Measurement-induced disturbance in Heisenberg *XY* spin model with Dzialoshinskii–Moriya interaction under intrinsic decoherence*

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Quantum correlations measured by measurement-induced disturbance (MID) in a two-qubit Heisenberg *XY* spin model with Dzialoshinskii–Moriya (DM) interaction under intrinsic decoherence are investigated. MID is studied under various circumstances and the influences of the external dependencies on the final quantum state which has stable MID are discussed. Two kinds of initial quantum states are considered as well as different conclusions. MID appears to decay periodically during the processing of intrinsic decoherence; both DM interaction and intrinsic decoherence have a negative impact on the correlations. The MID of the stable state depends on several factors, except the parameter of the intrinsic decoherence. Moreover, we find a special initial state that is able to maintain the maximum quantum correlations during the processing of intrinsic decoherence.

Keywords: intrinsic decoherence, measurement-induced disturbance, quantum correlations, dzialoshinskii–Moriya interaction

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1. Introduction

Quantum information theory has attracted much attention in recent years for its promising future.[1–3] Quantum entanglement is one of the most significant resources in quantum information theory. For a long period of time, scientists use quantum entanglement to do some information processing, etc. However, it is difficult to operate and maintain quantum entanglement. Recently, many researches have pointed out that quantum correlation is more general and more fundamental than quantum entanglement because there exist some quantum correlations that are different from entanglement which also have nonzero values even for separable mixed states.[4–7] Auyuanet *et al.* showed that for two initially excited qubits, entanglement is preceded by the emergence of quantum and classical correlations.[8] Quantum entanglement is just a specific kind of quantum correlations, but not the only kind. Since quantum correlations were seldom investigated before, many people take it for granted that quantum entanglement is exactly the quantum correlation. However, this identification is appropriate for pure states, but it is problematic when mixed states are involved.[9]

In recent years, there has been an ongoing effort to characterize qualitatively and quantitatively the quantum correlations and apply them in quantum information. Five popular measures to describe such quantum correlations are quantum entanglement (QE), measurement-induced disturbance (MID), measurement-induced nonlocality (MIN), quantum discord (QD), and geometric quantum discord (GQD).[10–23] Jiang *et al.* gave a symmetric measure of quantum correlation based on the Hilbert–Schmidt distance.[24] The quantum correlation of coupled qubits in squeezed vacuum reservoir and in a damping Jaynes–Cummings model were investigated in Refs. [25] and [26]. In this paper, we select MID as the measure to analyze a two-qubit Heisenberg *XY* spin model with Dzialoshinskii–Moriya (DM) interaction under intrinsic decoherence.

2. Quantum correlation via measurement-induced disturbance

According to Luo's theory,[1,9,27] we can apply local measurement $\{\Pi_k\}$ ($\Pi_k\Pi_{k'} = \delta_{kk'}\Pi_k$ and $\sum_k \Pi_k = 1$) to any bipartite state ρ and then explore the difference between the states before and after the measurement. Here, $\Pi_k = \Pi_i^a \otimes \Pi_j^b$ and Π_i^a, Π_j^b are complete projective measurements consisting of one-dimensional orthogonal projections for parties a and b. After the measurement, we get the state $\Pi(\rho) = \sum_{ij}\left(\Pi_i^a \otimes \Pi_j^b\right)\rho\left(\Pi_i^a \otimes \Pi_j^b\right)$ and it is a classical state. If the measurement Π is induced by the spectral resolutions of the reduced states $\rho^a = \sum_i \rho_i^a \Pi_i^a$ and $\rho^b = \sum_j \rho_j^b \Pi_j^b$, the measurement leaves the marginal information invariant and is in a certain sense the least disturbing. Then, we can use the quantum mutual information difference between ρ and $\Pi(\rho)$ to measure the quantum correlation in ρ. The total correlation in a bipartite state ρ can be well quantified by the quantum mutual information $I(\rho) = S(\rho^a) + S\left(\rho^b\right) - S(\rho)$, and $I(\Pi(\rho))$ quantifies the classical correlations in ρ since $\Pi(\rho)$ is a classical state. Here, $S(\rho) = -\mathrm{tr}(\rho \log \rho)$ denotes the von Neumann

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entropy, and the logarithm is always understood as base 2 in this paper, so the quantum correlation can be quantified by the measurement-induced disturbance[1,9]

$$Q(\rho) = I(\rho) - I(\Pi(\rho)). \tag{1}$$

3. Intrinsic decoherence

When a quantum system is coupled with the environment, correlations are established between them, and decoherence is essentially a manifestation of such correlations. One method to characterize and quantify the decoherence seeks to modify Schrodinger's equation in such a way that coherence is automatically destroyed as the physical properties of the system approach a macroscopic level, which is called intrinsic decoherence.[28] Milburn has proposed an assumption that on sufficiently short time steps, the system does not evolve continuously under unitary evolution but rather in a stochastic sequence of identical unitary transformations. Based on this assumption, Milburn put forward the time evolution density operator $\rho(t)$ of the quantum system that is described by the Hamiltonian H, which can be described as

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = \frac{1}{\Gamma}\left[\exp(-\mathrm{i}\Gamma H)\rho(t)\exp(\mathrm{i}\Gamma H) - \rho(t)\right], \tag{2}$$

where Γ is the parameter of the intrinsic decoherence. Under the Markovian approximation, equation (2) can be expressed as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = -\mathrm{i}[H,\rho(t)] - \frac{\Gamma}{2}[H,[H,\rho(t)]]. \tag{3}$$

The formal solution of the master equation can be expressed as follows:[29–31]

$$\rho(t) = \sum_{k=0}^{\infty}\frac{(\Gamma t)^k}{k!}M^k(t)\rho(0)M^{\dagger k}(t), \tag{4}$$

where $M^k = H^k\exp(-\mathrm{i}Ht)\exp\left(-\Gamma t H^2/2\right)$, and $\rho(0)$ is the density matrix of the initial system. Put the completeness relation $\sum_n |\psi_n\rangle\langle\psi_n| = \hat{I}$ into Eq. (4) then we obtain the expression of the density matrix with time, which is

$$\begin{aligned}\rho(t) = &\sum_{mn}\exp\left[-\frac{\Gamma t}{2}(E_m - E_n)^2 - \mathrm{i}t(E_m - E_n)\right]\\ &\times\langle\psi_m|\rho(0)|\psi_n\rangle|\psi_m\rangle\langle\psi_n|,\end{aligned} \tag{5}$$

where $|\psi_m\rangle$, $|\psi_n\rangle$, E_m, E_n $(m,n = 1,2,3,4)$ are the eigenvectors and their corresponding eigenvalues of the Hamiltonian H.

4. Model solution and analysis

The Hamiltonian of the two-qubit Heisenberg XY spin model with Dzialoshinskii–Moriya (DM) interaction can be described as

$$H = \frac{1}{2}\left[J_x\sigma_1^x\sigma_2^x + J_y\sigma_1^y\sigma_2^y + \boldsymbol{D}\cdot(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right], \tag{6}$$

where J_x, J_y are real coupling coefficients and $\sigma_i^{\varepsilon}(\varepsilon = x,\ y,\ i = 1,\ 2)$ are Pauli spin operators, $\boldsymbol{D}$ is the DM vector coupling and we set the direction of DM interaction along the z direction, i.e., $\boldsymbol{D} = D\boldsymbol{z}$. For simplicity, we define

$$\begin{aligned}&\Delta = \frac{J_x - J_y}{2},\quad \Sigma = \frac{J_x + J_y}{2},\\ &\Lambda = \sqrt{\Sigma^2 + D^2},\quad \alpha = \arctan\left(\frac{-D}{\Sigma}\right).\end{aligned} \tag{7}$$

Note that we are working in units so that J_x, J_y, D are dimensionless. We can obtain the MID in the case of different kinds of initial state respectively.

Case 1 The initial state is $\psi(0) = \cos(\theta)|00\rangle + \mathrm{e}^{\mathrm{i}\phi}\sin(\theta)|11\rangle$. We can obtain the density matrix in the standard basis $\{|0,0\rangle, |0,1\rangle, |1,0\rangle, |1,1\rangle\}$, which can be expressed as

$$\rho(t) = \begin{pmatrix} -a-b+c+d & 0 & 0 & -a+b+c-d\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ a-b+c-d & 0 & 0 & a+b+c+d\end{pmatrix}, \tag{8}$$

with

$$\begin{cases} a = \dfrac{1}{4}(\sin^2\theta - \cos^2\theta + 2\mathrm{i}\sin\phi\cos\theta\sin\theta)\\ \quad\times\exp\left(-2\Gamma t\Delta^2 + 2\mathrm{i}t\Delta\right),\\ b = \dfrac{1}{4}(\sin^2\theta - \cos^2\theta - 2\mathrm{i}\sin\phi\cos\theta\sin\theta)\\ \quad\times\exp\left(-2\Gamma t\Delta^2 - 2\mathrm{i}t\Delta\right),\\ c = \dfrac{1}{4}(1 + 2\cos\phi\cos\theta\sin\theta),\\ d = \dfrac{1}{4}(1 - 2\cos\phi\cos\theta\sin\theta).\end{cases}$$

Besides, the reduced density matrix is

$$\rho^a(t) = \rho^b(t) = \begin{pmatrix} -a-b+c+d & 0\\ 0 & a+b+c+d\end{pmatrix}. \tag{9}$$

On the other hand, by taking $\Pi_i^a = |i\rangle\langle i|$ and $\Pi_j^b = |j\rangle\langle j|$, we have

$$\Pi(\rho) = \begin{pmatrix} -a-b+c+d & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & a+b+c+d\end{pmatrix} \tag{10}$$

and

$$[\Pi(\rho)]^a = [\Pi(\rho)]^b = \rho^a = \rho^b. \tag{11}$$

Then we can calculate von Neumann entropies of the three quantum states and three classical states above via

$$S(\rho) = -\mathrm{tr}(\rho\log\rho) = -\sum_i\lambda_i\log\lambda_i, \tag{12}$$

where λ_i means the eigenvalue of ρ. The eigenvalues of $\rho(t)$ can be easily obtained as $\lambda_{1,2} = 0$, $\lambda_3 = c + d - X$, $\lambda_4 = c + d + X$, with $X = \sqrt{4ab + c^2 - 2cd + d^2}$. Therefore,

$$S(\rho) = -\mathrm{tr}(\rho\log_2\rho) = -\sum_i\lambda_i\log_2\lambda_i$$

$$= -\big[(c+d-X)\log_2[c+d-X] + (c+d+X)\log_2[c+d+X]\big], \quad (13)$$

$$S(\rho^a) = S(\rho^b) = -(-a-b+c+d)\log_2[-a-b+c+d] - (a+b+c+d)\log_2[a+b+c+d], \quad (14)$$

$$S(\Pi(\rho)) = S(\Pi(\rho^a)) = S\left(\Pi(\rho^b)\right) = -(-a-b+c+d)\log_2[-a-b+c+d] - (a+b+c+d)\log_2[a+b+c+d]. \quad (15)$$

By using $I(\rho) = S(\rho^a) + S\left(\rho^b\right) - S(\rho)$, quantum and classical mutual information can be expressed as

$$I(\rho) = -2\{(-a-b+c+d)\log_2[-a-b+c+d] + (a+b+c+d)\log_2[a+b+c+d]\} + [(c+d-X)\log_2[c+d-X] + (c+d+X)\log_2[c+d+X]], \quad (16)$$

$$I(\Pi(\rho)) = -(-a-b+c+d)\log_2[-a-b+c+d] - (a+b+c+d)\log_2[a+b+c+d]. \quad (17)$$

Consequently,

$$Q(t) = -(-a-b+c+d)\log_2[-a-b+c+d] - (a+b+c+d)\log_2[a+b+c+d] + [(c+d-X)\log_2[c+d-X] + (c+d+X)\log_2[c+d+X]]. \quad (18)$$

Moreover, the MID of the stable state can be written as

$$\lim_{t\to\infty} Q(t) = -2(c+d)\log_2[c+d] + 2d\log_2[2d] + 2c\log_2[2c]. \quad (19)$$

From Eqs. (8) and (18), we can figure out that the MID is independent of the DM interaction and the average of coupling coefficients $\Sigma = (J_x + J_y)/2$ under this initial condition. We set $\theta = \pi/4$, $\phi = \pi/2$, so that the initial states of the qubits are maximally entangled states.

From Fig. 1, we can see that the MID appears to decay periodically during the processing of intrinsic decoherence and Γ changes the speed of decay but not the period of oscillations. Besides, the MID collapses more quickly with the increase of Γ and this regular pattern is true for initial states in case 1 and case 2. Figure 2 shows the time evolution of the MID for different $\Delta = (J_x - J_y)/2$, which represents the anisotropy of coupling. As is shown, Δ accelerates the speed of intrinsic decoherence, i.e., the MID decreases totally and the period of damped oscillation is shortened. Furthermore, the MID is symmetric with respect to zero anisotropy of coupling, which can also be proved in theory. It is quite reasonable since the opposite value of Δ also corresponds to the same situation, as long as we rotate the axes.

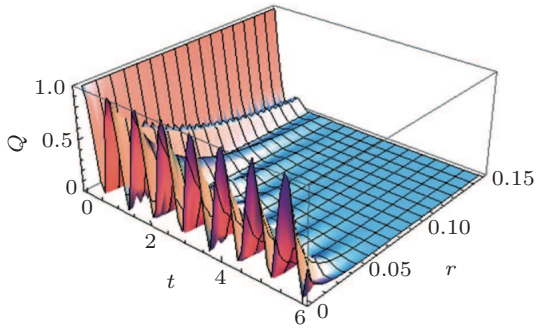


Fig. 1. (color online) MID as a function of time t and parameter of the intrinsic decoherence Γ when $\phi=\pi/2$, $\theta=\pi/4$, $\Delta = 2$.

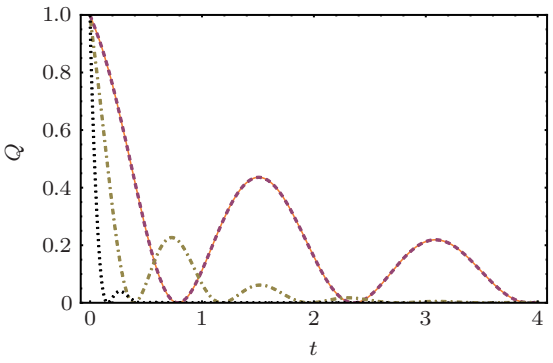


Fig. 2. (color online) The time evolution of MID for different Δ when $\phi=\pi/2$, $\theta=\pi/4$, $\Gamma=0.1$ (Solid-red line for $\Delta=-1$, dashed-purple line for $\Delta=1$, dotted-dashed-yellow line for $\Delta=2$, and dotted-black line for $\Delta=5$).

According to Eqs. (8) and (19), when time t approaches to infinity, the MID of the stable state depends only on initial phase ϕ, θ, while the parameter of intrinsic decoherence or coupling coefficients have no impact on it. The dependence of the initial phase on the MID is given in Fig. 3. As a result, we can manipulate the initial quantum state in order to get the stable one required. In addition, we find a special initial state $\psi(0) = (|00\rangle + |11\rangle)/\sqrt{2}$, which is time-independent and able to maintain the maximum quantum correlation during the processing of intrinsic decoherence.

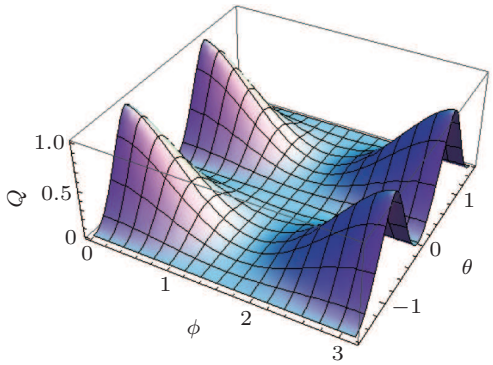


Fig. 3. (color online) MID of stable states as a function of the initial phase ϕ, θ.

Case 2 The initial state is $\psi(0) = \cos(\theta)|01\rangle + e^{i\phi}\sin(\theta)|10\rangle$. Similarly, we can obtain the density matrix in the standard basis $\{|0,0\rangle, |0,1\rangle, |1,0\rangle, |1,1\rangle\}$, which can be expressed as

$$\rho(t)=\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -a-b+c+d & -\mathrm{e}^{\mathrm{i}\alpha}a+\mathrm{e}^{\mathrm{i}\alpha}b+\mathrm{e}^{\mathrm{i}\alpha}c-\mathrm{e}^{\mathrm{i}\alpha}d & 0 \\ 0 & \mathrm{e}^{-\mathrm{i}\alpha}a-\mathrm{e}^{-\mathrm{i}\alpha}b+\mathrm{e}^{-\mathrm{i}\alpha}c-\mathrm{e}^{-\mathrm{i}\alpha}d & a+b+c+d & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \tag{20}$$

where

$$\begin{cases} a=\dfrac{1}{4}(\sin^2\theta-\cos^2\theta+2\mathrm{i}\sin(\alpha+\phi)\cos\theta\sin\theta) \\ \quad\times\exp\left(-2\Gamma t\Lambda^2+2\mathrm{i}t\Lambda\right), \\ b=\dfrac{1}{4}(\sin^2\theta-\cos^2\theta-2\mathrm{i}\sin(\alpha+\phi)\cos\theta\sin\theta) \\ \quad\times\exp\left(-2\Gamma t\Lambda^2-2\mathrm{i}t\Lambda\right), \\ c=\dfrac{1}{4}(1+2\cos(\alpha+\phi)\cos\theta\sin\theta), \\ d=\dfrac{1}{4}(1-2\cos(\alpha+\phi)\cos\theta\sin\theta). \end{cases}$$

Consequently,

$$\begin{aligned} Q(t) \;=\; & -(-a-b+c+d)\log_2[-a-b+c+d] \\ & -(a+b+c+d)\log_2[a+b+c+d] \\ & +[(c+d-X)\log_2[c+d-X] \\ & +(c+d+X)\log_2[c+d+X]], \end{aligned} \tag{21}$$

with $X=\sqrt{4ab+c^2-2cd+d^2}$. The MID of the stable state can be written as

$$\begin{aligned} \lim_{t\to\infty}Q(t) \;=\; & -2(c+d)\log_2[c+d]+2d\log_2[2d] \\ & +2c\log_2[2c]. \end{aligned} \tag{22}$$

Under this initial condition, the MID also oscillates and collapses with the evolution of time t and is independent on the anisotropy of coupling $\Delta=(J_x-J_y)/2$. Figures 4 and 5 show the impacts of D and Σ on MID. From Fig. 4, we can clearly see that the influence of the DM coupling coefficient is similar to that of the anisotropy of the coupling in case 1. The increasing of DM coupling coefficient D not only lowers the MID totally but also shortens the period of damped oscillation. Additionally, when D takes the opposite value, the situation stays the same, i.e., it makes no difference whether the direction of $\boldsymbol{D}$ is along the forward or reverse direction of the z axis.

The influence of Σ is shown in Fig. 5. We can find that MID decreases sharply when the absolute value of Σ increases. Besides, the period of damped oscillation decreases as well and the MID of stable states also decreases. For ferromagnetic ($\Sigma<0$) and anti-ferromagnetic ($\Sigma>0$), the MID is symmetric about Σ and MID of the stable state reaches the maximal value when $\Sigma=0$. In fact, if $\phi\neq\pi/2$, the MID of stable states is non-monotonic and can reach a peak at a certain value of Σ. This will be detailed below.

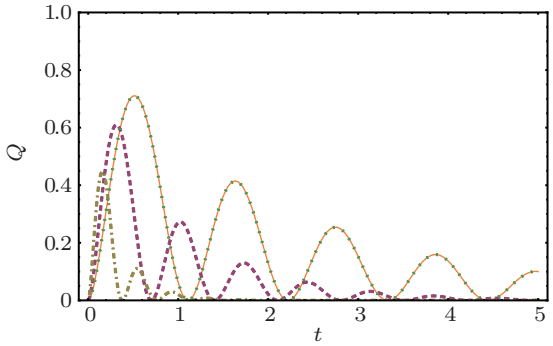


Fig. 4. (color online) The time evolution of MID for different D when $\phi=\pi/2$, $\theta=\pi/2$, $\Sigma=1$, $\Gamma=0.05$ (solid-red line for $D=1$, dashed-purple line for $D=2$, dotted-dashed-yellow line for $D=4$, and dotted-green line for $D=-1$).

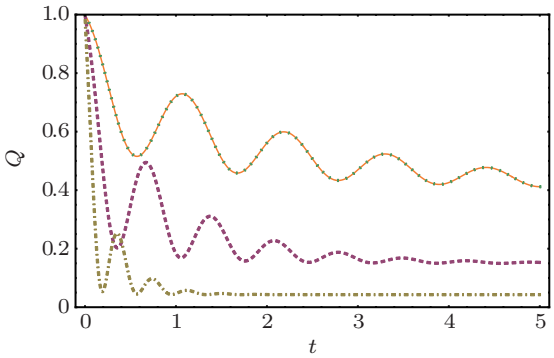


Fig. 5. (color online) The time evolution of MID for different Σ when $\phi=\pi/2$, $\theta=\pi/4$, $D=1$, $\Gamma=0.05$ (solid-red line for $\Sigma=1$, dashed-purple line for $\Sigma=2$, dotted-dashed-yellow line for $\Sigma=4$, and dotted-green line for $\Sigma=-1$).

We have defined $\Lambda=\sqrt{\Sigma^2+D^2}$ as a reflection of the absolute values of D and Σ, and $\alpha=\arctan(-D/\Sigma)$ as a reflection of comparative ratios of the two interactions. Through the theoretical derivation above, the MID of stable states can be written as

$$\begin{aligned} \lim_{t\to\infty}Q(t) \;=\; & 1+\frac{1}{2}(1-2\cos(\alpha+\phi)\cos\theta\sin\theta) \\ & \times\log_2\left[\frac{1}{2}(1-2\cos(\alpha+\phi)\cos\theta\sin\theta)\right] \\ & +\frac{1}{2}(1+2\cos(\alpha+\phi)\cos\theta\sin\theta) \\ & \times\log_2\left[\frac{1}{2}(1+2\cos(\alpha+\phi)\cos\theta\sin\theta)\right]. \end{aligned} \tag{23}$$

From Eq. (23), we can figure out only whether ϕ, θ, and α are relevant to the MID of stable states. The absolute intensity of two interactions as well as the parameter of intrinsic decoherence Γ accelerates the speed and extent of decoherence rather than changes the MID of stable states. On the other hand, the

impacts of α and ϕ are not independent since they appear in pairs according to Eq. (23). For simplicity, we set $\beta = \alpha + \phi$. Figure 6 shows the influence of θ and β on the MID of stable states. It can be observed that θ and β play the same role as θ and ϕ in case 1. It is quite reasonable due to the expression of MID in the two cases since β in case 2 takes the place of ϕ in case 1. Besides, the other differences between the two cases only appear in the processing of decoherence instead of in the final state. Additionally, if θ and ϕ are determined, the MID of stable states changes periodically with α, so we can manipulate the initial quantum state and the comparative ratios of DM interaction and coupling coefficients in order to get the stable one required. Furthermore, when $\beta = 0$, $\theta = \pi/4$, the quantum state is time-independent and able to maintain the maximum quantum correlation all the time.

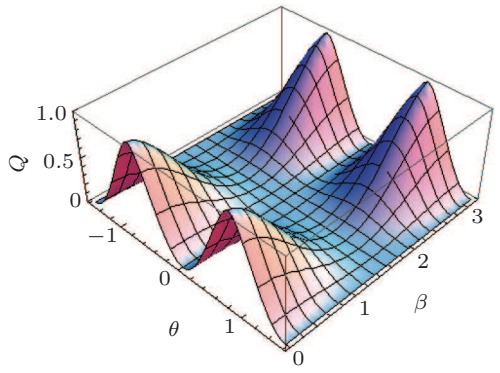


Fig. 6. (color online) MID of stable states as a function of θ and β.

5. Conclusion

We have investigated the time evolution of the MID in a two-qubit Heisenberg *XY* spin model with DM interaction under intrinsic decoherence. We chose two Bell states as the initial state, where case 1 means the mixed state of both ground states $|00\rangle$ and both excited states $|11\rangle$, while case 2 means the mixed state of two kinds of one-ground-one-excited state $|01\rangle$ and $|10\rangle$. It can be concluded that the MID collapses more quickly with the increase of Γ in both case 1 and case 2, but Γ will not change the period of oscillations and the MID of stable states. For case 1, anisotropy of coupling Δ accelerates the speed of intrinsic decoherence. For case 2, both DM interaction D and intensity of coupling Σ have negative effects on the maintenance of quantum correlations during the processing of intrinsic decoherence. In addition, the MID of stable states can be controlled by manipulating the initial state (case 1) or the initial state and intensity of interactions (case 2). There also exist some specific initial states that are able to maintain the maximum quantum correlations all the time. We hope that our conclusion would be applied in quantum information processing and the experiments of quantum correlation.

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