Algebraic versus Exponential Decoherence in Dissipative Many-Particle Systems

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The interplay between dissipation and internal interactions in quantum many-body systems gives rise to a wealth of novel phenomena. Here we investigate spin-1/2 chains with uniform local couplings to a Markovian environment using the time-dependent density matrix renormalization group. For the open XXZ model, we discover that the decoherence time diverges in the thermodynamic limit. The coherence decay is then algebraic instead of exponential. This is due to a vanishing gap in the spectrum of the corresponding Liouville superoperator and can be explained on the basis of a perturbative treatment. In contrast, decoherence in the open transverse-field Ising model is found to be always exponential. In this case, the internal interactions can both facilitate and impede the environment-induced decoherence.

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Introduction.—Every quantum system that we wish to study or model is inevitably coupled to some form of environment and hence an *open* quantum system [1–5]. The coupling to the environment can for example induce decay of quantum coherence (decoherence) and dissipation. To take account of these effects is particularly interesting and complex when the system itself is already an interacting many-body system. Recently, first theoretical [6–20] and experimental [21–23] investigations were presented for this scenario. Whereas decoherence is usually seen as an obstacle for quantum simulation [24] and information processing [25,26], it has also been suggested that one could exploit the effect for the preparation of desired many-body states by engineering the dissipative processes [27–30].

For *Markovian* environments [31–33], the system state ρ evolves according to the Lindblad master equation $\partial_t\rho(t) = \hat{\mathcal{L}}\rho(t)$. The decoherence behavior is determined by the spectral gap of the Liouville superoperator $\hat{\mathcal{L}}$. For the textbook-type scenarios of finite-size systems or many-body systems without interaction, the gap is necessarily finite and, consequently, quantum coherence decays exponentially with time [1–4]. This imposes strong limitations for many quantum simulation and information processing applications. In this Letter, we find however that Markovianity does *not* necessarily imply exponential decoherence. For cases where the system itself is a many-body system with internal interactions as displayed in Fig. 1, we show that the Liouvillian gap can close in the thermodynamic limit and lead to a divergent decoherence time due to an interplay of dissipation and interaction. The coherence decay then becomes algebraic, i.e., follows a power law, instead of being exponential. This novel phenomenon is reminiscent of the importance of the Hamiltonian gap for closed many-body systems, which is intimately related to quantum phase transitions [34], the scaling behavior of entanglement, and the spatial decay of quantum correlations [35,36].

Specifically, let us consider spin-1/2 lattice systems with local couplings to a Markovian environment. The Lindblad master equation [31–33] reads ($\hbar = 1$)

$$\partial_t\rho = \hat{\mathcal{L}}\rho = \hat{\mathcal{H}}\rho + \hat{\mathcal{D}}\rho = -i[H,\rho] + \gamma\sum_i\Big(L_i\rho L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i,\rho\}\Big). \quad (1)$$

The Liouville superoperator $\hat{\mathcal{L}}$ contains two parts: $\hat{\mathcal{H}}\rho = -i[H,\rho]$ generates the evolution due to the system Hamiltonian H whereas the dissipative process is described by $\hat{\mathcal{D}}\rho$. This equation of motion describes, for example, systems in the weak-coupling regime (Born-Markov-secular approximation), singular-coupling regime, or the time average of a system with stochastic Hamiltonian terms (Supplemental Material [37]). Throughout the Letter we consider uniform Lindblad operators $L_i = S_i^z$ with a coupling strength γ. This type of coupling was first introduced in the study of dissipative two-state systems [38] and, as discussed below, is widely applicable for the description of environment-induced decoherence. For the simplest case of a single spin with $H = 0$, the master equation (1) predicts the typical exponential decay of off-diagonal density matrix elements $\rho_{\uparrow,\downarrow}(t) \sim e^{-\gamma t/4}$, implying a rapid destruction of superpositions of states (quantum coherence).

In this Letter, we demonstrate using the example of spin-1/2 chains with internal interactions and the uniform couplings to the environment how the interplay

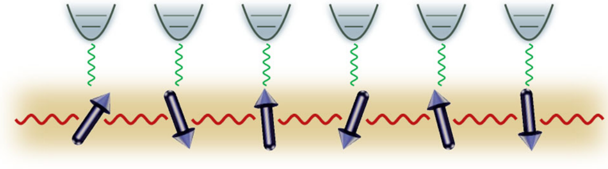

FIG. 1 (color online). A quantum spin chain uniformly coupled to the environment via the z components of the spins.

between interaction and dissipation can fundamentally alter the decoherence behavior. In particular, (i) for the Heisenberg *XXZ* model in the thermodynamic limit, the coherence decay becomes algebraic instead of exponential, and (ii) for the transverse-field Ising model, the coherence decay remains exponential, but the internal interactions can both facilitate and impede the decoherence in comparison to the noninteracting case. We provide quasiexact numerical results using the time-dependent density matrix renormalization group (tDMRG) method [39–42] and explain both features on the basis of a perturbative treatment for the Liouville superoperator.

Experimental realizations and applications.—Besides being of fundamental theoretical interest, the two dissipative models addressed in this Letter are of broad experimental and technological relevance. We shortly mention a few examples. A uniform coupling to the environment via Lindblad operators $L_i = S_i^z$ occurs for example naturally in quantum computer architectures [43,44] based on superconducting flux qubits through fluctuations of the external magnetic flux [45–47]. Inductive coupling of flux qubits yields the Ising-type interaction $S_i^z S_j^z$ [48–50]. In ultracold atom systems where both interaction and dissipation can be controlled, the corresponding Lindblad operators $L_i = n_i$ describe laser fluctuations and incoherent scattering of the laser light [51–53]. With quantum dot spin qubits [54,55], one can implement both the transverse Ising model [56] and the Heisenberg model [54], where $L_i = S_i^z$ describes the effect of variations in the longitudinal nuclear magnetic field.

Liouville spectrum.—Before addressing the two specific spin models, some general remarks are appropriate. First, as long as $L_i^\dagger = L_i \,\forall_i$, the maximally mixed state $\rho_0 \propto \mathbb{1}$ is always a steady state ($\partial_t \rho = 0$) of Eq. (1). For the models addressed in this Letter, ρ_0 or restrictions of it to certain symmetry sectors are the unique steady states. Although all the initial states will eventually converge to such a steady state, the approach towards it is typically highly nontrivial and depends on the quantum many-body Hamiltonian. The dynamics is governed by the non-Hermitian superoperator $\hat{\mathcal{L}}$. Its eigenvalues λ_α have nonpositive real parts $\mathrm{Re}\lambda_\alpha \le 0$, and the steady state has the eigenvalue $\lambda_0 = 0$. We call

$$\Delta := \min_{\alpha>0} \mathrm{Re}(-\lambda_\alpha) \quad (2)$$

the spectral gap of the Liouville operator. If the gap is finite, the distance of the time-evolved state to the steady state will decrease exponentially with time, and Δ sets the corresponding relaxation rate. However, as we will see below, the many-body interactions in the system may qualitatively alter the dynamics by closing the gap of $\hat{\mathcal{L}}$ in the thermodynamic limit, which gives rise to a novel algebraic decoherence behavior.

Algebraic coherence decay in the open XXZ model.—First, let us consider the spin-1/2 *XXZ* chain

$$H_{XXZ} = \sum_i \left[\frac{J_{xy}}{2} (S_i^+ S_{i+1}^- + S_i^- S_{i+1}^+) + J_z S_i^z S_{i+1}^z \right] \quad (3)$$

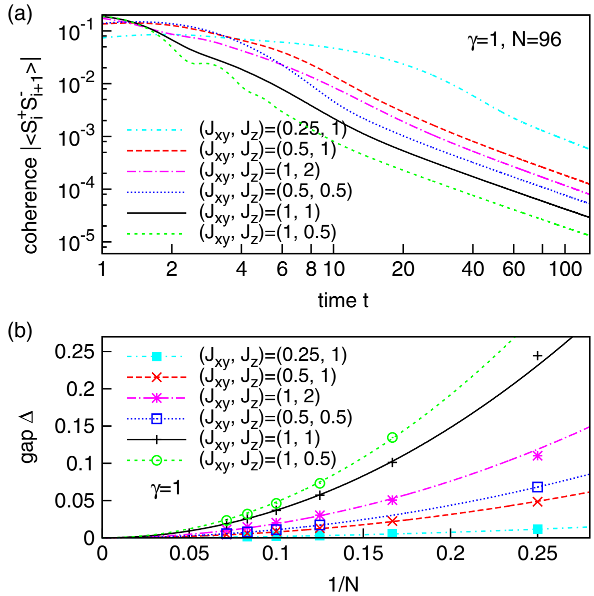

FIG. 2 (color online). (a) Power-law decay of the off-diagonal density matrix element $C = \langle S_i^+ S_{i+1}^- \rangle$ in the dissipative *XXZ* chain (3) of length $N = 96$ for different J_{xy}, J_z, and fixed bath coupling $\gamma = 1$, evaluated in the center of the chain. (b) Finite-size scaling of the gap (2) of the Liouville superoperator $\hat{\mathcal{L}}$ for the open *XXZ* model, obtained by exact diagonalization.

uniformly coupled to the environment via the z components of the spins $L_i = S_i^z$. We study the time evolution of the system density matrix $\rho(t)$ based on the master equation (1) with the initial state $\rho(0) = |\Psi_0\rangle\langle\Psi_0|$ being the Néel state $|\Psi_0\rangle = |\uparrow\downarrow \cdots \uparrow\downarrow\rangle$. In the absence of dissipation ($\gamma = 0$), the time evolution for this setup has, for example, been studied in the context of quantum quenches [57–59], where the long-time behavior decisively depends on J_z/J_{xy}. In this model, the total magnetization $\sum_i S_i^z$ is conserved. As a consequence, the off-diagonal element $\rho_{\uparrow\downarrow}^i = \langle S_i^+ \rangle$ of the single-site density matrices are strictly zero for all times and can not be used to monitor the decoherence. Instead, we can choose the off-diagonal term $C = \langle S_i^+ S_{i+1}^- \rangle$ of the two-site density matrix to quantify the decoherence, where sites i and $i+1$ are located in the center of the chain. For the simplest case of a two-site system ($N = 2$), it is easy to show that the off-diagonal element C decays exponentially.

In order to study the effects of the many-body correlations on the decoherence, we employ tDMRG [39–42]. As shown in Ref. [60], the propagator $\exp(\hat{\mathcal{L}}t)$ can be approximated by a circuit of two-site gates with an accuracy that is well controlled in terms of the operationally relevant $1 \to 1$ norm. Here, we specifically employ a fourth-order Trotter-Suzuki decomposition with a time step of size $\Delta t = 0.125$. Starting from certain product states $\rho(0)$, the time-evolved states are obtained by applying the local Trotter gates and approximating $\rho(t)$ by matrix product states [61,62]. The essence of the DMRG procedure is to express $\rho(t)$ in every step of the simulation in a reduced Hilbert-Schmidt orthonormal operator basis $\{O_i^L \otimes O_i^R\}$ for a spatial splitting of the system into a left and a right part so that $\rho(t) = \sum_i \nu_i O_i^L \otimes O_i^R$. The approximation consists in discarding all components i with weights $\nu_i^2/\sum_j \nu_j^2$ below a certain threshold ϵ (between 10^{-10} and 10^{-12} in this work). One has to ensure convergence of the numerical results with respect to the truncation threshold ϵ and the system size N to capture the physics of the thermodynamic limit. See the Supplemental Material [37].

The evolution of the coherence $C(t)$ in open XXZ chains is shown in Fig. 2. In the long-time limit, we find the coherence to decay algebraically, instead of exponentially, according to the power law

$$C(t) \propto t^{-\eta} \quad \text{with} \quad \eta \approx 1.58. \tag{4}$$

The exponent η is in the studied parameter regime independent of the system parameters J_{xy}, J_z, and γ. In general, an algebraic decay implies the absence of a characteristic time scale in the long-time dynamics. It results from the vanishing of the gap Δ of the Liouvillian $\hat{\mathcal{L}}$ in the thermodynamic limit. That this is indeed the case can be verified numerically by exact diagonalization as shown in Fig. 2(b).

To get a better understanding of this phenomenon, let us perform a second-order perturbative analysis to derive an effective Liouvillian $\hat{\mathcal{L}}_{\text{eff}}$ for the limit $\gamma \gg |J_z|, |J_{xy}|$ of strong dissipation. The Liouvillian can be split into an unperturbed part $\hat{\mathcal{L}}_0\rho := -i[H_z, \rho] + \hat{\mathcal{D}}\rho$, where $H_z = J_z\sum_i S_i^z S_{i+1}^z$, and the perturbation $\hat{\mathcal{L}}_1\rho := -i[H_{xy}, \rho]$ with $H_{xy} = (J_{xy}/2)\sum_i(S_i^+ S_{i+1}^- + S_i^- S_{i+1}^+)$. The steady states of $\hat{\mathcal{L}}_0$ (eigenvalue $\lambda_0 = 0$) are $\rho_0^{\boldsymbol{\sigma}} = |\boldsymbol{\sigma}\rangle\langle\boldsymbol{\sigma}|$, where $|\boldsymbol{\sigma}\rangle = |\sigma_1, \ldots, \sigma_N\rangle$ are the $\{S_i^z\}$ eigenstates spanning the Hilbert space of the spin configurations with zero total magnetization. The effect of a small coupling J_{xy} is to lift the degeneracy in the steady-state manifold through a superexchange process that leads us to an effective Liouvillian $\hat{\mathcal{L}}_{\text{eff}}$, constrained to the subspace $\mathbb{H}$ spanned by the operators $\rho_0^{\boldsymbol{\sigma}}$. $\mathbb{H}$ is to be understood as a subspace of the vector space $\mathcal{B}(\mathcal{H})$ of linear operators on the Hilbert space $\mathcal{H}$, i.e., $\hat{\mathcal{L}}$: $\mathcal{B}(\mathcal{H}) \to \mathcal{B}(\mathcal{H})$ and $\hat{\mathcal{L}}_{\text{eff}}$: $\mathbb{H} \to \mathbb{H}$. One obtains

$$\hat{\mathcal{L}}_{\text{eff}} = \hat{\mathcal{P}}\hat{\mathcal{L}}_1 \frac{1}{\lambda_0 - \hat{\mathcal{L}}_0} \hat{\mathcal{L}}_1 \hat{\mathcal{P}}. \tag{5}$$

$\hat{\mathcal{P}}$ is the projector onto the subspace $\mathbb{H}$. The intermediate states in the perturbation theory are of the form $\Lambda_1^{\boldsymbol{\sigma}\boldsymbol{\sigma}'} = |\boldsymbol{\sigma}\rangle\langle\boldsymbol{\sigma}'|$, where $|\boldsymbol{\sigma}'\rangle = (S_i^+ S_{i+1}^- + S_i^- S_{i+1}^+)|\boldsymbol{\sigma}\rangle$ for some bond $(i, i+1)$. Their $\hat{\mathcal{L}}_0$ eigenvalues, needed to evaluate the denominator in Eq. (5), are $-\gamma$ or $-\gamma \pm iJ_z$, depending on $\boldsymbol{\sigma}$. However, the term $\pm iJ_z$ can be ignored as it represents an irrelevant contribution of order $1/\gamma^2$ to $\hat{\mathcal{L}}_{\text{eff}}$. The full calculation given in the Supplemental Material [37] shows that the matrix elements of the effective Liouvillian are identical with those of the ferromagnetic Heisenberg model

$$K = \frac{-J_{xy}^2}{\gamma} \sum_i \left[\frac{1}{2}(S_i^+ S_{i+1}^- + S_i^- S_{i+1}^-) + S_i^z S_{i+1}^z - \frac{1}{4}\right]$$

in the sense that

$$\hat{\mathcal{L}}_{\text{eff}}|\boldsymbol{\sigma}\rangle\langle\boldsymbol{\sigma}| = -\sum_{\boldsymbol{\sigma}'}\langle\boldsymbol{\sigma}'|K|\boldsymbol{\sigma}\rangle \cdot |\boldsymbol{\sigma}'\rangle\langle\boldsymbol{\sigma}'|. \tag{6}$$

As a consequence, at the level of the second-order perturbation theory, the gap (2) of the effective Liouvillian $\hat{\mathcal{L}}_{\text{eff}}$ is that of the Heisenberg ferromagnet K. Its gap vanishes as $1/N^2$ due to the quadratic spin-wave dispersion around zero momentum and the $2\pi/N$ spacing of the quasimomenta. This explains the quadratic behavior of the gaps Δ for the full model in Fig. 2(b).

Decoherence in the open transverse Ising model.— A second paradigmatic example is the dissipative transverse-field Ising chain

$$H_{\text{TI}} = \sum_i (J_z \sigma_i^z \sigma_{i+1}^z - h_x \sigma_i^x) = \sum_i (4J_z S_i^z S_{i+1}^z - 2h_x S_i^x) \tag{7}$$

with the interaction strength J_z, the transverse magnetic field h_x, and the Pauli matrices σ_i^α. To study the interplay of interaction and dissipation, we set for simplicity $h_x = 1$ and vary J_z and the bath coupling γ. As Lindblad operators, we choose again $L_i = S_i^z$ and study the time evolution of the system density matrix based on Eq. (1) starting from a fully polarized state, i.e., $\rho(0) = |\Psi_0'\rangle\langle\Psi_0'|$ with $|\Psi_0'\rangle = |\uparrow\uparrow\cdots\uparrow\uparrow\rangle$. Alternative initial states have also been checked. However, as we are foremost interested in the long-time behavior, the choice of the initial state is of minor importance. Let us first consider the noninteracting case with $J_z = 0$, which reduces to the decoherence problem of a single spin subject to an external field. In this case, the off-diagonal element $\rho_{\uparrow,\downarrow}^i = \langle S_i^+\rangle$ of the single-site reduced density matrix decays exponentially as $\rho_{\uparrow,\downarrow}^i(t) \sim e^{-\Delta_0 t}$, where the decay rate is $\Delta_0 = \gamma/4$ (as long as $\gamma \le 8|h_x|$; see the Supplemental Material [37]). For the interacting many-body system, one can use $|\rho_{\uparrow,\downarrow}^i(t)|$, with site i in the middle of the chain, to monitor the coherence decay. In contrast to the situation for the open XXZ model, we find here that the coherence always decreases exponentially as shown in the inset of Fig. 3(a),

$$|\rho_{\uparrow,\downarrow}^i(t)| = |\langle S_i^+(t)\rangle| \sim e^{-\Delta t}. \tag{8}$$

The decoherence rate (inverse relaxation time) Δ is determined by the interplay of the internal interaction and the dissipation.

For small J_z, the decoherence dynamics is well described by oscillations of exponentially decaying amplitude. For large J_z, $\rho_{\uparrow,\downarrow}^i(t)$ decays exponentially without oscillations. Now, let us turn to the question of whether the internal interaction facilitates or impedes the decoherence, i.e., whether the decoherence rate Δ is below or above that of the noninteracting case $J_z = 0$ with $\Delta_0 = \gamma/4$. As shown in Fig. 3(a), the answer to this question depends in an intricate manner on the values of γ and J_z. In the presence of weak dissipation (small γ), the

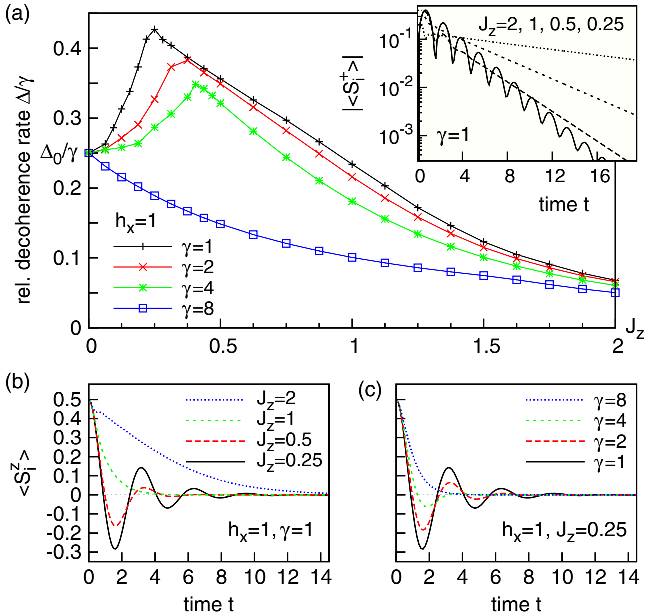

FIG. 3 (color online). (a) The relative decoherence rate Δ/γ [Eq. (8)] for the dissipative transverse Ising model (7) as a function of J_z for different bath couplings γ. (b) Time evolution of the magnetization $\langle S_i^z \rangle$ for fixed $\gamma = 1$ and different J_z values, where site i is in the middle of the chain. (c) Dynamics of $\langle S_i^z \rangle$ for fixed $J_z = 0.25$ and different γ values. In all cases, the system contained $N = 64$ sites.

dependence of Δ on J_z is nonmonotonic. The interaction facilitates the environment-induced decoherence ($\Delta > \Delta_0$) for small J_z, whereas it impedes the decoherence ($\Delta < \Delta_0$) for large J_z. For sufficiently strong dissipation, the interaction always suppresses the decoherence.

A qualitative understanding of the fact that interaction and dissipation cooperate to enhance the decoherence in the case of small J_z and γ can be gained by analyzing the magnetization dynamics $\langle S_i^z(t) \rangle$ for different J_z and γ values, as shown in Figs. 3(b) and 3(c). For small J_z and γ, $\langle S_i^z \rangle$ is well described by an exponentially decaying oscillation. Generally, for open many-body systems, the long-range quantum correlations are usually destroyed during the long-time dissipative dynamics. As a consequence, the quantum entanglement between a single spin and the rest of the system is weak. This allows us to explain the above observations in a mean-field framework corresponding to the decoupling of the interaction term $S_i^z S_{i+1}^z \sim S_i^z \langle S^z \rangle$. On a qualitative level, the decoherence in the long-time limit can be understood as that of a single spin in a constant transverse field and a longitudinal field $2\langle S^z(t) \rangle$ due to its nearest neighbors. Figures 3(b) and 3(c) show that, for small J_z and γ, the longitudinal field $\langle S^z(t) \rangle$ is quickly oscillating—hence, playing a role similar to that of noise and thus accelerating the decoherence. Once the oscillations of $\langle S^z(t) \rangle$ vanish (large J_z or γ), the decoherence is suppressed.

The second key observation, that strong interaction impedes the decoherence, can again be explained on the basis of a perturbative analysis, here in the limit of a weak magnetic field, $\gamma \gg |h_x|$. The field terms $\propto h_x$ of the Liouvillian are considered as a perturbation so that $\hat{\mathcal{L}} = \hat{\mathcal{L}}_0 + \hat{\mathcal{L}}_1$ with

$$\hat{\mathcal{L}}_0 \rho = -i[H_z, \rho] + \hat{\mathcal{D}}\rho \quad \text{and} \quad \hat{\mathcal{L}}_1 \rho = -i[H_x, \rho], \tag{9}$$

where $H_z = 4J_z \sum_i S_i^z S_{i+1}^z$ and $H_x = -2h_x \sum_i S_i^x$. In the second-order perturbation theory, the eigenoperators of $\hat{\mathcal{L}}_0$ are similar to those in the treatment of the open XXZ model (now the dynamics is not constrained to sectors of constant magnetization), but the intermediate states are different. Their $\hat{\mathcal{L}}_0$ eigenvalues are $-\gamma/2$ and $-\gamma/2 \pm i4J_z$. The effective Liouville superoperator (5) is again of the form of Eq. (6), and the effective Hamiltonian reads

$$K = \sum_i \left[\frac{\alpha + \alpha'}{4} - (\alpha - \alpha') S_{i-1}^z S_{i+1}^z \right] \left(\frac{1}{2} - S_i^x \right) \tag{10}$$

in this case, where $\alpha = 16h_x^2/\gamma$ and $\alpha' = 4h_x^2\gamma/[\gamma^2/4 + (4J_z)^2]$. On the basis of Eq. (10), one can show that the gap (2) of the effective Liouvillian has for small J_z a value $\lesssim (\alpha + \alpha')/4$. For sufficiently large J_z, the gap is given by α'. The corresponding eigenstate of K is the spin-wave-like state $\sum_j |\uparrow^x \cdots \uparrow^x \downarrow_j^x \downarrow_{j+1}^x \uparrow^x \cdots \uparrow^x \rangle$, where $S_i^x |\uparrow_i^x\rangle = (1/2)|\uparrow_i^x\rangle$. A detailed derivation is given in the Supplemental Material [37]. So the gap decays as $1/J_z^2$; i.e., strong interaction impedes decoherence as we have found in the quasiexact numerical analysis.

Conclusion.—In summary, we have studied the long-time dynamics of open quantum spin systems, discovering that the quantum many-body effects can significantly change the nature of the environment-induced decoherence by either altering the exponential coherence decay to being algebraic or, alternatively, by increasing or decreasing the decay rate. Besides illustrative quasiexact tDMRG simulations, we have explained those effects by a perturbative analysis. The latter also indicates that these phenomena are certainly not limited to spin chains. Generically, algebraic coherence decay will occur for models where the eigenspace of the dissipative terms is highly degenerate, and this degeneracy is then broken through interactions within the system. A further specific example is the Bose-Hubbard model with $L_i = n_i$. Another interesting direction for future investigations is that of driven-dissipative quantum many-body systems, where external forces drive the system far from equilibrium and the interplay between driving, dissipation, and internal interaction may give rise to further novel nonequilibrium phenomena.

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[37] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.111.150403 containing derivations of the Lindblad master equation for three important generic scenarios (weak coupling, singular coupling, and external stochastic fields), the detailed perturbative analyses of the open spin-$1/2$ XXZ model and the open transverse-field Ising model, the computations of exact decoherence rates for one and two spins, and the convergence analysis of the tDMRG results with respect to the system size N and the truncation threshold ϵ.

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