outer chains are equally large, the quality factors degrade faster than when a single QD has a nonzero energy [see Figs. 7(c) and 7(d)].

While these QD energies seem to be detrimental, it is worth noting that they also bring additional functionality for the nonlocal Josephson diode. To see this, we first notice that the polarity of the diode, reflected in the sign of η_L , is highly controllable by the phase across the junction between the middle and right chains ϕ_R . The diode's polarity is also determined by strength of ETC and CAR, as observed in Fig. 7. Notably, the nonzero values of the on-site energies in the outer chains have the capability to change the diode's polarity around $\phi_R = \pi$. Depending on whether a single ε_1 or both $\varepsilon_{1,2}$ energies are varied, the change in the diode's polarity can be fast or slow, respectively. Since the QD energies are expected to be tunable by means of gates [62], $\varepsilon_{1,2}$ add important control of the nonlocal Josephson diode effect discussed here.

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