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Effects of intrinsic decoherence on the entanglement of a two-qutrit 1D optical lattice chain with nonlinear coupling

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We have investigated the intrinsic decoherence on the entanglement of a two-qutrit one-dimensional (1D) optical lattice chain with nonlinear coupling. As a measure of the entanglement, the negativity of the system is calculated. It is shown that the influence of intrinsic decoherence on the entanglement varies in different initial systems.

Keywords: optical lattice chain, intrinsic decoherence, entanglement dynamics
PACC: 0367, 4250, 3280

1. Introduction

To realize quantum information processing (QIP), the problem of how to create stable entanglement in various physical systems has been extensively explored in recent years. As a simple but realistic solid-state system, the Heisenberg model is an ideal candidate for the generation and the manipulation of an entangled state. The model has been used to simulate quantum dots,[1] nuclear spins,[2] cavity QED[3] and optical lattices.[4] By suitable coding, the Heisenberg interaction alone can be used for quantum computation.[5] Since the Heisenberg model plays such an important role, the entanglement in the one-dimensional (1D) Heisenberg chains has been studied extensively.[6,7] For a specific Heisenberg chain in condensed matter physics, the only ranging variables are the magnetic field and the temperature,[6] a in cavity-QED system, the exchange constant (the linear coupling in our case) is adjustable in addition to the temperature and magnetic field. The development of laser cooling and trapping provides us more ways to control the atoms in traps. Indeed, we can manipulate the atom-atom coupling constants and the atom number in each lattice well with a very well accuracy.[8,9]

In practice, a quantum system will unavoidably interact with the environment and thus lead to decoherence, which may tamper with or even destroy the QIP. Thus it is of great importance to study the effects of environmental decoherence on the entanglement of the quantum system. Generally, the standard way to deal with decoherence is to consider the system of interest as a part of a larger closed system involving the surrounding environment.[10] An alternative approach is to modify the Schrödinger equation in such a way that coherence is automatically destroyed as the physical properties of the system approach a macroscopic level. This kind of decoherence is usually called intrinsic decoherence.[11] In Ref.[12], Milburn proposed a simple modification of the Schrödinger equation which contains a term responsible for the decay of quantum coherence in the energy eigenstate basis based on an assumption that for sufficiently short time steps the system does not evolve continuously under unitary transformation. The Milburn model of intrinsic decoherence has been applied to the study of decoherence effects in a Jaynes–Cummings (JC) model with a single quantized field mode,[13] decoherence in a multiphoton a JC model,[14] decoherence of open systems,[15] decoherence of a two-level particle coupled to photon field[16] and decoherence of a quantum gate.[17] Moreover, several authors have considered the intrinsic decoherence effects on the entanglement of the Heisenberg chains. In Ref.[18], Li and Xu studied the entanglement of a multi-qubit quantum Heisenberg XY chain with intrinsic decoherence. It is shown that the neighboring pairwise entanglement of the XY chain with odd number length is more robust against intrinsic decoherence than that with even number length. They also investigated

the magnetic impurity effects on the entanglement of the three-qubit Heisenberg XY chain with intrinsic decoherence,[19] and found that the neighboring pairwise entanglement decays faster than the next to neighboring pairwise entanglement in the case without field impurity and that the magnetic impurity in the middle qubit can protect the neighboring pairwise entanglement from the intrinsic decoherence. Subsequently, Yu *et al* [20] studied the intrinsic decoherence effects on the entanglement of a two-qubit anisotropic Heisenberg XYZ model.

On the other hand, the system of atoms in optical lattices is among the promising candidates for quantum information processing. It may take advantage of the technology used in atom optics and laser cooling based on the optical manipulation of atoms.[21] Besides, it also holds the merit of the eventual possibility to scale, parallelize and miniaturize the device in QIP. In order to manipulate the entanglement in optical lattice, thus, it is desirable to investigate the entanglement dynamics in optical lattice chains under decoherence environments. In this paper, we will examine the intrinsic decoherence effects on the entanglement of a two-qutrit 1D optical lattice chain with nonlinear coupling. By far, most works are focused on the decoherence effects of qubit systems, however, the 2-qutrit system is also a promising candidate for QIP. It was demonstrated that key distributions based on three-level quantum systems are more secure against eavesdropping than those based on two-level systems.[22] Key distribution protocols based on entangled three-level systems were also proposed.[23] The security of these protocols is related to the violation of the Bell inequality. It has been shown that the quantum prediction differs more radically from classical physics in the case of three-level systems than in the case of two-level systems. The three-level system provides in this context a much smaller level of noise.[24] Thus the results of this paper may provide some knowledge of coherence loss due to intrinsic decoherence in the two-qutrit system.

The paper is organized as follows. In Section 2 we give the theoretic Hamiltonian model describing the optical lattice chains with nonlinear coupling. In Section 3, entanglement dynamics of a two-qutrit 1D optical lattice chain with intrinsic decoherence will be studied thoroughly. In Section 4 we summarize our conclusions.

2. Theoretic model

Our system consists of two wells in the optical lattice with one spin-1 atom in each well, and the lattices are formed by three orthogonal laser beams with effective potential $V(x,y,z) = V_x \sin^2(kx) + V_y \sin^2(ky) + V_z \sin^2(kz)$, where k is the wave vector of the lasers, and the bosonic atoms with spin 1 are trapped in the wells. The strengths $V_{x,y,z}$ are proportional to the intensities of the laser beams and can be adjusted separately. We assume that only one orbital state is involved for each well, and we may use an effective Hamiltonian of the Bose–Hubbard form[25] to describe the system. The atoms in the Mott regime make sure that each well contains only one atom. In the case of $V_x \ll V_{y,z}$, the couplings along the y and z directions can be ignored. Thus the system is a collection of one-dimensional spin chains. The effective Hamiltonian can be written as[9]

$$H = \sum_i J(\boldsymbol{S}_i \cdot \boldsymbol{S}_{i+1}) + K(\boldsymbol{S}_i \cdot \boldsymbol{S}_{i+1})^2, \qquad (1)$$

where $J = -2t^2/U_2, K = -2t^2/3U_2 - 4t^2/U_0$ with t being the hopping matrix elements. The hopping matrix elements depend on the direction of hopping, i.e. $t_{x,y,z} \sim (E_R V_{x,y,z})^{1/2} \mathrm{e}^{-2(V_{x,y,z}/E_R)^{1/2}}$, where $E_R \equiv \hbar^2 k^2/2m$ and m is the mass of the atoms. $U_s\,(s = 0, 2)$ represents the Hubbard repulsion potential with total spin s, a potential U_s with $s = 1$ is not allowed due to the identity of the bosons with one orbital state per well, $\boldsymbol{S}_i\,(i = 1, 2)$ denotes the spin vector $\boldsymbol{S}_i = (S_{ix}, S_{iy}, S_{iz})$. This Hamiltonian differs from the usual Heisenberg model by the nonlinear couplings. When the magnetic field $\boldsymbol{B}$ along the z-direction is assumed, the Hamiltonian (1) becomes

$$H = \sum_i J(\boldsymbol{S}_i \cdot \boldsymbol{S}_{i+1}) + K(\boldsymbol{S}_i \cdot \boldsymbol{S}_{i+1})^2 + B(S_{iz} + S_{i+1z}), \qquad (2)$$

where $S_i = 1\ (i = 1, 2)$ is the total spin for each site and its components take the form

$$S_{ix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$S_{iy}=\frac{1}{\sqrt{2}}\begin{pmatrix}0&-\mathrm{i}&0\\ \mathrm{i}&0&-\mathrm{i}\\ 0&\mathrm{i}&0\end{pmatrix},$$

$$S_{iz}=\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\ 0&0&0\\ 0&0&-1\end{pmatrix}. \tag{3}$$

The eigenvalues and the corresponding eigenstates of the Hamiltonian (2) can be derived as

$$\begin{aligned}
&E_1=K+J-B,\\
&|\psi_1\rangle=\frac{1}{\sqrt{2}}\left(|0,-1\rangle+|-1,0\rangle\right);\\
&E_2=K+J+B,\\
&|\psi_2\rangle=\frac{1}{\sqrt{2}}\left(|1,0\rangle+|0,1\rangle\right);\\
&E_3=K-J+B,\\
&|\psi_3\rangle=\frac{1}{\sqrt{2}}\left(-|1,0\rangle+|0,1\rangle\right);\\
&E_4=K-J-B,\\
&|\psi_4\rangle=\frac{1}{\sqrt{2}}\left(-|0,-1\rangle+|-1,0\rangle\right);\\
&E_5=K+J,\\
&|\psi_5\rangle=\frac{1}{\sqrt{6}}\left(|1,-1\rangle+|-1,1\rangle+2\,|0,0\rangle\right);\\
&E_6=K-J,\\
&|\psi_6\rangle=\frac{1}{\sqrt{2}}\left(|1,-1\rangle-|-1,1\rangle\right);\\
&E_7=K+J+2B,\\
&|\psi_7\rangle=|1,1\rangle;\\
&E_8=K+J-2B,\\
&|\psi_8\rangle=|-1,-1\rangle;\\
&E_9=4K-2J,\\
&|\psi_9\rangle=\frac{1}{\sqrt{3}}\left(|1,-1\rangle+|-1,1\rangle-|0,0\rangle\right).
\end{aligned} \tag{4}$$

3. Influence of intrinsic decoherence on the entanglement of the two-qutrit optical lattice chain

Taking the intrinsic decoherence into account, we now study the entanglement dynamics of a two-qutrit 1D optical lattice chain. In Milburn's model, decoherence is caused by the assumption that the system evolves in a stochastic sequence of identical unitary transformations in sufficiently short time intervals, and the time evolution of density matrix in Milburn's model can be expressed as

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho\left(t\right)=\frac{1}{\gamma}\left\{\exp\left[-\mathrm{i}\,\gamma H\right]\rho\left(t\right)\exp\left[\mathrm{i}\,\gamma H\right]-\rho\left(t\right)\right\}, \tag{5}$$

where γ is the phase decoherence rate. Under Markovian approximation, the master equation governing the time evolution for the system can be expanded as

$$\frac{\mathrm{d}\rho\left(t\right)}{\mathrm{d}t}=-\mathrm{i}\left[H,\rho\left(t\right)\right]-\frac{\gamma}{2}\left[H,\left[H,\rho\left(t\right)\right]\right]. \tag{6}$$

The formal solution of the master equation (6) can be expressed as[13]

$$\rho\left(t\right)=\sum_{k=0}^{\infty}\frac{\left(\gamma t\right)^k}{k!}M^k\left(t\right)\rho\left(0\right)M^{\dagger k}\left(t\right), \tag{7}$$

where $\rho\left(0\right)$ is the initial density operator of the system and M^k is defined as

$$M^k=H^k\exp\left(-\mathrm{i}\,Ht\right)\exp\left(-\frac{\gamma t}{2}H^2\right). \tag{8}$$

Inserting the complete relation $\sum\limits_n|\phi_n\rangle\langle\phi_n|$ into Eq.(7), we obtain the time-dependent density matrix

$$\begin{aligned}\rho\left(t\right)=&\sum_{mn}\exp\left[-\frac{\gamma t}{2}\left(E_m-E_n\right)^2-\mathrm{i}\,t\left(E_m-E_n\right)\right]\\ &\times\langle\phi_m|\,\rho\left(0\right)|\phi_n\rangle\,|\phi_m\rangle\,\langle\phi_n|.\end{aligned} \tag{9}$$

where $E_{m,n}$ and $\phi_{m,n}\,(m,n=1,\ldots 9)$ are the eigenvalues and corresponding eigenvectors of the Hamiltonian given in Eq.(2), respectively.

In order to discuss the entanglement dynamics in the above system, we choose the negativity[26] to quantify the degree of entanglement. The negativity is a simple computable measure and Vidal *et al* [26] have proved that the negativity is an entanglement monotone, thus it is a good measure of entanglement. In Ref.[27] it is also shown that the negativity can be measured by the noiseless quantum circuit in experiment. The negativity $N\left(\rho\right)$ for an arbitrary bipartite system is defined as

$$N\left(\rho\right)=\frac{\left\|\rho^{T_{\mathrm{A}}}\right\|-1}{2}, \tag{10}$$

where $\left\|\rho^{T_{\mathrm{A}}}\right\|$ denotes the trace norm of the partial transpose $\rho^{T_{\mathrm{A}}}$. The negativity $N\left(\rho\right)$ is equivalent to the absolute value of the sum of the negative eigenvalues of $\rho^{T_{\mathrm{A}}}$.

(i) Firstly, we consider the case that the qutrits 1 and 2 are initially in the unentangled state $\rho_1(0) = |00\rangle\langle 00|$. In Milburn's model of decoherence, the element of the density matrix of the system at time t can be calculated with Eqs.(4) and (9). Through a straightforward algebra, the negativity of the system is

$$N(\rho_1(t)) = \frac{2}{9}\sqrt{1+5\mathrm{e}^{-9(J-K)^2\gamma t} - 4\cos[6(J-K)t]\,\mathrm{e}^{-9(J-K)^2\gamma t} - 2\cos[3(J-K)t]\,\mathrm{e}^{-\frac{9}{2}(J-K)^2\gamma t}} + \frac{2}{9}\left(1-\cos[3(J-K)t]\,\mathrm{e}^{-\frac{9}{2}(J-K)^2\gamma t}\right). \tag{11}$$

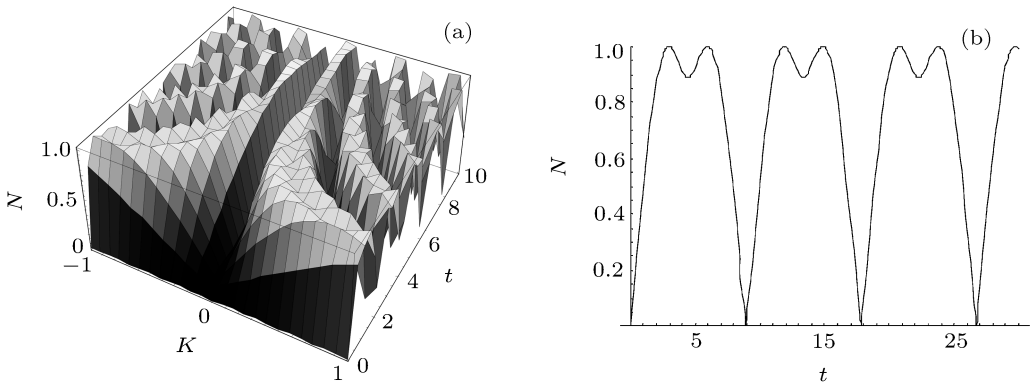


Fig.1. (a) The negativity as a function of time t and the nonlinear coupling constant K with $\gamma = 0, J = -0.065E_R$, (b) the special case of (a) by setting $K = -0.3E_R$. In the two cases, the units of t are both $(E_R)^{-1}$.

At first, we consider the case of $\gamma = 0$, i.e., the absence of intrinsic decoherence. According to condensed matter theory, for sodium in the Mott regime when a red detuned laser is involved, the hopping matrix element between adjacent sites $t = 0.07E_R$, $U_2 = 0.15E_R$, thus $J = -0.065E_R$[28] (hereafter J and K are both in units of E_R, γ and t are both in units of $(E_R)^{-1}$). The time evolution behaviors of the negativity are shown in Fig.1 as the function of time t and the nonlinear coupling constant K for $J = -0.065E_R$. In particular, we plot the negativity as the function of t with a specific $K = -0.3E_R$ in Fig.1(b). It is shown that the entanglement evolves periodically in the absence of intrinsic decoherence. We find that the initially unentangled state can generate entanglement by the Heisenberg interaction in the optical lattice chain.

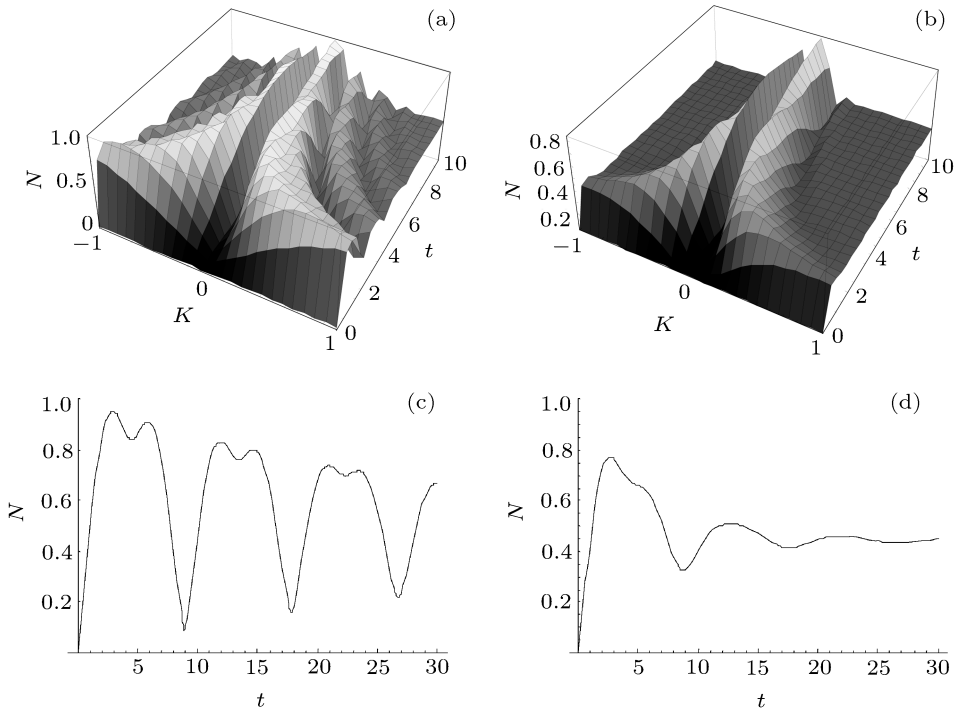


Fig.2. The negativity as a function of time t and the nonlinear coupling constant K with different phase decoherence rates γ, where (a) $\gamma = 0.1(E_R)^{-1}$; (b) $\gamma = 0.6(E_R)^{-1}$; (c) and (d) correspond to (a) and (b) respectively, for $K = -0.3E_R$. For all plots $J = -0.065E_R$.

In Fig.2, we plot the negativity as a function of time t and the nonlinear coupling constant K with different nonzero phase decoherence rates γ. From Fig.2 we see that the negativity is always larger than zero for any time $t > 0$, which means that the intrinsic decoherence does not completely destroy the entanglement but generates entanglement. By choosing appropriate K and t, the negativity of the two qutrits can reach a maximum value. Furthermore, with the increase of K and t, the negativity will approach a finite value 4/9. By comparing Figs.2(a), 2(c), and Figs.2(b), 2(d), it is easy to see that the destructive effect of the decoherence becomes more visible after the decoherence rate γ is raised, and the intrinsic decoherence of the system gives an evident suppression to the oscillation. In our plots, we let the coupling K change. In fact, in the Mott regime, the values of the tunneling and the interaction are fixed for a kind of atom. However, there are different kinds of atoms in which the relations between J and K are different. For example, for ^{23}Na atoms, $U_2 > U_0$; hence $K < J < 0$, while for ^{87}Rb, $U_0 > U_2$, in this case, $J < K < 0$.

(ii) Assume that the system is initially in an entangled state $\rho_2(0) = (a|1,0\rangle + b|0,1\rangle)(a\langle 1,0| + b\langle 0,1|)$, where a and b are real parameters satisfying $a^2 + b^2 = 1$. After a decoherence evolution time t, the negativity is

$$N(\rho_2(t)) = \frac{1}{2}\sqrt{4ab^2 + 2(a^2 - b^2)^2 \mathrm{e}^{-4\gamma t J^2} \sin[2Jt]^2}. \tag{12}$$

The negativity with intrinsic decoherence as a function of time t and the linear coupling constant J for different phase decoherence rates γ is plotted in Fig.3, where we have assumed $a = 1/2$, $b = \sqrt{3}/2$. To have a vivid illustration, we also plot the negativity as the function of the linear coupling constant J at a given time $t = 10(E_R)^{-1}$ in Figs.3(c) and 3(d). From Fig.3 we find that no matter what the value of the decoherence rate is, the negativity of the system with the same initial state will arrive at a stable nonzero value in the end. Here, in our case, the negativity will approach $\sqrt{6}/4$ as t or J increases to infinity. It is also shown that at some definite K and t, the negativity of the two-qutrits can reach a maximum value. This indicates that the entanglement can be effectively controlled by choosing the parameters of the system, and the effect of intrinsic decoherence may be weakened by choosing appropriate linear coupling constant J.

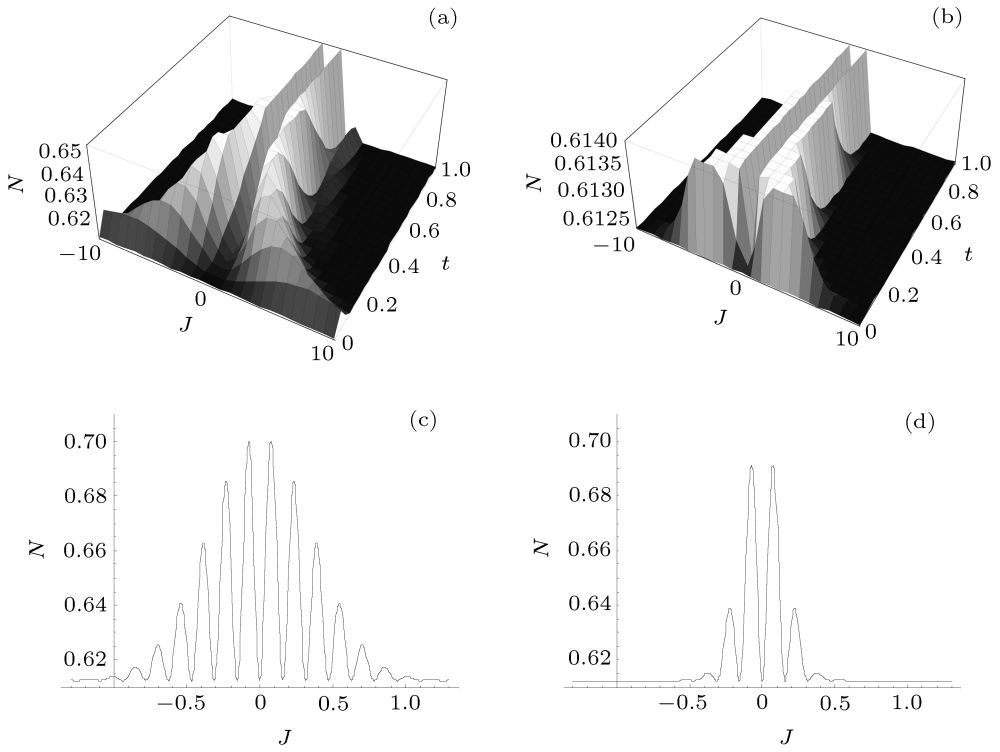


Fig.3. The negativity as a function of time t and the linear coupling constant J for two different cases: (a) $\gamma = 0.1(E_R)^{-1}$, (b) $\gamma = 0.6(E_R)^{-1}$, while (c) and (d) correspond to (a) and (b) respectively for time $t = 10(E_R)^{-1}$.

(iii) Consider another case when the system is initially in an entangled state $\rho_3(0) = (c|1,1\rangle + d|-1,-1\rangle)(c\langle 1,1| + d\langle -1,-1|)$, where c and d are real parameters satisfying $c^2 + d^2 = 1$. Similarly, we can plot the

negativity with intrinsic decoherence as a function of time t and the external magnetic field B for different phase decoherence rates γ. In this case, the negativity is a function of the external magnetic field, while the nonlinear or linear coupling constant has no effect on the entanglement. Figure 4 shows that the negativity decays faster with the increase of the external magnetic field B, and at certain finite t or B it will finally decrease to zero.

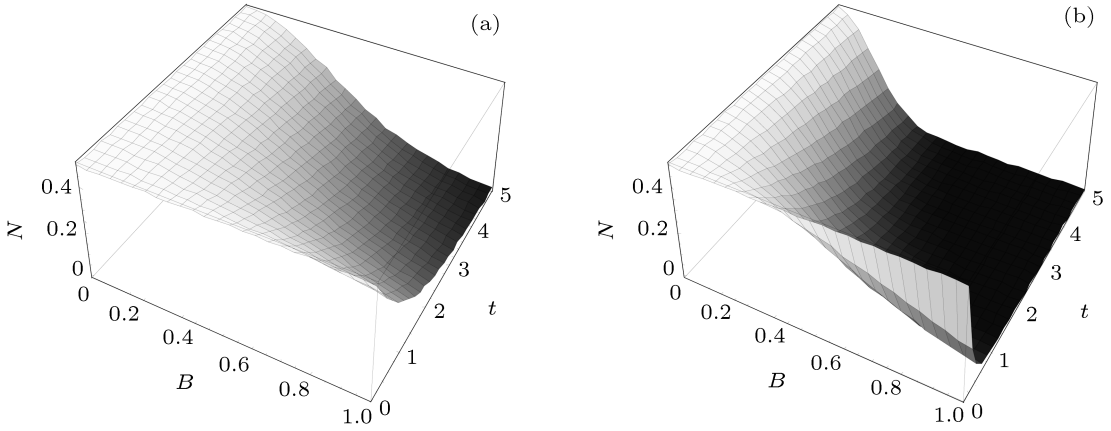


Fig.4. The negativity versus time t and the external magnetic field B for different phase decoherence rates γ, (a) $\gamma = 0.1\,(E_R)^{-1}$; (b) $\gamma = 0.6\,(E_R)^{-1}$. We have assumed $c = d = 1/\sqrt{2}$.

4. Conclusion

In summary, we have studied entanglement dynamics of a two-qutrit 1D optical lattice chain with intrinsic decoherence. It is shown that the initial state of the system plays an important role in the time evolution of the entanglement. For the $\rho_1(0) = |00\rangle\langle 00|$ and $\rho_2(0) = (a|1,0\rangle + b|0,1\rangle)(a\langle 1,0| + b\langle 0,1|)$ cases, the external magnetic field B has no effect on the entanglement. We show that the intrinsic decoherence causes the decay of entanglement but does not completely destroy the entanglement. With the increase of the intrinsic decoherence effect, the entanglement will quickly become a nonzero stable value. Furthermore, the amount of the entanglement can be increased by adjusting the linear coupling constant J or nonlinear coupling constant K. In the $\rho_3(0) = (c|1,1\rangle + d|-1,-1\rangle)(c\langle 1,1| + d\langle -1,-1|)$ case, the entanglement is sensitive to the external magnetic field B and phase decoherence rate γ, and at certain finite t or B it will finally decrease to zero. This suggests that the effect of intrinsic decoherence may be weakened by choosing an appropriate initial state. We hope our results may have potential applications in future manipulations of quantum entanglement in 1D optical lattice chain.

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