

Temporal Entanglement Transitions in the Periodically Driven Ising Chain

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Periodically driven quantum systems can host nonequilibrium phenomena without static analogs, including in their entanglement dynamics. Here, we discover *temporal entanglement transitions* (TETs) in a Floquet spin chain, which correspond to a quantum phase transition in the spectrum of the entanglement Hamiltonian and are signaled by dynamical spontaneous symmetry breaking. We identify the symmetry principles underlying these transitions: they appear when the driven Hamiltonian preserves global symmetry (here, $\mathbb{Z}_2$), the initial state respects this symmetry, and the reduced density matrix carries weight in both subsystem-parity sectors, with TETs occurring precisely when the sector weights become equal (given the previous two conditions are also satisfied). Intriguingly, we find these transitions across a broad range of driving frequencies (from adiabatic to high-frequency regime) and independent of drive details, where they manifest as periodic, sharp entanglement spectrum reorganizations marked by the Schmidt-gap closure, a vanishing entanglement echo, and symmetry-quantum-number flips, while remaining invisible to conventional local observables. At high frequencies, the entanglement Hamiltonian acquires an intrinsic timescale decoupled from the drive period, rendering the transitions genuine steady-state features. Finite-size scaling reveals universal critical behavior with correlation-length exponent $\nu = 1$, matching equilibrium Ising universality despite its emergence from purely dynamical mechanisms decoupled from static criticality. Our Letter establishes TETs as novel features in Floquet quantum matter.

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Introduction—Periodically driven quantum many-body systems are a powerful platform for exploring quantum phases inaccessible in equilibrium, opening the door to the coherent control and engineering of quantum matter via time-periodic fields [1–5]. The study of Floquet-driven systems has unveiled remarkable phenomena ranging from Floquet topological insulators [6,7] and time crystals [8–10] to dynamical localization [11,12] and prethermalization [13–15]. While extensive research has focused on conventional observables like magnetization and transport properties, exploring the entanglement structure of driven quantum systems remains an active area of research, given its fundamental role in characterizing quantum phases and phase transitions [16,17]. Of particular interest is the entanglement spectrum (ES) [18], which provides direct access to the “entanglement Hamiltonian” and encodes information beyond that contained in the entanglement

entropy alone. The ES serves as a powerful diagnostic for capturing the universal features of quantum phases in equilibrium, especially in the context of gapped ground states but also for critical points [19–40]. There is growing recognition that the ES also reveals distinctive signatures of quantum chaos, thermalization, and criticality out of equilibrium [41–44].

Recent work has begun exploring the interplay between driving and entanglement, including for Floquet-driven conformal field theories [45–48] and in driven-dissipative systems [49–51]. Particularly relevant are studies of Page curves [52–54], where entanglement transitions emerge from competition between entanglement generation and relaxation in the presence of conserved charges. While equilibrium quantum phase transitions are intimately connected to entanglement scaling and the structure of the many-body ground state [17,55,56], the analogous relationship in driven systems remains unexplored. Since driven systems can access dynamical phases with no equilibrium counterpart, this suggests new entanglement phenomena waiting to be uncovered. However, whether nonanalytic entanglement transitions can occur in generic periodically driven systems remains an open question.

In this Letter, we report the discovery of “temporal entanglement transitions” (TETs) via dynamical spontaneous symmetry breaking in the entanglement Hamiltonian (EH) of a periodically driven spin chain. These transitions

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require $\mathbb{Z}_2$ -symmetric-driven Hamiltonian and initial state, with critical times occurring at sector-weight degeneracies (made precise below), and manifest through three synchronized signatures: Schmidt-gap closure [57–59], vanishing entanglement echo [60], and parity flips [61–63], while remaining invisible to conventional observables (magnetization, Loschmidt echo). Crucially, these transitions occur across all driving frequencies and exhibit universal critical behavior with correlation length exponent $\nu = 1$, matching the equilibrium Ising universality class [64,65], despite emerging purely dynamically, decoupled from any underlying equilibrium criticality.

Our findings establish TETs as a distinct class of nonequilibrium phenomenon that is uniquely detectable through entanglement measures while remaining hidden from conventional observables, revealing that the EH itself can undergo quantum phase transitions. At high frequencies, we find that the EH gains an intrinsic timescale decoupled from the drive, rendering its Floquet-periodic transitions as genuine steady-state features. The universal critical behavior persists whenever the above $\mathbb{Z}_2$ -symmetry condition and sector-weight equality are satisfied (including across different equilibrium phases that preserve $\mathbb{Z}_2$), confirming a fundamentally nonequilibrium character decoupled from the underlying equilibrium phase diagram (see Supplemental Material [66] for details).

Model and results—We consider the transverse-field Ising model (TFIM) with open boundary conditions, consisting of L spin-1/2 particles with time-dependent Hamiltonian

$$\mathcal{H}(t) = -J \sum_{i=1}^{L-1} \sigma_i^z \sigma_{i+1}^z - h(t) \sum_{i=1}^L \sigma_i^x, \quad (1)$$

where J is the Ising coupling, $h(t) = (h_0/2) \cos(\omega t)$ is the oscillating transverse field, and σ_i^α are Pauli matrices. We initialize the system in the ground state of the static Hamiltonian $\mathcal{H}_{\text{static}} = \mathcal{H}(t)|_{t=0}$ and evolve under $\mathcal{H}(t)$ using time-dependent variational principle (TDVP) [67–69] for matrix product states [70], as implemented in the ITensor’s library [71] (see Supplemental Material [66]). Note that our results are independent of the specific Floquet drive.

Our primary focus is the entanglement dynamics of subsystem A , comprising the first L_A spins. From the reduced density matrix $\rho_A = \text{Tr}_{\bar{A}} |\psi(t)\rangle \langle \psi(t)|$ ($\bar{A}$ is the remaining $L - L_A$ sites), we extract Schmidt values $\lambda_i(t)$ (which satisfies $\sum_i \lambda_i = 1$ at each instant of time t) and define the entanglement Hamiltonian $\mathcal{H}_{\text{ent}}(t)$ via $\rho_A(t) \equiv e^{-\mathcal{H}_{\text{ent}}(t)}$ [18,39]. Since they commute, the eigenstates are shared by $\mathcal{H}_{\text{ent}}(t)$ and $\rho_A(t)$ at each instant of time. We probe the dynamics of $\mathcal{H}_{\text{ent}}(t)$ by examining its instantaneous eigenspectrum, $\mathcal{H}_{\text{ent}}(t)|\lambda_n(t)\rangle = \epsilon_n(t)|\lambda_n(t)\rangle$, and the expectation values of subsystem operators within these states. Here, the index $n = 0, 1, 2, \dots$ labels the eigenstates

with eigenvalues ϵ_n in ascending order, where ϵ_0 denotes the “ground-state” eigenvalue. The transformation $\lambda_n = e^{-\epsilon_n}$ gives the eigenvalues of the reduced density matrix ρ_A (the Schmidt values), with λ_0 being the largest. Note that the reduced density matrix ρ_A allows us to evaluate all Rényi entropies $S_n(\rho_A) = (1/(1-n)) \ln(\sum_{i=1}^r \lambda_i^n)$, where the min-entropy ($n \rightarrow \infty$) is given by $S_{\text{min}} = -\ln \lambda_0 = \epsilon_0$ (ground-state energy of the EH). Moreover, a fictitious temperature $1/n$ can be associated with the EH (see Ref. [53]).

TETs are a universal consequence at all driving frequencies provided (i) the driven Hamiltonian and (ii) the initial state preserve the global $\mathbb{Z}_2$ symmetry, and (iii) $\rho_A(t)$ has support in both subsystem-parity sectors. We quantify (iii) by the sector weights $w_{\pm}(t) = \text{Tr}[P_{\pm} \rho_A(t)]$, with $P_{\pm} = (\mathbb{1}_A \pm P_A)/2$ and $P_A = \prod_{i \in A} \sigma_i^x$. Conditions (i) and (ii) imply $[\rho_A(t), P_A] = 0$, which we verify using $C(t) = \|\rho_A(t), P_A\|$. Within this symmetry-preserving regime, the critical times $t_c^{(k)}$ are selected by the operational criterion $w_+(t_c^{(k)}) = w_-(t_c^{(k)})$ (within the evolution window), at which the Schmidt gap closes and the leading Schmidt vectors exchange subsystem-parity discontinuously. By contrast, an isolated suppression of the Schmidt gap or a smooth parity drift—even if accompanied by a sector-weight crossing—indicates a rounded crossover rather than a TET (see Sec. III of Supplemental Material [66]).

A crossing in the two largest Schmidt values, $\lambda_0(t)$ and $\lambda_1(t)$, signifies a fundamental reorganization of the ES, corresponding to a nonanalyticity in the ground-state energy $\epsilon_0(t)$ of $\mathcal{H}_{\text{ent}}(t)$ (with fictitious temperature $T_{\text{fict}} = \lim_{n \rightarrow \infty} (1/n) = 0$), signaling a *sharp* temporal quantum phase transition in the EH. Surprisingly, we observe this behavior from the adiabatic to the high-frequency regime. This behavior emerges when the global $\mathbb{Z}_2$ symmetry is preserved by the driven Hamiltonian and respected by the initial state, with critical times occurring at sector-weight crossings $w_+(t_c^{(k)}) = w_-(t_c^{(k)})$. Conversely, $\mathbb{Z}_2$ -breaking initial states (including symmetry-broken ferromagnetic ground states as well as product states such as domain wall and random product states) do not exhibit TET, independent of the drive protocol (see Sec. III of Supplemental Material [66]).

To diagnose dynamical transitions within the entanglement spectrum, we introduce and track specific observables designed to detect symmetry breaking. The central quantity is the “entanglement echo” $E(t) = \langle \lambda_0(0) | \lambda_0(t) \rangle$, which measures the fidelity of the instantaneous entanglement ground state to its initial configuration [60]. A vanishing echo signals an orthogonalization of $|\lambda_0(t)\rangle$, suggesting a crossing into a distinct symmetry sector. To directly test this, we compute the expectation values of symmetry operators within the entanglement eigenstates. Specifically, we monitor the subsystem parity $\langle \lambda_n(t) | P_A | \lambda_n(t) \rangle$. A spontaneous

change in the parity of the dominant state $|\lambda_0(t)\rangle$, coinciding with a vanishing entanglement echo and a vanishing Schmidt gap $\lambda_0 - \lambda_1$, constitutes the hallmark of a TET. For each subsequent interval, the dynamics alternate between two dwell times: T_- , during which the dominant state carries $\langle P_A \rangle = -1$, and T_+ , during which it carries $\langle P_A \rangle = +1$. At intermediate drives ($\omega \gtrsim 7$), these intervals become individually regular yet remain unequal, $T_- \neq T_+$, evidencing partial “Floquet inheritance” by the EH. For higher frequencies ($\omega \gtrsim 10$), the alternation persists but the intervals synchronize, $T_- \approx T_+ \equiv T_c$, and T_c saturates to an ω -independent constant value (Fig. 3). This synchronization and saturation indicate complete Floquet inheritance: the EH dynamics are governed by a high-frequency effective (Floquet-Magnus) description, in which the entanglement transitions form a uniformly spaced temporal lattice set by an emergent, drive-induced timescale rather than the bare period. See Table II and Secs. III and IV B in Supplemental Material [66] for further details.

Unless otherwise noted, we use $L = 24$ (open boundaries), $L_A = 4-12$, $J = 1.0$, $h_0 = 2.0$ (corresponding to equilibrium criticality), and $\omega = 5.0$. Time steps $dt \leq 0.1/\omega$ ensure numerical stability; convergence is verified in Supplemental Material [66].

Temporal entanglement transitions—The combined signatures of a TET are unambiguously observed in the driven TFIM (Fig. 1, $L_A = 9$). The Schmidt gap $\Delta\lambda = \lambda_0 - \lambda_1$ [Fig. 1(a)] closes to numerical precision at critical times $t_c^{(k)}$ (with first critical time $t_c^{(k=1)} \equiv t^*$), signaling energy-level crossing in $\mathcal{H}_{\text{ent}}(t)$. Concurrently, the entanglement echo $E(t) = \langle \lambda_0(0) | \lambda_0(t) \rangle$ [Fig. 1(b)] vanishes at odd $t_c^{(k=\text{odd})}$, confirming that $|\lambda_0(t_c)\rangle$ orthogonalizes into a distinct symmetry sector. The subsystem parity $\langle P_A \rangle$ [Fig. 1(c)] flips discontinuously at each $t_c^{(k)}$ between $+1$ and -1 , evidencing dynamical spontaneous $\mathbb{Z}_2$ breaking with respect to the largest Schmidt vector $|\lambda_0(t)\rangle$, while the first excited state $|\lambda_1(t)\rangle$ carries opposite parity.

We observe these signatures across all nonzero driving frequencies, indicating the generic nature of this phenomenon in the periodically driven Ising chain. While the transitions remain sharp, the spacing of critical times $t_c^{(k)}$ becomes nearly periodic only at higher driving frequencies, indicating a crossover in the timing (Floquet inheritance) rather than in the transition itself (see Supplemental Material [66]).

The synchronization of these three diagnostics: the closing of the Schmidt gap, the vanishing of the entanglement echo, and the discontinuous flip in parity, provides definitive evidence of a TET. These are not independent events but are intrinsically linked manifestations of the same underlying phenomenon: a periodically driven, dynamical quantum phase transition of the EH $\mathcal{H}_{\text{ent}}(t)$.

Finite-size scaling—The TETs are marked by nonanalytic kinks in the ground-state energy $\epsilon_0(t) = -\ln \lambda_0(t)$ of

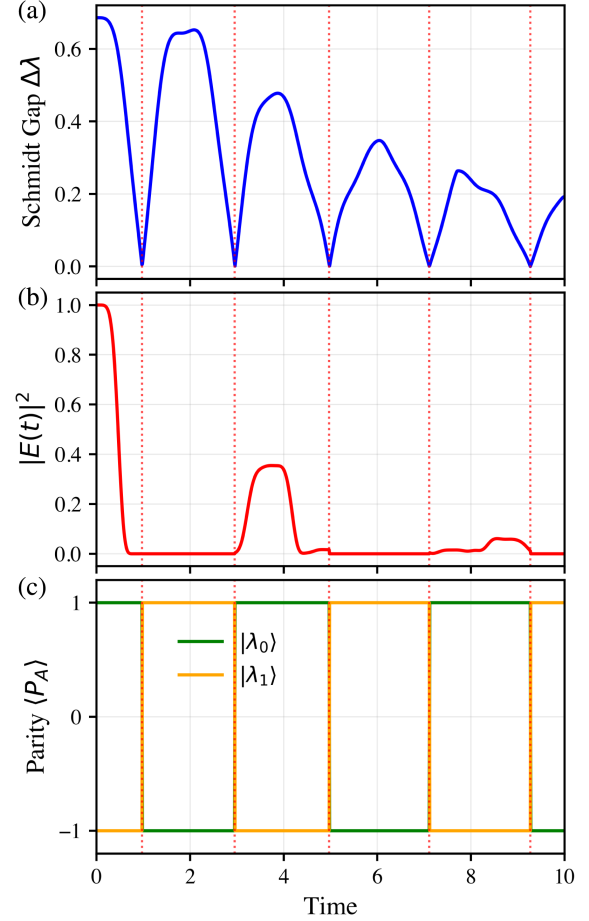


FIG. 1. TETs in the driven TFIM. (a) Schmidt gap $\Delta\lambda = \lambda_0 - \lambda_1$ closing periodically at critical times. (b) Entanglement echo $|E(t)|^2$ vanishing at odd critical times $t_c^{(k=\text{odd})}$, as the dominant Schmidt vector $|\lambda_0\rangle$ orthogonalizes into a distinct symmetry sector. (c) Subsystem-parity expectations showing dynamical spontaneous $\mathbb{Z}_2$ -symmetry breaking in the entanglement ground state (green) and complementary behavior in the first excited state (orange). The alternating parity pattern physically underlies the echo’s behavior. Red vertical lines mark critical times of symmetry breaking and are overlaid across all panels to provide a synchronized, consistent picture. Parameters: $L = 24$, $L_A = 9$, $J = 1.0$, $h_0 = 2.0$, $\omega = 5.0$, $dt = 0.01$.

the EH. To establish the critical nature and universality of TETs for the critical initial state (where all three conditions are robustly satisfied in the short-time dynamics), we perform comprehensive finite-size scaling analysis across subsystem sizes $L_A = 4-12$.

Figure 2 demonstrates the scaling properties of the first critical time $t_c^{(1)} = t^*$ and the minimum Schmidt-gap density S_{min}/L_A at criticality. The critical time exhibits power-law scaling $t^*/L_A \propto L_A^{-1/\nu}$ with critical exponent $\nu \simeq 1.00$ [Fig. 2(a)] that corresponds to the divergence of correlation length. Simultaneously, the critical entropy density follows $S_{\text{min}}/L_A \propto L_A^{-a}$ with $a \simeq 1$ [Fig. 2(b)]. Surprisingly, the correlation length exponent $\nu = 1$

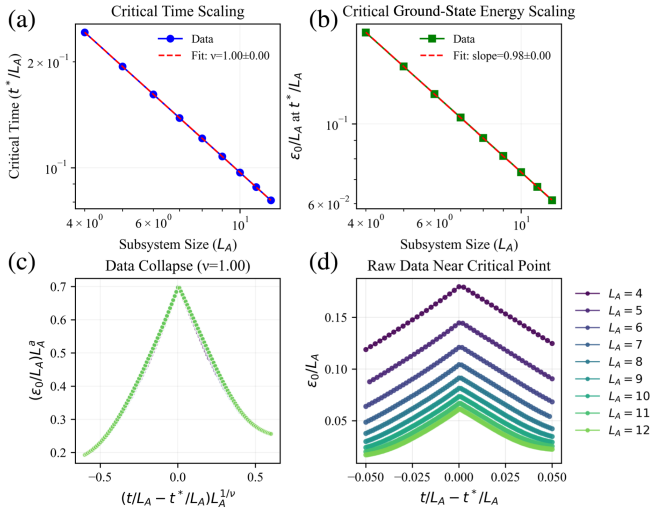


FIG. 2. Finite-size scaling analysis of TET starting with critical initial state ($h_0/2 = 1.0$). (a) Critical time scaling $t^*/L_A \propto L_A^{-1/\nu}$ with $\nu = 1.00$. (b) Critical entropy density scaling $\epsilon_0/L_A \propto L_A^{-a}$ with $a = 1.00$. (c) Universal data collapse using scaling ansatz in Eq. (2). (d) Raw data before scaling collapse. The exponent $\nu = 1$ establishes the same universality class for our driven non-equilibrium entanglement spectrum as equilibrium 2D classical Ising/1D quantum TFIM. Parameters: $L = 24$, $J = 1.0$, $h_0 = 2.0$, $\omega = 5.0$, $dt = 0.01$.

establishes this as a continuous quantum phase transition for all ranges of driving frequencies, belonging to the same universality class as the equilibrium two-dimensional (2D) classical Ising/1D quantum TFIM. Note that this exponent match $\nu = 1$ appears coincidental; TETs seem to emerge independent of the equilibrium phase diagram, as confirmed in Supplemental Material [66].

The universality of these transitions for the critical initial state is demonstrated through data collapse using the scaling ansatz (recall $\epsilon_0 = S_{\min}$),

$$\frac{\epsilon_0}{L_A} = \frac{1}{L_A^a} \mathcal{F} \left[\left(\frac{t}{L_A} - \frac{t^*}{L_A} \right) L_A^{1/\nu} \right], \quad (2)$$

where $\mathcal{F}$ is a universal scaling function, and ν is the critical exponent corresponding to diverging correlation length. For our critical initial state, t^* occurs within the simulated time window for all driving frequencies studied, enabling a uniform finite-size scaling analysis from the adiabatic to the high-frequency regime. Figure 2(c) shows excellent collapse of data from all subsystem sizes onto a universal curve, validating the scaling hypothesis. The agreement is further verified in Fig. 2(d), which shows the raw data near the critical point.

Significantly, the same exponent describes all subsequent kinks at $t_c^{(k \geq 1)}$ for higher driving frequencies ($\omega \gtrsim 5.0$ for our parameter choices), where the EH inherits Floquet-like periodicity. This universality across multiple transitions suggests a common underlying fixed point. For

the critical initial state, the exponent $\nu \simeq 1.0$ defines a new universality class for nonequilibrium entanglement dynamics in driven systems, which appears to be completely decoupled from the underlying equilibrium criticality (more on this below).

Effective steady state at high frequency—At high driving frequencies, TETs acquire an intrinsic timescale explained by Floquet-Magnus theory [72–74]. We decompose the time-dependent Hamiltonian as $\mathcal{H}(t) = \mathcal{A} + \mathcal{B} \cos(\omega t)$, where $\mathcal{A} = -J \sum_i \sigma_i^z \sigma_{i+1}^z$ and $\mathcal{B} = -(h_0/2) \sum_i \sigma_i^x$. The effective time-independent Hamiltonian emerges as a systematic expansion $\mathcal{H}_{\text{eff}} = \mathcal{H}_0 + \mathcal{H}_1 + \mathcal{H}_2 + \dots [\mathcal{H}_{(n)} \text{ is of order } \mathcal{O}(\omega^{-n})]$, where the leading corrections are

$$\begin{aligned} \mathcal{H}_{\text{eff}} = & -J \left(1 + \frac{h_0^2}{2\omega^2} \right) \sum_{i=1}^{L-1} \sigma_i^z \sigma_{i+1}^z + \frac{h_0^2 J}{2\omega^2} \sum_{i=1}^{L-1} \sigma_i^y \sigma_{i+1}^y \\ & - \frac{2h_0 J^2}{\omega^2} (\sigma_1^x + \sigma_L^x) - \frac{4h_0 J^2}{\omega^2} \sum_{i=2}^{L-1} \sigma_i^x \\ & - \frac{4h_0 J^2}{\omega^2} \sum_{i=2}^{L-1} \sigma_{i-1}^z \sigma_i^x \sigma_{i+1}^z + \mathcal{O}(\omega^{-3}). \end{aligned} \quad (3)$$

Beyond renormalizing the Ising coupling, the expansion generates new terms: YY interactions, enhanced transverse fields at boundaries, and crucially, three-body interactions $\sim \sigma_{i-1}^z \sigma_i^x \sigma_{i+1}^z$ that couple neighboring bonds through local spin flips.

As demonstrated in Supplemental Material [66], exact time evolution under $\mathcal{H}(t)$ shows good agreement with that under $\mathcal{H}_{\text{eff}}$ at higher frequencies, with entanglement entropy, Schmidt-gap dynamics, and state fidelity exhibiting near-perfect overlap. TETs persist in the effective evolution with identical critical exponent ν , confirming that these phenomena represent genuine features of the driven steady state where the EH develops an intrinsic timescale.

Discussion and conclusion—We have demonstrated that the Floquet-driven Ising chain hosts TETs characterized by dynamical spontaneous symmetry breaking within the EH. These transitions exhibit universal critical behavior with exponent $\nu = 1$ for critical initial state ($h_0/2 = 1.0$), identical to equilibrium quantum criticality in the transverse-field Ising universality class, yet emerge from non-equilibrium dynamics that are decoupled from static criticality, as shown by their persistence across different equilibrium phases ($h_0 = 1.6$ – 2.4 , see Supplemental Material [66]).

This Letter establishes that (1) the ES develops non-analyticities for all ω , with periodic reorganizations at higher frequencies; (2) transitions are diagnosed by synchronized Schmidt-gap closure, entanglement echo vanishing, and parity flipping, evidencing dynamical spontaneous symmetry breaking; (3) finite-size scaling for the critical initial state reveals universal $\nu = 1$ critical behavior

TABLE I. Conditions for TETs.

System	Drive $\mathbb{Z}_2$	Initial state $\mathbb{Z}_2$	TETs
Equilibrium TFIM	...	...	No
Driven TFIM	Yes	No (symmetry broken)	No
Driven TFIM	Yes	Yes	Yes ^a
Conserved-charge models	...	Any	Yes ^b

^aProvided $\rho_A(t)$ carries weight in both subsystem-parity sectors, with TETs occurring when $w_+(t_c^{(k)}) = w_-(t_c^{(k)})$ while $[\rho_A, P_A]$ remains negligible, see Supplemental Material Sec. III [66]. Many standard product-state preparations are $\mathbb{Z}_2$ breaking and thus excluded, while $\mathbb{Z}_2$ -symmetric (often entangled) initial states are allowed.

^bOnly when ρ_A is dynamically forced between disconnected sectors [52,53].

across frequencies; (4) at high frequencies, Floquet-Magnus theory provides an effective description accurately capturing the transition; and (5) TETs occur precisely when the sector weights become equal, $w_+(t_c^{(k)}) = w_-(t_c^{(k)})$, provided the driven Hamiltonian and initial state preserve global $\mathbb{Z}_2$ symmetry (Table I; also see Supplemental Material, Sec. III [66]). Experimental access to these transitions is feasible: the key observables (Schmidt gap, parity expectations, entanglement echo) require only low-lying eigenstates of the EH, measurable via randomized measurements [75,76], or Ramsey spectroscopy [77].

Figure 3 shows critical times t^* saturating to ω -independent values at high frequencies, indicating intrinsic timescales of the driven steady state. The collapse of t^* curves across subsystem sizes demonstrates universal Floquet inheritance, where the EH acquires periodicity and full data collapse is satisfied by the same $\nu = 1$ exponent for all transitions [66].

These findings establish TETs as fundamental aspects of nonequilibrium Floquet quantum dynamics. Notably, previous work on Floquet symmetry-protected topological systems has demonstrated band crossings in entanglement spectrum [78]; however, the question of robust universality has been an open question. This is what we have addressed in this Letter, where our TETs arise whenever the driven Hamiltonian and initial state respect global $\mathbb{Z}_2$, with critical times determined by sector-weight crossings $w_+(t_c^{(k)}) = w_-(t_c^{(k)})$, yielding a nonanalytic reorganization (quantum phase transition) of the EH with Ising-class critical exponents $\nu = 1$. TETs define a class of nonequilibrium criticality distinct from Loschmidt echo singularities and magnetization dynamics (see Supplemental Material [66]). The exact Jordan-Wigner equivalence between the TFIM and Kitaev chain suggests that these transitions should also manifest in driven topological superconductors, opening pathways to entanglement-based probes of Floquet Majorana physics [79,80]. The requirement of symmetry-preserving initial conditions with critical times selected by sector-weight degeneracies motivates future exploration of

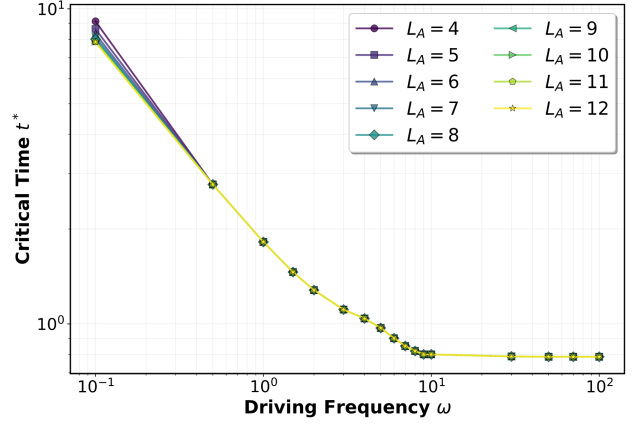


FIG. 3. Frequency dependence of the first critical time t^* across subsystem sizes $L_A = 4$ –12 for critical initial state ($h_0/2 = 1.0$). At low frequencies, $t^* \propto \omega^{-1}$ (adiabatic regime), while at high frequencies ($\omega \gtrsim 10$), t^* saturates to frequency-independent values determined solely by subsystem size, indicating a crossover to Floquet steady-state behavior where the EH develops an intrinsic timescale. The universal saturation indicates that TETs become intrinsic properties of the effective time-independent dynamics rather than driven phenomena, validating the Floquet-Magnus description and establishing characteristic timescales independent of the external driving protocol. Parameters: $L = 24$, $J = 1.0$, $h_0 = 2.0$. Time steps are chosen as $dt = 0.01$ for $\omega = [0.1, 10.0]$, $dt = 0.002$ for $\omega = \{30, 50\}$ and $dt = 0.001$ for $\omega = \{70, 100\}$. A total of 153 data points in this plot show excellent collapse (see Fig. 9 of Supplemental Material [66]).

how symmetry and entanglement resources jointly control nonequilibrium criticality structures in quantum resource theories [81]. Beyond the TFIM (despite its free-fermion Jordan-Wigner mapping), our symmetry and sector-competition criterion [global symmetry, symmetric initial state, and sector-weight equality $w_+(t) = w_-(t)$] suggests analogous transitions in interacting $\mathbb{Z}_2$ -symmetric chains and, more broadly, in other driven systems with discrete symmetries (higher-spin chains, symmetry-protected topological phases, and lattice gauge theories), with experimental prospects in cold-atom and trapped-ion platforms [75,82–84].

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Data availability—The data that support the findings of this article are openly available [85], embargo periods may apply.

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