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Quantum dephasing dynamics in the presence of asymmetric random telegraph noise

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Random telegraph noise (RTN) has been widely used to describe the environmental effects on open quantum systems. In most cases, it is assumed that the environmental noise described by RTN has symmetric properties. However, in some important physical processes, the asymmetric characteristics of environmental noise play a crucial role in the dynamical evolution of the quantum systems. We theoretically study the dephasing dynamics of a two-level quantum system induced by RTN with asymmetric properties. Within the framework of the stochastic Liouville equation, we derive the exact expression of the decoherence function quantifying the coherence evolution of the quantum system. It is shown that, in contrast to the case of the symmetric RTN, the asymmetric RTN can induce a frequency shift and may lead to non-Markovian behavior in the decoherence dynamics of the quantum system. Furthermore, by adjusting the average transition rate, the transition rate difference, and the transition amplitude difference of the environmental noise, the decoherence dynamics of the quantum system can be effectively modulated.

Keywords: open systems, quantum decoherence, random telegraph noise, stochastic fluctuations

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1. Introduction

With the development of quantum technologies, the dynamics of open quantum systems have recently attracted widespread attention. Realistic quantum systems inevitably interact with their environments, leading to decoherence during the dynamical evolution.[1–13] In quantum information science, the loss of quantum coherence due to environmental noise is considered a major obstacle in the realization of quantum information processors.[14–18] Therefore, studying the dynamics of open quantum systems and understanding how the environment influences the time evolution of quantum systems are of great theoretical significance and practical importance for protecting quantum coherence, enabling precise quantum control, and improving quantum measurement techniques.[19–23]

Numerous theoretical frameworks have been developed to investigate the dynamics of open quantum systems.[24–55] Within the framework of Kubo–Anderson spectral diffusion theory, classical noise has been widely used to model the influences of the environments on open quantum systems.[56–59] Random telegraph noise (RTN) can be modeled as a stochastic two-state jump process with Markovian statistics, effectively simulating the dynamical effects induced by non-Gaussian environments.[60–64] In conventional studies, the RTN is often treated to be symmetric, based on some assumptions made under specific physical conditions. For instance, in the high temperature limit of quantum decoherence in qubit systems, the environmental noise exhibiting RTN statistics can be assumed to be symmetric with equal transition rates.[65,66] This is due to the fact that when the energy splitting of the fluctuator is less than a few $k_{\mathrm{B}}T$ with k_{B} being the Boltzmann constant and T denoting the environmental temperature, the transition rates of the environmental noise are of comparable magnitude.[45,60] However, in reality, the environmental noise with RTN statistics is not always symmetric. The asymmetric RTN has been commonly observed in experimental measurements of various physical systems, such as semiconductor devices,[67] quantum dots,[68] and graphene interferometers.[69] The quantum decoherence induced by asymmetric environmental noise has been observed in Josephson charge qubits.[70] The decoherence dynamics in the presence of asymmetric RTN has been studied by introducing asymmetric probabilities to describe the symmetric weight within some approximations.[71] To date, theoretical investigations on quantum dynamics under the influence of asymmetric RTN remain relatively scarce. In the presence of asymmetric RTN, the exact expression of the decoherence function has not yet been derived. To study how the asymmetric statistical property influences dynamical decoherence can help us better understand the dynamics of open quantum systems.

In this paper, we theoretically study the quantum dynam-

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ics of a two-level system induced by the asymmetric RTN. By means of the stochastic Liouville equation, we derive the exact expression of the decoherence function which quantifies the coherence evolution of the quantum system. It is shown that different from the case in the presence of the symmetric RTN, the asymmetric RTN gives rise to a frequency shift of the quantum system. Furthermore, by tuning the average transition rate, the transition rate difference, and the transition amplitude difference of the environmental noise, the quantum system can exhibit non-Markovian behavior or experience suppressed decoherence dynamics. Specifically, we consider two distinct cases in our analysis. When the transition rate is sufficiently large, the decoherence dynamics of the quantum system are always Markovian. In the long-time limit, increasing the average transition rate suppresses both the decoherence dynamics and the frequency shift. On the other hand, when the transition rate is sufficiently small, the decoherence dynamics become more complex. Variations in the average transition rate, the transition rate difference, and the transition amplitude difference can potentially trigger coherence recovery in the system, leading to non-Markovian behavior in its decoherence dynamics. In this regime, reducing the average transition rate enhances coherence recovery in a short time and also suppresses the decoherence dynamics in the long-time limit, while simultaneously increasing the frequency shift. Increasing the transition rate difference or decreasing the transition amplitude difference inhibits coherence recovery in a short time, but reduces the decoherence dynamics in the long-time limit. However, these two strategies have opposite effects on the frequency shift: the former increases it, whereas the latter decreases it.

This paper is arranged as follows. In Section 2, we introduce the theoretical framework of the quantum dynamics of a two-level system coupled to a stochastically fluctuating environment. In Section 3, we show the numerical results of the dephasing dynamics induced by the asymmetric RTN in detail. Then, in Section 4, we summarize the main conclusions of the study.

2. Physical model and methods

2.1. Quantum dynamics in a stochastically fluctuating environment

We consider the dephasing dynamics of a two-level quantum system interacting with a stochastically fluctuating environment. The effects of the environmental fluctuations on the quantum system can be described by the spectral diffusion theory within the framework of Kubo and Anderson.[72,73] Based on the spectral diffusion framework, the Hamiltonian of the quantum system under the environmental influence stochastically fluctuates as[74,75]

$$H(t)=\frac{\hbar}{2}[\omega_0+\xi(t)]\sigma_z, \tag{1}$$

where σ_z represents the Pauli matrix, ω_0 corresponds to the intrinsic frequency splitting between the energy levels $|1\rangle$ and $|0\rangle$, and $\xi(t)$ denotes the environmental noise which obeys a classical stochastic process.

Due to the stochastic property of the environmental noise, the density matrix of the two-level quantum system is also stochastic. The time evolution of the stochastic density matrix is governed by

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t;\xi(t))=-\frac{\mathrm{i}}{2}[\omega_0+\xi(t)][\sigma_z,\rho(t;\xi(t))]. \tag{2}$$

Here the notation $\rho(t;\xi(t))$ indicates its stochastic dependence of the environmental noise $\xi(t)$. By taking an ensemble average of the environmental noise $\xi(t)$, the reduced density matrix of the quantum system can be expressed as

$$\rho(t)=\begin{pmatrix}\rho_{11}(0) & F(t)\,\mathrm{e}^{-\mathrm{i}\omega_0 t}\rho_{10}(0)\\ F^*(t)\,\mathrm{e}^{\mathrm{i}\omega_0 t}\rho_{01}(0) & \rho_{00}(0)\end{pmatrix}. \tag{3}$$

As shown in Eq. (3), the coherence evolution of the quantum system depends solely on the off-diagonal elements of the reduced density matrix. Here, $F(t)$ denotes the decoherence function, which quantifies the decoherence effect induced by environmental noise. It is defined as the ensemble-average of the stochastic coherence function $F(t;\xi(t))$ which satisfies a linear differential equation

$$\frac{\mathrm{d}}{\mathrm{d}t}F(t;\xi(t))=-\mathrm{i}\xi(t)F(t;\xi(t)), \tag{4}$$

over all realizations of the environmental noise $\xi(t)$, that is

$$F(t)=\langle F(t;\xi(t))\rangle=\left\langle \mathrm{e}^{-\mathrm{i}\int_0^t\xi(t')\,\mathrm{d}t'}\right\rangle, \tag{5}$$

and the dynamical evolution of the reduced density matrix in Eq. (3) can be described by a time-local master equation[76–78]

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) &= -\frac{\mathrm{i}}{2}[\omega_0+S(t)][\sigma_z,\rho(t)]\\ &\quad+\frac{1}{2}\Gamma(t)[\sigma_z\rho(t)\sigma_z-\rho(t)],\end{aligned} \tag{6}$$

where $\Gamma(t)$ and $S(t)$ represent the decoherence rate and the frequency shift, respectively, defined as

$$\Gamma(t)=-\mathrm{Re}\left[\frac{\mathrm{d}F(t)/\mathrm{d}t}{F(t)}\right],\quad S(t)=-\mathrm{Im}\left[\frac{\mathrm{d}F(t)/\mathrm{d}t}{F(t)}\right]. \tag{7}$$

The decoherence rate $\Gamma(t)$ is intimately linked to the information exchange between the system and environment, whereas the frequency shift $S(t)$ is tied to the frequency renormalization of the quantum system.

Markov stochastic processes with the stationary property have been widely used to describe the effects of the environmental noise on open quantum systems.[1,79,80] For a stationary Markov process, its statistical properties are described by a

stationary one-time probability $P(\xi,0)$ and the transition probability $P(\xi,t|\xi',t')$ which yields a master equation

$$\frac{\partial}{\partial t}P(\xi,t|\xi',t') = \mathcal{M}_\xi P(\xi,t|\xi',t'), \tag{8}$$

where $\mathcal{M}_\xi$ denotes a differential operator with respect to ξ for a continuous stochastic process while it is a transition matrix for a discrete stochastic process. Based on the Markov statistical property, the n-time joint probabilities $P(\xi_1,t_1;\cdots;\xi_n,t_n)$ can be written as

$$P(\xi_1,t_1;\cdots;\xi_n,t_n) = \prod_k^{n-1} P(\xi_{k+1},t_{k+1}|\xi_k,t_k)P(\xi_1,t_1). \tag{9}$$

Thus, the statistical characterizations of the environmental noise $\xi(t)$, such as, the n-th moment, can be expressed as

$$\begin{aligned}&\langle \xi(t_1)\cdots\xi(t_n)\rangle \\ &= \int \xi_1\cdots\xi_n P(\xi_1,t_1;\cdots;\xi_n,t_n)\mathrm{d}\xi_1\cdots\mathrm{d}\xi_n.\end{aligned} \tag{10}$$

The decoherence function $F(t)$ in Eq. (5) closely depends on the statistical properties of the environmental noise $\xi(t)$. Formally, the decoherence function $F(t)$ can be expanded in terms of the statistical characterizations of the environmental noise $\xi(t)$, such as, moments and cumulants.[78,81] It is worth mentioning that these formal expansions involve all the environmental correlations with orders tend to infinity. To derive the exact expression of the decoherence function $F(t)$, we generally need to obtain the closed time evolution equation of $F(t)$ based on the statistical characterizations of the environmental noise $\xi(t)$.[81–83] However, only a few exact time evolution equation of $F(t)$ have been obtained and in most cases, we need to use some approximation methods to obtain the expression of the decoherence function $F(t)$.[42,44,77]

The stochastic Liouville equation approach makes it possible to derive the decoherence function $F(t)$ numerically or even analytically without involving any environmental correlations.[78,84] In the following, we utilize the stochastic Liouville approach to derive the exact expression for the decoherence function $F(t)$. Firstly, we define a marginal average $F(\xi,t)$, which satisfies the master equation

$$\frac{\mathrm{d}}{\mathrm{d}t}F(\xi,t) = \mathbb{M}F(\xi,t), \tag{11}$$

where $\mathbb{M} = -\mathrm{i}\xi + M_\xi$ is the marginal averaging operator, and the initial condition satisfies $F(\xi,0) = F(0)P(\xi,0)$ with $F(0) = 1$. Secondly, by means of a complete average, namely, further integrating the marginal average $F(\xi,t)$ over ξ, we can obtain the decoherence function $F(t)$ as

$$F(t) = \int F(\xi,t)\mathrm{d}\xi. \tag{12}$$

Although we here consider the case where the environmental noise $\xi(t)$ is subject to a continuous stochastic process, to extend the analysis to the scenario where the environmental noise $\xi(t)$ is governed by a discrete stochastic process, we only need to replace the integral in Eq. (12) with a summation over a set of discrete values ξ_n. Whether we can obtain the analytical expression of the decoherence function $F(t)$ is contingent on both the form of the differential operator M_ξ for the transition probability $P(\xi,t|\xi',t')$ in Eq. (8) and the solution of the marginal average $F(\xi,t)$ in Eq. (11).

A widely used method to derive the expression of the marginal average $F(\xi,t)$ is the eigenfunction expansion. However, it should be mentioned that the marginal averaging operator $\mathbb{M}$ in Eq. (11) is generally not a Hermitian operator, which means that it does not satisfy the condition of $\mathbb{M} = \mathbb{M}^\dagger$. Therefore, we need to use the non-Hermitian method to solve for the eigenvalues of marginal averaging operator $\mathbb{M}$ and the corresponding eigenfunctions. The marginal averaging operator $\mathbb{M}$ satisfies the eigen-equation

$$\mathbb{M}|\psi_n(\xi)\rangle = \lambda_n|\psi_n(\xi)\rangle, \tag{13}$$

and the corresponding adjoint equation

$$\langle\widetilde{\psi}_n(\xi)|\mathbb{M} = \langle\widetilde{\psi}_n(\xi)|\lambda_n, \tag{14}$$

where $|\psi_n(\xi)\rangle$ and $\langle\widetilde{\psi}_n(\xi)|$ denote, respectively, the right and left eigenfunctions of the operator $\mathbb{M}$ with the eigenvalues λ_n and the normalization relation $\langle\widetilde{\psi}_n(\xi)|\psi_{n'}(\xi)\rangle = \delta_{nn'}$. By means of the method of eigenfunction expansion, we can express $F(\xi,t)$ as a linear superposition of all the eigenfunctions of the marginal averaging operator $\mathbb{M}$ as

$$F(\xi,t) = \sum_n c_n(0)\,\mathrm{e}^{\lambda_n t}|\psi_n(\xi)\rangle, \tag{15}$$

where $c_n(0) = \langle\widetilde{\psi}_n(\xi_0)|F(\xi_0,0)$ are the initial expansion coefficients.

2.2. Dephasing dynamics in the presence of the asymmetric RTN

We now consider decoherence under the influence of the environmental noise $\xi(t)$ governed by the asymmetric RTN. Standard RTN is an important stationary non-Gaussian process characterized by signals switching randomly between two discrete states. It has been extensively applied in fields such as quantum decoherence, quantum state evolution control, and noise suppression.

The asymmetric RTN $\xi(t)$ is a two-state jump Markov process which switches between the two states ν_1 and ν_2 with the transition rates k_1 and k_2,[85] respectively,

$$\nu_1 \underset{k_2}{\overset{k_1}{\rightleftharpoons}} \nu_2, \tag{16}$$

where k_1 represents the transition rate of the environmental noise $\xi(t)$ from the ν_1 state to the ν_2 state, and k_2 denotes the transition rate from the ν_2 state to the ν_1 state. When $k_1 = k_2$

and $\nu_1 = -\nu_2$, the process is referred to as a symmetric two-state jump Markov process and the RTN exhibits symmetric statistical properties.

For the asymmetric RTN, the master equation governing its transition probability is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} P(\nu_1,t|\xi',t') \\ P(\nu_2,t|\xi',t') \end{pmatrix} = M_\xi \begin{pmatrix} P(\nu_1,t|\xi',t') \\ P(\nu_2,t|\xi',t') \end{pmatrix}, \tag{17}$$

where M_ξ denotes a transition matrix

$$M_\xi = \begin{pmatrix} -k_1 & k_2 \\ k_1 & -k_2 \end{pmatrix}. \tag{18}$$

In conventional analytical frameworks, environmental noise is typically modeled as a stationary random process, with its probabilistic characteristics initially described through a single-point probability distribution. For the asymmetric RTN with stationary statistics, its initial single-point probability can be expressed as

$$P(\xi,0) = \frac{k_2}{k_1+k_2}\delta_{\xi,\nu_1} + \frac{k_1}{k_1+k_2}\delta_{\xi,\nu_2}. \tag{19}$$

Within the framework of the stochastic Liouville equation, the master equation satisfied by the marginal average of the decoherence function under the influence of the environmental noise governed by the asymmetric RTN can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} F(\nu_1,t) \\ F(\nu_2,t) \end{pmatrix} = \mathbb{M}\begin{pmatrix} F(\nu_1,t) \\ F(\nu_2,t) \end{pmatrix}, \tag{20}$$

where the marginal average operator $\mathbb{M}$ can be written in the form of

$$\mathbb{M} = \begin{pmatrix} -k_1 - \mathrm{i}\nu_1 & k_2 \\ k_1 & -k_2 - \mathrm{i}\nu_2 \end{pmatrix}, \tag{21}$$

and the initial conditions satisfy $F(\nu_1,0) = k_2/(k_1+k_2)$ and $F(\nu_2,0) = k_1/(k_1+k_2)$.

Next, we will use the eigenfunction expansion method to derive the decoherence function in the presence of the asymmetric RTN. Based on the expression of the marginal averaging operator $\mathbb{M}$ in Eq. (21), we can obtain the eigenvalues

$$\lambda_{1,2} = -k - \mathrm{i}\nu \pm m, \tag{22}$$

the right eigenfunctions

$$|\psi_{1,2}\rangle = N_{1,2}\begin{pmatrix} -k_2 \\ \Delta_k/2 + \mathrm{i}\Delta_\nu/2 \mp m \end{pmatrix}, \tag{23}$$

and the corresponding left eigenfunctions

$$\langle\widetilde{\psi}_{1,2}| = N'_{1,2}\begin{pmatrix} -k_1 & \Delta_k/2 + \mathrm{i}\Delta\nu/2 \mp m \end{pmatrix}, \tag{24}$$

where $k = (k_1+k_2)/2$, $\nu = (\nu_1+\nu_2)/2$, $\Delta_k = k_2 - k_1$, $\Delta_\nu = \nu_2 - \nu_1$, and $m = \sqrt{k^2 - (\Delta_\nu/2)^2 + \mathrm{i}\Delta_k\Delta_\nu/2}$. According to the eigenvalues in Eq. (22) and the eigenfunctions in Eqs. (23) and (24), the marginal average decoherence function $F(\xi,t)$ can be expanded as

$$\begin{aligned}\begin{pmatrix} F(\nu_1,t) \\ F(\nu_2,t) \end{pmatrix} &= c_1|\psi_1\rangle \mathrm{e}^{\lambda_1 t} + c_2|\psi_2\rangle \mathrm{e}^{\lambda_2 t} \\ &= \frac{\mathrm{e}^{(-k-\mathrm{i}\nu)t}}{2km}\begin{pmatrix} k_2\left[f(t) + \frac{\mathrm{i}}{2}\Delta\nu\sinh(mt)\right] \\ k_1\left[f(t) - \frac{\mathrm{i}}{2}\Delta\nu\sinh(mt)\right] \end{pmatrix},\end{aligned} \tag{25}$$

where $f(t) = m\cosh(mt) + k\sinh(mt)$.

Therefore, we can derive the analytical expression of the decoherence function under the influence of environmental noise governed by the asymmetric RTN as

$$\begin{aligned}F(t) =& F(\nu_1,t) + F(\nu_2,t) \\ =& \frac{\mathrm{e}^{(-k-\mathrm{i}\nu)t}}{m}\left[f(t) + \frac{\mathrm{i}\Delta_\nu\Delta_k}{4k}\sinh(mt)\right].\end{aligned} \tag{26}$$

Correspondingly, the decoherence rate $\Gamma(t)$ can be expressed as

$$\Gamma(t) = k - \mathrm{Re}\left[\frac{m^2\tanh(mt) + m\left(k + \frac{\mathrm{i}\Delta_\nu\Delta_k}{4k}\right)}{m + \left(k + \frac{\mathrm{i}\Delta_\nu\Delta_k}{4k}\right)\tanh(mt)}\right], \tag{27}$$

and the frequency shift $S(t)$ can be written as

$$S(t) = \nu - \mathrm{Im}\left[\frac{m^2\tanh(mt) + m\left(k + \frac{\mathrm{i}\Delta_\nu\Delta_k}{4k}\right)}{m + \left(k + \frac{\mathrm{i}\Delta_\nu\Delta_k}{4k}\right)\tanh(mt)}\right]. \tag{28}$$

In the case that the environmental noise is governed by the standard RTN, namely, $k_1 = k_2 = \kappa$ and $\nu_1 = -\nu_2 = \vartheta$ the decoherence function in Eq. (26) can be reduced to

$$\begin{aligned}F(t) =& \mathrm{e}^{-\kappa t}\left[\cosh\left(\sqrt{\kappa^2 - \vartheta^2}t\right)\right. \\ &\left. + \frac{\kappa}{\sqrt{\kappa^2 - \vartheta^2}}\sinh\left(\sqrt{\kappa^2 - \vartheta^2}t\right)\right].\end{aligned} \tag{29}$$

The corresponding decoherence rate $\Gamma(t)$ in Eq. (27) can be rewritten as

$$\Gamma(t) = \frac{\vartheta^2\tanh\left(\sqrt{\kappa^2 - \vartheta^2}t\right)}{\sqrt{\kappa^2 - \vartheta^2} + \kappa\tanh\left(\sqrt{\kappa^2 - \vartheta^2}t\right)}, \tag{30}$$

and there is no frequency shift, namely, $S(t) = 0$. The expressions of the decoherence function $F(t)$ in Eq. (29) and the decoherence rate $\Gamma(t)$ in Eq. (30) are consistent with the existing results in previous studies.[78,82,86,87]

3. Results and discussion

In this section, we show the numerical results of the dephasing dynamics of the two-level quantum system in the presence of the asymmetric RTN. We discuss the influences of parameters k, Δ_k, and Δ_ν of the asymmetric RTN on the decoherence function $F(t)$, the decoherence rate $\Gamma(t)$, and the frequency shift $S(t)$ in detail.

Figure 1 illustrates the time evolution of the decoherence function $|F(t)|$, the decoherence rate $\Gamma(t)$, and the frequency shift $S(t)$ for different values of k in the presence of asymmetric RTN. From $k_1 = k - \Delta_k/2$ and $k_2 = k + \Delta_k/2$, we observe that in all three cases presented in Fig. 1, at least one of the transition rates k_1 or k_2 exceeds $|\Delta_\nu|/2$. In this regime, the decoherence function, as shown in Fig. 1(a), always decreases monotonically with time. Moreover, the decoherence rates in Fig. 1(b) are strictly positive throughout the dynamics, indicating a continuous and unidirectional flow of information from the system to the environment, without any recoherence effects due to environmental backaction. This implies that the decoherence dynamics remain Markovian at all times. In the long-time limit, the decoherence rate approaches a steady value. Notably, the steady value is significantly smaller for $k = 10$ compared to $k = 3$ and $k = 6$, suggesting that higher average transition rates can suppress dynamical decoherence effects under these conditions. As shown in Fig. 1(c), the frequency shift $S(t)$ is symmetric about $S(t) = \nu$ for both $\Delta_\nu\Delta_k > 0$ and $\Delta_\nu\Delta_k < 0$, and approaches a steady value in the long-time limit. Moreover, larger values of k result in the steady-state value being closer to the symmetry axis, indicating that a higher average transition rate can reduce the frequency shift of the system.

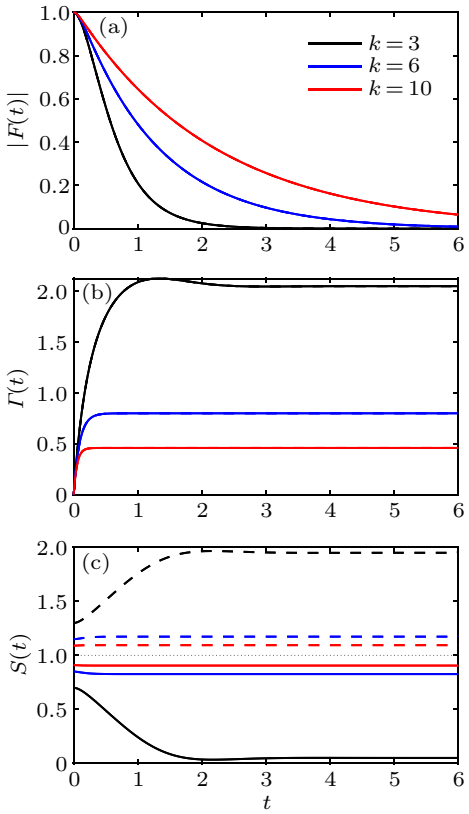


Fig. 1. Time evolution of (a) the decoherence function $|F(t)|$, (b) the decoherence rate $\Gamma(t)$, and (c) the frequency shift $S(t)$ induced by the asymmetric RTN, for different values of k, when at least one of k_1 or k_2 exceeds $|\Delta_\nu|/2$. The solid lines correspond to the case $\Delta_\nu\Delta_k > 0$, and the dashed lines correspond to $\Delta_\nu\Delta_k < 0$. The parameters are set as $\nu = 1$, $\Delta_\nu = \pm 6$, and $\Delta_k = \pm 0.6$.

Figure 2 illustrates the time evolution of the decoherence function $|F(t)|$, the decoherence rate $\Gamma(t)$, and the frequency shift $S(t)$ for different values of k in the presence of asymmetric RTN, under the condition that both k_1 and k_2 are less than $|\Delta_\nu|/2$. As shown in Fig. 2(a), as k decreases, the decoherence function is no longer always monotonically decreasing with time. When k falls below a critical value, the decoherence function exhibits short-term fluctuations. In Fig. 2(b), the decoherence rate is not always positive; when k is below a critical value, negative values of $\Gamma(t)$ appear, indicating information backflow from the environment to the system and the presence of coherent environmental backaction. This behavior suggests that the decoherence dynamics become non-Markovian under these conditions. In the long-time limit, the decoherence rates in Fig. 2(b) still approach steady values, but the smaller the k, the smaller the steady value. This indicates that, in the long-time limit, a lower average transition rate can also suppress dynamical decoherence effects. As shown in Fig. 2(c), it is evident that higher average transition rates reduce the frequency shift of the quantum system in the long-time limit.

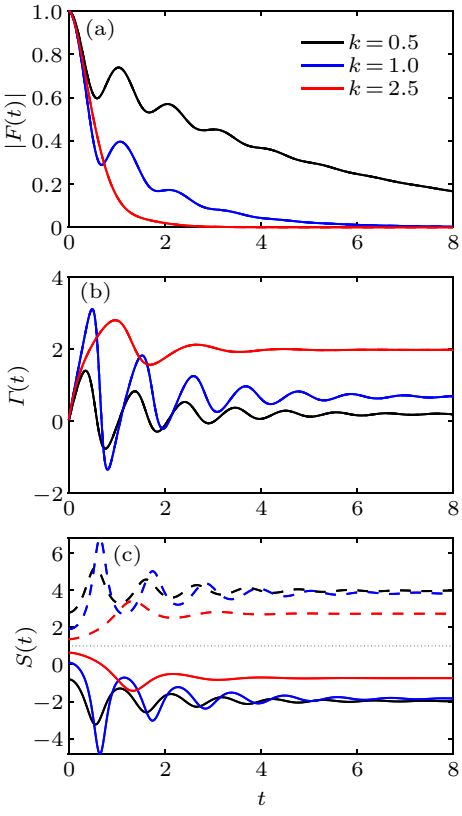


Fig. 2. Time evolution of (a) the decoherence function $|F(t)|$, (b) the decoherence rate $\Gamma(t)$, and (c) the frequency shift $S(t)$ induced by the asymmetric RTN, for different values of k, when both k_1 and k_2 are less than $|\Delta_\nu|/2$. The solid lines correspond to the case $\Delta_\nu\Delta_k > 0$, and the dashed lines correspond to $\Delta_\nu\Delta_k < 0$. The parameters are set as $\nu = 1$, $\Delta_\nu = \pm 6$, and $\Delta_k = \pm 0.6$.

From the preceding discussion, it is evident that when the transition rates are small, the decoherence dynamics become more complex. To better analyze the dynamical decoherence effects when both k_1 and k_2 are less than $|\Delta_\nu|/2$, figure 3

presents the time evolution of the decoherence function $|F(t)|$, the decoherence rate $\Gamma(t)$, and the frequency shift $S(t)$ for different values of Δ_k in the presence of asymmetric RTN. As shown in Fig. 3(a), when $\Delta_k = 0$ (i.e., when the transition rates are symmetric), the decoherence function is a non-monotonic function of time and exhibits significant fluctuations over short periods. As $|\Delta_k|$ increases, the amplitude of these fluctuations decreases until the decoherence function becomes a monotonic function of time t. For $\Delta_k = 0$, the decoherence rate in Fig. 3(b) shows periodic oscillations with time t. When $\Delta_k \neq 0$, the decoherence rate fluctuates only over short times and then approaches a steady value in the long-time limit. The larger the Δ_k, the smaller this steady value, indicating that asymmetry in transition rates can mitigate dynamical decoherence effects in the long-time limit. Additionally, as $|\Delta_k|$ increases, the amplitude of the decoherence rate's temporal fluctuations decreases. Once $|\Delta_k|$ exceeds a critical value, the decoherence rate remains positive at all times, suggesting that asymmetry in transition rates suppresses information backflow from the environment to the system, making the decoherence dynamics purely Markovian. When $\Delta_\nu\Delta_k > 0$ and $\Delta_\nu\Delta_k < 0$, the frequency shift $S(t)$ remains symmetric about $S(t) = \nu$ and for $\Delta_k = 0$, $S(t) = \nu$. When $\Delta_k \neq 0$, $S(t)$ exhibits fluctuations over short times, with the amplitude of these fluctuations decreasing as $|\Delta_k|$ increases. In the long-time limit, $S(t)$ approaches a steady value, which is closer to the symmetry axis for smaller $|\Delta_k|$. This indicates that asymmetry in transition rates enhances the frequency shift in the dephasing dynamics of the quantum system, as illustrated in Fig. 3(c).

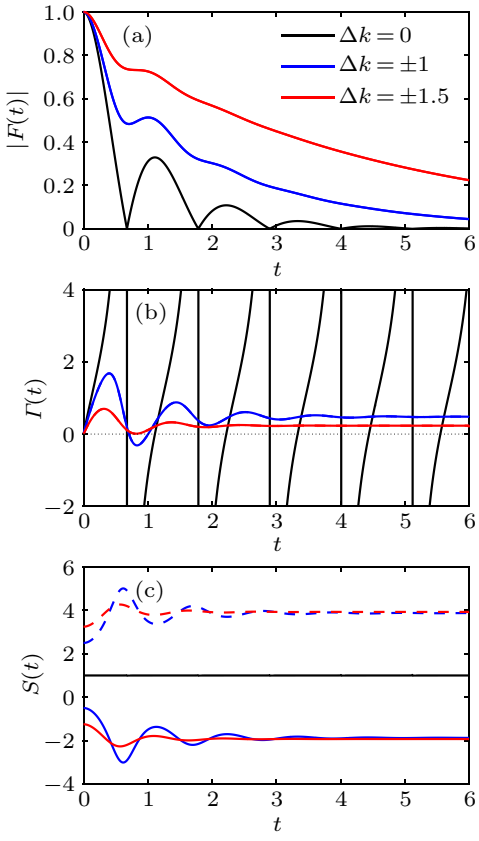


Fig. 3. Time evolution of (a) the decoherence function $|F(t)|$, (b) the decoherence rate $\Gamma(t)$, and (c) the frequency shift $S(t)$ induced by the asymmetric RTN, for different $\Delta_k/2$ values, when both k_1 and k_2 are less than $|\Delta_\nu|/2$. The solid lines correspond to the case $\Delta_\nu\Delta_k > 0$, and the dashed lines correspond to $\Delta_\nu\Delta_k < 0$. The parameters are set as $\nu = 1$, $\Delta_\nu = \pm 6$, and $k = 1$.

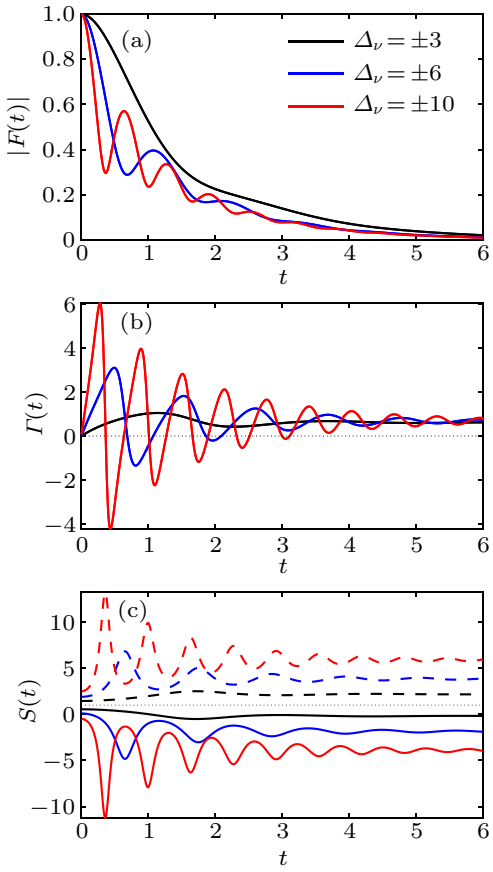


Fig. 4. Time evolution of (a) the decoherence function $|F(t)|$, (b) the decoherence rate $\Gamma(t)$, and (c) the frequency shift $S(t)$ induced by the asymmetric RTN, for different $\Delta_\nu/2$ values, when both k_1 and k_2 are less than $|\Delta_\nu|/2$. The solid lines correspond to the case $\Delta_\nu\Delta_k > 0$, and the dashed lines correspond to $\Delta_\nu\Delta_k < 0$. The parameters are set as $\nu = 1$, $k = 1$, and $\Delta_k = \pm 0.6$.

Figure 4 illustrates the time evolution of the decoherence function $|F(t)|$, the decoherence rate $\Gamma(t)$, and the frequency shift $S(t)$ for different values of Δ_ν in the presence of asymmetric RTN, under the condition that both k_1 and k_2 are less than $|\Delta_\nu|/2$. When $\Delta_\nu = \pm 3$, the decoherence function in Fig. 4(a) is a monotonic function of time. As $|\Delta_\nu|$ increases, the decoherence function is no longer always monotonically decreasing with time. When $|\Delta_\nu|$ exceeds a critical value, the decoherence function exhibits short-term fluctuations, and the larger the $|\Delta_\nu|$, the greater the amplitude of these fluctuations. For $\Delta_\nu = \pm 3$, the decoherence rate in Fig. 4(b) is a non-monotonic function of time but remains non-negative throughout, indicating purely Markovian dynamics. As $|\Delta_\nu|$ increases, the amplitude of the decoherence rate's temporal fluctuations grows, and negative values begin to appear, suggesting information backflow from the environment to the system and the presence of coherent environmental backaction. This indicates

that increasing $|\Delta_v|$ promotes coherence recovery in the system. As shown in Fig. 4(c), the frequency shift $S(t)$ is symmetric with respect to the line $S(t) = v$ for the cases $\Delta_v\Delta_k > 0$ and $\Delta_v\Delta_k < 0$. Over short times, $S(t)$ exhibits fluctuations, with larger $|\Delta_v|$ resulting in greater fluctuation amplitudes. In the long-time limit, $S(t)$ approaches a steady value, which is closer to the symmetry axis for smaller $|\Delta_v|$. This suggests that increasing $|\Delta_v|$ can increase the frequency shift of the quantum system.

As shown in Figs. 1–4, the decoherence dynamics are influenced by variations in the transition rates k_1 and k_2, the transition rate difference $|\Delta_k|$, and the transition amplitude difference $|\Delta_v|$. To clarify these effects, we summarize the impact of parameter modulation on decoherence dynamics under asymmetric RTN in Table 1. In the high-transition-rate regime, where at least one of k_1 or k_2 exceeds $|\Delta_v|/2$, the dynamics remain Markovian. In the long-time limit, the decoherence rate and frequency shift tend toward stable values, and as k increases, these stable values gradually decrease. In the low-transition-rate regime, where both k_1 and k_2 are less than $|\Delta_v|/2$, reducing k, decreasing $|\Delta_k|$, or increasing $|\Delta_v|$ can transiently restore coherence and induce a transition from Markovian to non-Markovian dynamics. However, in the long-time limit, these parameters exert distinct influences on the steady values of the decoherence rate and frequency shift.

Table 1. The influence of the environmental parameter on the decoherence dynamics under asymmetric RTN.

Parameter	Markovianity	Decoherence rate	Frequency shift
• Case 1: High transition rate with $\max(k_1,k_2) > \|\Delta_v\|/2$			
$k \nearrow$	Markovian	$\Gamma(\infty) \searrow$	$S(\infty) \searrow$
• Case 2: Low transition rate with $\max(k_1,k_2) < \|\Delta_v\|/2$			
$k \searrow$	Markovian $\rightarrow$ non-Markovian	$\Gamma(\infty) \searrow$	$S(\infty) \nearrow$
$\|\Delta_k\| \searrow$	Markovian $\rightarrow$ non-Markovian	$\Gamma(\infty) \nearrow$	$S(\infty) \searrow$
$\|\Delta_v\| \nearrow$	Markovian $\rightarrow$ non-Markovian	$\Gamma(\infty) \nearrow$	$S(\infty) \nearrow$

4. Conclusion

We have theoretically investigated the decoherence dynamics of a two-level quantum system induced by RTN with asymmetric properties using the stochastic Liouville equation approach. Our results show that, in contrast to the symmetric RTN case, the asymmetric RTN can lead to a frequency shift in the quantum system and may lead to non-Markovian behavior in its decoherence dynamics. When the transition rate is sufficiently large, the decoherence dynamics of the quantum system are always Markovian. In a long time, increasing the average transition rate suppresses both the decoherence dynamics and the frequency shift of the system. However, when the transition rate is sufficiently small, variations in the average transition rate, the transition rate difference, and the transition amplitude difference can potentially trigger coherence recovery in the system, leading to non-Markovian decoherence dynamics. Reducing the average transition rate enhances short-time coherence recovery and also suppresses the decoherence dynamics in a long time, while simultaneously increasing the frequency shift. Increasing the transition rate difference or decreasing the transition amplitude difference suppresses coherence recovery in a short time but reduces the decoherence dynamics in a long time. Notably, the former increases the frequency shift, whereas the latter decreases it.

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