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Effects of Dzyaloshinski–Moriya interaction and intrinsic decoherence on teleportation via a two-qubit Heisenberg XYZ model*

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Quantum teleportation via the entangled channel composed of a two-qubit Heisenberg XYZ model with Dzyaloshinski–Moriya (DM) interaction in the presence of intrinsic decoherence has been investigated. We find that the initial state of the channel plays an important role in the teleported state and the average fidelity of teleportation. When the initial channel is in the state $|\psi_1(0)\rangle = a|00\rangle + b|11\rangle$, the average fidelity is equal to 1/3 constantly, which is independent of the DM interaction and the intrinsic decoherence effect. But when the channel is initially in the state $|\psi_2(0)\rangle = c|01\rangle + d|10\rangle$, the average fidelity is always larger than 2/3. Moreover, under a certain condition, the average fidelity can be enhanced by adjusting the DM interaction, and the intrinsic decoherence leads to a suppression of the fluctuation of the average fidelity.

Keywords: Heisenberg model, intrinsic decoherence, DM interaction, average fidelity
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1. Introduction

Quantum entanglement is an important and securable resource in quantum information theory. It has attracted extensive attention in recent years due to its potential applications in quantum communication and information processing,[1] such as superdense coding,[2] quantum teleportation,[3] quantum key distribution,[4] and telecloning.[5] However, in the real world entangled states of system are very fragile, since quantum systems are never isolated from the surrounding environment, which induces various noises and constitutes a major obstacle to implement quantum information processing. Thus, it is indispensable to take these noises into account when we investigate an open quantum system. The proposal of intrinsic decoherence, generally speaking, is to seek an approach to modify Schrödinger's equation in such a way that coherence is automatically destroyed when the physical properties of the system approach a macroscopic level. To demonstrate such decoherence, a number of models have been proposed.[6−9] Based on a simple modification of unitary Schrödinger evolution, in 1999 Milburn demonstrated a very common model for intrinsic decoherence in quantum mechanics in Ref.[10], which will be used in our paper.

It is well accepted that spin chains can be used as qubits in many real physical systems, and Heisenberg spin chain is the simplest spin chain in condensed matter physics,[11] which is regarded as one of the natural candidates for us to investigate quantum information processing. In recent years, there has been an ongoing effort to characterize the entanglement properties of Heisenberg spin chain.[12] But for some practical systems, it is insufficient to only consider the Hamiltonian and entanglement of Heisenberg spin-spin interaction, generally some external interaction was often introduced to the system of Heisenberg spin chain.[13−20] For example, in Ref.[13], Wang studied the thermal entanglement in a two-qubit isotropic and anisotropic XY model with an external magnetic field. Kamta *et al*[14] examined anisotropy and magnetic field effects on the entanglement of a two-qubit

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Heisenberg XY chain. By using the entanglement of the Heisenberg spin chain as quantum channel, much attention was paid to the achievement of quantum teleportation.[21−23] Yeo[21] considered entanglement teleportation via two separate thermally entangled states of a two-qubit Heisenberg XX chain. Taking the spin-orbit coupling effect into account, Zhang[22] discussed the entanglement and teleportation in a two-qubit Heisenberg XXX chain with Dzyaloshinski–Moriya (DM) anisotropic antisymmetric interaction.

In the present paper, our goal is to investigate the effects of DM interaction and intrinsic decoherence on average fidelity when a two-qubit Heisenberg XYZ model is used as the teleportation channel. Our results show that when the initial channel is in an entangled state $|\psi_1(0)\rangle = a|00\rangle + b|11\rangle$, the channel is unsuitable for quantum teleportation. But when the channel is initially in another entangled state $|\psi_2(0)\rangle = c|01\rangle + d|10\rangle$, the value of average fidelity is always larger than $\frac{2}{3}$, which means that such a teleportation through the two-qubit Heisenberg XYZ model is better than any classical communication protocol, and if we set the evolution time in some fixed values, a weak DM interaction can excite the average fidelity to a larger value than that without DM interaction except that the initial channel is in a maximally entangled state. Besides, the phase decoherence effect can suppress the oscillation of the average fidelity. This paper is organized as follows. In Section 2, we introduce the Hamiltonian of a two-qubit Heisenberg XYZ model with DM interaction. By considering two different forms of initial states, we give the corresponding time evolution of the channel with intrinsic decoherence taken into account. In Section 3, the concurrence of the teleported states is calculated. In Section 4, we study the effects of DM interaction and phase decoherence on the average fidelity of teleportation. Finally, conclusions are given in Section 5.

2. Model and its concurrence

The Hamiltonian of a two-qubit anisotropic Heisenberg XYZ model with DM interaction can be described by

$$H = \frac{1}{2}\big[J_x\sigma_x^1\sigma_x^2 + J_y\sigma_y^1\sigma_y^2 + J_z\sigma_z^1\sigma_z^2 + \boldsymbol{D}\cdot(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\big], \tag{1}$$

where J_α ($\alpha = x, y, z$) are the real coupling coefficients for the spin interaction. The chain is in anti-ferromagnetic case for $J_\alpha > 0$ and ferromagnetic case for $J_\alpha < 0$. The last term of Eq.(1) denotes DM anisotropic antisymmetric interaction, arising from spin-orbit coupling.[24,25] To see the effect of the DM interaction, we assume the DM vector coupling $\boldsymbol{D} = D\boldsymbol{z}$ for simplicity. Then the Hamiltonian H becomes

$$H = (J + \mathrm{i}D)\sigma_+^1\sigma_-^2 + (J - \mathrm{i}D)\sigma_-^1\sigma_+^2 + \frac{\Delta}{2}(\sigma_+^1\sigma_+^2 + \sigma_-^1\sigma_-^2) + \frac{J_z}{2}\sigma_z^1\sigma_z^2, \tag{2}$$

where $J = \frac{1}{2}(J_x + J_y)$ is the mean coupling coefficient of the XY plane; $\Delta = J_x - J_y$ stands for the anisotropy in the XY plane; $\sigma_\pm = \frac{1}{2}(\sigma_x \pm \mathrm{i}\sigma_y)$ are spin raising and lowering operators, respectively. The eigenvectors and the corresponding eigenvalues of H can be given by

$$\begin{aligned}
|\psi^+\rangle &= \frac{\sqrt{2}}{2}(|00\rangle + |11\rangle), & \lambda_1 &= \frac{1}{2}(J_z + \Delta),\\
|\psi^-\rangle &= \frac{\sqrt{2}}{2}(|00\rangle - |11\rangle), & \lambda_2 &= \frac{1}{2}(J_z - \Delta),\\
|\Phi^+\rangle &= \frac{\sqrt{2}}{2}(|01\rangle + \mathrm{e}^{\mathrm{i}\omega}|10\rangle), & \lambda_3 &= \frac{1}{2}(-J_z + \delta),\\
|\Phi^-\rangle &= \frac{\sqrt{2}}{2}(|01\rangle - \mathrm{e}^{\mathrm{i}\omega}|10\rangle), & \lambda_4 &= \frac{1}{2}(-J_z - \delta),
\end{aligned} \tag{3}$$

where $\delta = \sqrt{4D^2(J^2/D^2+1)}$ and $\omega = \mathrm{arctg}\,(D/J)$. In the case of a pure phase decoherence, the master equation characterizing the time-dependent evolution of the system under the Markovian approximation can be given by[10]

$$\frac{\mathrm{d}\rho(t)}{\mathrm{d}t} = -\mathrm{i}[H, \rho(t)] - \frac{\gamma}{2}[H, [H, \rho(t)]], \tag{4}$$

where γ is the phase decoherence rate. The formal solution of the above master equation can be obtained as

$$\rho(t) = \sum_{\kappa=0}^{\infty}\frac{(\gamma t)^\kappa}{\kappa!}M^\kappa\rho(0)M^{+\kappa}, \tag{5}$$

where $\rho(0)$ is the initial density matrix of the system and M^κ is defined as

$$M^\kappa = H^\kappa\exp(-\mathrm{i}Ht)\exp\left(-\frac{\gamma t}{2}H^2\right). \tag{6}$$

As a consequence, the time evolution of the density operator of the two-qubit Heisenberg XYZ model described by Eq.(2) can be written as

$$\rho(t) = \sum_{mn}\exp\left[-\frac{\gamma t}{2}(E_m - E_n)^2 - \mathrm{i}\,(E_m - E_n)\,t\right]$$

$$\times \langle \Phi_m | \rho(0) | \Phi_n \rangle | \Phi_m \rangle \langle \Phi_n |, \tag{7}$$

where $|\Phi_{m,n}\rangle$ and $E_{m,n}$ are the eigenvectors and the corresponding eigenvalues of the Hamiltonian H, respectively. In what follows, we will give the time evolution of the Heisenberg model and its entanglement degree for different initial states. In this paper, we use the concurrence to character the entanglement between two qubits, which can be defined as[26]

$$C = \max\{\lambda_4 - \lambda_3 - \lambda_2 - \lambda_1, 0\}, \tag{8}$$

here λ_i $(i = 1, 2, 3, 4)$ are the square roots of the eigenvalues of the matrix $R = \rho S \rho^* S$ and $\lambda_4 > \lambda_3 > \lambda_2 > \lambda_1$; ρ is the density matrix of the two qubits, asterisk stands for the complex conjugate, and $S = \sigma_y \otimes \sigma_y$.

Case (a): Assume that the two qubits are initially in an entangled state $|\psi_1(0)\rangle = a|00\rangle + b|11\rangle$, where a and b are real parameters satisfying $a^2 + b^2 = 1$. On the standard basis $\{|11\rangle, |10\rangle, |01\rangle, |00\rangle\}$, the time evolution of the density operator of the model can be given by

$$\begin{aligned}\rho_1(t) = {} & \alpha|00\rangle\langle 00| + \eta|00\rangle\langle 11| + \eta^*|11\rangle\langle 00| \\ & + \beta|11\rangle\langle 11|,\end{aligned} \tag{9}$$

where

$$\alpha = \frac{1}{2}\left[1 + (a^2 - b^2)\cos(\Delta t)\exp\left(\frac{-\gamma\Delta^2 t}{2}\right)\right],$$

$$\eta = ab + \frac{\mathrm{i}}{2}(a^2 - b^2)\sin(\Delta t)\exp\left(\frac{-\gamma\Delta^2 t}{2}\right),$$

$$\beta = \frac{1}{2}\left[1 - (a^2 - b^2)\cos(\Delta t)\exp\left(\frac{-\gamma\Delta^2 t}{2}\right)\right].$$

In this case, the concurrence of the Heisenberg XYZ model can be expressed as

$$C_1 = 2\sqrt{a^2 b^2 + \frac{1}{4}(a^2 - b^2)^2 \sin^2(\Delta t)\exp(-\gamma\Delta^2 t)}. \tag{10}$$

According to Eqs.(9) and (10), we notice that all parameters α, β, η, C_1 contain the coefficient Δ and do not contain the coefficient D, which shows that both the time evolution of the density matrix and its concurrence depend on the anisotropy of the XY plane but are independent of the DM interaction. It can also be seen that when $\Delta = 0$, the density matrix $\rho_1(t)$ keeps the initial state $|\psi_1(0)\rangle$ unchanged no matter what the intrinsic decoherence is.

Case (b): Suppose that the initial state of the two qubits is in another entangled state $|\psi_2(0)\rangle = c|01\rangle + d|10\rangle$, where c and d are real parameters satisfying $c^2 + d^2 = 1$. Then, the time evolution of the density operator of the model can be described by

$$\rho_2(t) = \mu|01\rangle\langle 01| + \nu|01\rangle\langle 10| + \nu^*|10\rangle\langle 01| + \xi|10\rangle\langle 10|, \tag{11}$$

where

$$\mu = \frac{1}{2}\left\{1 + \exp\left(\frac{-\gamma\delta^2 t}{2}\right)\left[(c^2 - d^2)\cos(\delta t) - 2cd\sin\omega\sin(\delta t)\right]\right\},$$

$$\nu = \frac{\mathrm{e}^{-\mathrm{i}\omega}}{2}\left\{2cd\cos\omega + \mathrm{i}\exp\left(\frac{-\gamma\delta^2 t}{2}\right)\left[(c^2 - d^2)\sin(\delta t) + 2cd\sin\omega\cos(\delta t)\right]\right\},$$

$$\xi = \frac{1}{2}\left\{1 - \exp\left(\frac{-\gamma\delta^2 t}{2}\right)\left[(c^2 - d^2)\cos(\delta t) - 2cd\sin\omega\sin(\delta t)\right]\right\}.$$

The concurrence of the Heisenberg XYZ model in this case will be

$$C_2 = \sqrt{4c^2 d^2\cos^2\omega + \exp(-\gamma\delta^2 t)[(c^2 - d^2)\sin(\delta t) + 2cd\sin\omega\cos(\delta t)]^2}. \tag{12}$$

According to Eqs.(11) and (12), we find that different from the case (a), both the time evolution of the density matrix and its concurrence in the case (b) are independent of the anisotropy of the XY plane but depend on the DM interaction. Next, we consider a protocol of teleportation using the entangled state of the Heisenberg XYZ model as quantum channel.

3. Output state of teleportation and its concurrence

It is well known that standard teleportation with an arbitrary mixed state resource is equivalent to a generalized depolarizing channel with probabilities given by the maximally entangled components of the resource.[27] Suppose that the input state to be teleported is an unknown two-qubit pure state $|\psi_{\rm in}\rangle = \cos\left(\frac{\theta}{2}\right)|10\rangle + {\rm e}^{{\rm i}\phi}\sin\left(\frac{\theta}{2}\right)|01\rangle$ ($0 \leqslant \theta \leqslant \pi$, $0 \leqslant \phi \leqslant 2\pi$), where θ and ϕ denote the amplitude and phase of the state, respectively. The concurrence of the input state is easily derived as $C_{\rm in} = \sin\theta$. When the mixed channel $\rho(t)$ is used to teleport the state $|\psi_{\rm in}\rangle$, the output state of the teleportation can be defined as[28]

$$\rho_{\rm out} = \sum_{ij} p_{ij}(\sigma_i \otimes \sigma_j)\rho_{\rm in}(\sigma_i \otimes \sigma_j), \tag{13}$$

where σ_i ($i = 0, 1, 2, 3$) are the unit matrix and the three components of the Pauli matrix σ, respectively, $p_{ij} = {\rm tr}\,[E^i\rho(t)]\ {\rm tr}\,[E^j\rho(t)]$, $\sum_{ij} p_{ij} = 1$ and $\rho_{\rm in} = |\psi_{\rm in}\rangle\langle\psi_{\rm in}|$. Here $E^0 = |\Psi^-\rangle\langle\Psi^-|$, $E^1 = |\Phi^-\rangle\langle\Phi^-|$, $E^2 = |\Phi^+\rangle\langle\Phi^+|$, $E^3 = |\Psi^+\rangle\langle\Psi^+|$, and $|\Psi^\pm\rangle$, $|\Phi^\pm\rangle$ are four Bell states with $|\Psi^\pm\rangle = \frac{\sqrt{2}}{2}(|01\rangle \pm |10\rangle)$ and $|\Phi^\pm\rangle = \frac{\sqrt{2}}{2}(|00\rangle \pm |11\rangle)$.

After we use the Heisenberg XYZ model mentioned in Section 2 as the teleportation channel, based on Eqs.(13) and (8), the output state and the corresponding concurrence can be obtained as follows. For the case (a), the output state is

$$\begin{aligned}\rho_{\rm out,1} =\ & \sin^2\frac{\theta}{2}|10\rangle\langle 10| + 2a^2b^2{\rm e}^{{\rm i}\phi}\sin\theta|10\rangle\langle 01| \\ & +2a^2b^2{\rm e}^{-{\rm i}\phi}\sin\theta|01\rangle\langle 10| \\ & +\cos^2\frac{\theta}{2}|01\rangle\langle 01|,\end{aligned} \tag{14}$$

and its concurrence is given by

$$C_{\rm out,1} = 4\sin\theta\cdot a^2b^2 = 4C_{\rm in}a^2b^2. \tag{15}$$

For the case (b), the output state is

$$\begin{aligned}\rho_{\rm out,2} =\ & \cos^2\left(\frac{\theta}{2}\right)|10\rangle\langle 10| + \frac{G^2}{2}\sin\theta{\rm e}^{-{\rm i}\phi}|10\rangle\langle 01| \\ & +\frac{G^2}{2}\sin\theta{\rm e}^{{\rm i}\phi}|01\rangle\langle 10| \\ & +\sin^2\left(\frac{\theta}{2}\right)|01\rangle\langle 01|,\end{aligned} \tag{16}$$

where

$$\begin{aligned}G =\ & 2cd\cos^2\omega + \sin\omega\exp\left(-\frac{\gamma\delta^2 t}{2}\right)[(c^2-d^2)\sin(\delta t) \\ & +2cd\sin\omega\cos(\delta t)].\end{aligned}$$

In this regard, the concurrence can be expressed as

$$C_{\rm out,2} = \sin\theta\cdot G^2 = C_{\rm in}G^2. \tag{17}$$

Comparing Eqs.(14) and (15) with Eqs.(9) and (10), we find that for the case (a), the channel's parameters ρ_1 and C_1 change with Δ and γ, but the parameters $\rho_{\rm out,1}$ and $C_{\rm out,1}$ only depend on the initial state $|\psi_1(0)\rangle$ of the channel and the input state $|\psi_{\rm in}\rangle$, whereas for the case (b), all the parameters ρ_2, C_2, $\rho_{\rm out,2}$, and $C_{\rm out,2}$ are related to ω, δ, and γ, so the parameters can be adjusted by the DM interaction and the phase decoherence rate. From Eqs.(15) and (17), one can also see that when the DM interaction is ignored, i.e., $D = 0$, the value of $C_{\rm out,2}$ becomes similar to that of $C_{\rm out,1}$, which is just the product of the entanglement degree for the state to be teleported and the square of the initial channel's concurrence.

4. Average fidelity of quantum teleportation

To describe the quality of the teleportation process, it is often quite useful to look at the fidelity between the input state $\rho_{\rm in}$ and the output state $\rho_{\rm out}$. Generally, the state to be teleported is unknown for both the sender and the receiver. To characterize how much information is transferred from the input state to the output state, it is more beneficial to calculate the average fidelity defined as[29]

$$F_A(\rho_{\rm in}, \rho_{\rm out}) = \frac{1}{4\pi}\int_0^{2\pi}{\rm d}\phi\int_0^{\pi}F(\rho_{\rm in}, \rho_{\rm out})\sin\theta{\rm d}\theta,$$

where the fidelity $F(\rho_{\rm in},\ \rho_{\rm out}) = \langle\psi_{\rm in}|\rho_{\rm out}|\psi_{\rm in}\rangle$.

For the case (a), we calculate the fidelity between $\rho_{\rm out}$ and $\rho_{\rm in}$ to be

$$F_1(\rho_{\rm in}, \rho_{\rm out}) = \frac{1}{2}\sin^2\theta + 2a^2b^2\sin^2\theta\cos(2\phi), \tag{18}$$

the average fidelity is

$$\begin{aligned}& F_{A,1}(\rho_{\rm in}, \rho_{\rm out}) \\ &= \frac{1}{4\pi}\int_0^{2\pi}{\rm d}\phi\int_0^{\pi}\langle\psi_{\rm in}|\rho_{\rm out,1}|\psi_{\rm in}\rangle\sin\theta{\rm d}\theta \\ &= \frac{1}{3}.\end{aligned} \tag{19}$$

Clearly, when the initial state of the teleportation channel is in the form of $|\psi_1(0)\rangle = a|00\rangle + b|11\rangle$, the

average fidelity $F_{A,1}$ is always equal to $\frac{1}{3}$, which is independent of any one of the parameters of the system D, Δ, γ, a, and b. In order to make the teleportation protocol superior than any classical communication, we require the average fidelity to be strictly larger than $\frac{2}{3}$. Since $F_{A,1} < \frac{2}{3}$, in this case, the channel is not suitable for quantum teleportation.

For the case (b), the fidelity between $\rho_{\rm out}$ and $\rho_{\rm in}$ can be obtained as

$$F_2(\rho_{\rm in}, \rho_{\rm out}) = 1 + \frac{1}{2}\sin^2\theta(G^2 - 1), \tag{20}$$

the average fidelity is given by

$$\begin{aligned} & F_{A,2}(\rho_{\rm in}, \rho_{\rm out}) \\ = & \frac{1}{4\pi}\int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} \langle\psi_{\rm in}|\rho_{\rm out,2}|\psi_{\rm in}\rangle \sin\theta \mathrm{d}\theta \\ = & \frac{2}{3} + \frac{1}{3}G^2. \end{aligned} \tag{21}$$

Apparently, the value of $F_{A,2}$ is always larger than $\frac{2}{3}$, which implies that if the initial state of channel is in the form of $|\psi_2(0)\rangle = c|01\rangle + d|10\rangle$, the teleportation is superior to any classical communication protocol[21] no matter what the other parameters of the system are.

In Fig.1 we depict the average fidelity $F_{A,2}$ as a function of DM interaction D and time t for different c and d. From Fig.1(a), we can see that when $D = 0$, the average fidelity is equal to $\frac{2}{3}$, but with proper increasing D, the value of average fidelity can be increased from $\frac{2}{3}$ to a larger value and the peak value depends on the time t. It indicates that when the two qubits is initially unentangled, proper DM interaction can make the Heisenberg XYZ model more useful for quantum teleportation. From Fig.1(b), it can be seen that $F_{A,2} = 1$ when $D = 0$, however introducing DM interaction makes $F_{A,2}$ smaller than 1. Similar to Fig.1(b), in Fig.1(c) the average fidelity $F_{A,2}$ is a fixed value for $D = 0$, $F_{A,2}$ oscillates if DM interaction is taken into account, and the steady value of $F_{A,2}$ decreases with increasing D for the long-time limit, which can be seen more clearly from Fig.1(d).

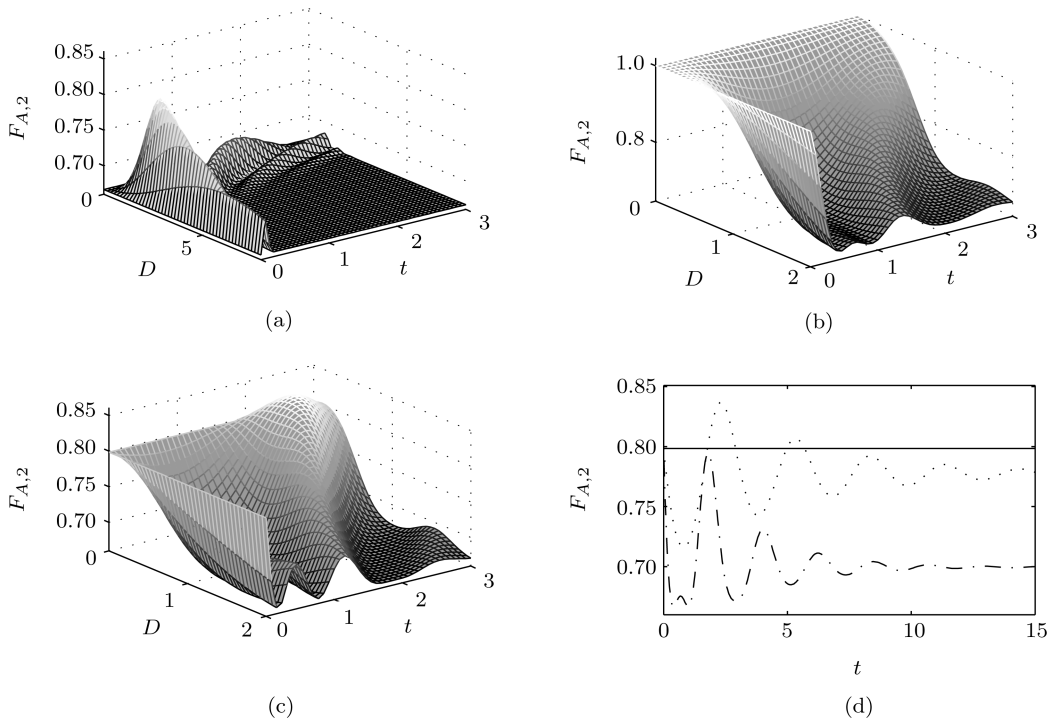


Fig.1. The average fidelity $F_{A,2}$ is plotted as a function of D and t with phase decoherence rate $\gamma = 0.1$ for different initial states, where (a) $c = 1$, $d = 0$; (b) $c = d = \frac{\sqrt{2}}{2}$; (c) $c = \frac{1}{3}$, $d = \frac{2\sqrt{2}}{3}$; (d) the given two-dimensional figure for case (c), where the solid line corresponds to $D = 0$, the dotted line to $D = 0.3$, the dashed line to $D = 1.0$. Here and after, we set $J = 1$.

As shown in Figs.1(c) and 1(d), for some small values of D, there also exists the interesting phenomenon that the value of $F_{A,2}$ at some areas is larger than that without DM interaction. With the increase of D, such a phenomenon disappears. Further numerical calculation shows that if we select the other values of c and d other than $c = d = \frac{1}{\sqrt{2}}$, the phenomenon for small DM interaction enhancing the average fidelity will always occur, apart from the different values of D or time t. Therefore, for the case of the teleportation channel being in the initial nonmaximally entangled state $|\psi_2(0)\rangle$, the average fidelity $F_{A,2}$ can be improved by the introduction of proper DM interaction and the selection of appropriate evolution time.

Figure 2 displays the average fidelity $F_{A,2}$ versus D and t for different values of γ. From the figure, we find that $F_{A,2}$ is a fixed value for $D = 0$, which is independent of the phase decoherence rate γ. But when $D \neq 0$, the larger the γ is, the smaller the fidelity oscillates. It means that the intrinsic decoherence leads to a suppression of the fluctuation of average fidelity in the presence of DM interaction.

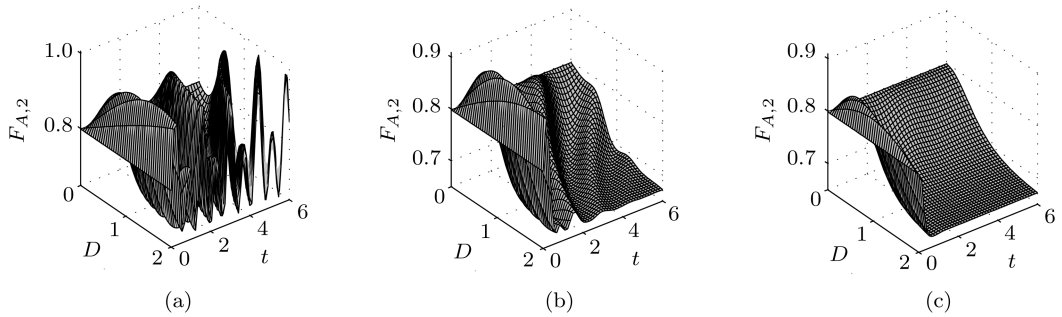


Fig.2. The average fidelity $F_{A,2}$ is plotted as a function of D and t for different γ, where (a) $\gamma = 0$, (b) $\gamma = 0.1$, (c) $\gamma = 0.4$. The other parameters are $c = \frac{2\sqrt{2}}{3}$ and $d = \frac{1}{3}$.

5. Conclusions

In summary, we have investigated the influence of DM interaction and intrinsic decoherence on the quantum teleportation via a two-qubit Heisenberg XYZ model as quantum channel. It is found that the initial state of the channel plays a very important role in the output state and average fidelity of teleportation. When the channel is initially in the entangled state $|\psi_1(0)\rangle = a|00\rangle + b|11\rangle$, the concurrence C_1 and $C_{\text{out},1}$ do not depend on the DM interaction and the corresponding average teleportation fidelity is invariably equal to $\frac{1}{3}$. On the other hand, when the channel is initially in another entangled state $|\psi_2(0)\rangle = c|01\rangle + d|10\rangle$, the average fidelity is always larger than $\frac{2}{3}$, which means that such teleportation is better than any classical communication protocol since $F_A = \frac{2}{3}$ is the limited value for classical communication.[21] Moreover, the phase decoherence rate γ can suppress the fluctuation of the average fidelity, and except that the initial state of channel is maximally entangled, there are regions in D–t plane where a weak DM interaction can enhance the average fidelity to a larger value as compared with the value without DM interaction. In addition, no matter whether the initial channel is in the state $|\psi_1(0)\rangle$ or $|\psi_2(0)\rangle$, the anisotropy of the Heisenberg XYZ model does not affect the teleported state's concurrence and the average fidelity.

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