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Steady Quantum Discord Behavior for Two Qubits Heisenberg XYZ Chain with Intrinsic Decoherence

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Abstract By taking into account the intrinsic decoherence and the nonuniform magnetic field, quantum discord (QD) and steady quantum discord (SQD) behavior of a two-qubit anisotropic Heisenberg XYZ chain with different initial states are investigated. We find that properly tuning the external and self parameters not only can improve the quantum correlation and steady quantum correlation but also can weaken the effects of decoherence such as increasing anisotropic parameter Δ, decreasing B or b. When t is infinity, the SQD value and the physical about the SQD phenomenon are studied in detail, the SQD value is strongly dependent on the external and self parameters, which is increased evidently by increasing anisotropic parameter and decreasing nonuniform field. Through analyzing the physical about SQD phenomenon, the conditions about the existence of SQD phenomenon are analyzed with different initial states. These investigations can imply us more control parameters on quantum correlation and steady quantum correlation in solid state systems.

Keywords Quantum discord · Entanglement · Heisenberg model

1 Introduction

Quantum entanglement is one of the most amazing nonlocal feature of quantum mechanics, which is a kind of quantum correlation that has been playing a central role in quantum information and communication theory [1–3]. However, entanglement is not the only type of correlation useful for quantum technology. There exist nonclassical correlations which are more general and possibly more fundamental than entanglement, it is found that there are some quantum nonlocality without entanglement [4, 5], and some quantum correlations different from entanglement which are also nonclassical and offer some advantage even in a composite state without entanglement [4, 6]. Therefore, in order to account quantum correlation in a given quantum state, various measures of correlations have been proposed in several literatures, such as QD [7, 8], measurement induced disturbance [9], quantum deficit [10]

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and so on. Among them, the most popular one is the QD, which has received a great deal of recent attention, concerned with quantum phase transition [11], quantum computation [12, 13], broadcasting of quantum states [14]. Some recent results [15, 16] suggest that QD captures the nonlocal correlation more general than entanglement. Even for some separable states, the entanglement is zero while it can have nonzero QD, which indicates the presence of quantum correlation. Nonclassical correlation measured by the QD can be considered as more effective than entanglement in some sense, and the QD might be responsible for the quantum computational efficiency of some quantum computation tasks [17–19]. Due to the fundamental and practical significance of quantum correlation, QD has attracted increasing attention in the past few years, which is believed to be a very useful probe to analyze mixed state quantum correlation. By this conception, over last two years, QD was analyzed in a number of contexts, such as the open quantum systems [20–23], biological [24], relativistic systems [25], and low-dimensional spin models [26–29]. Compared with other physics systems, solid state spin systems, as the natural candidates, not only can describe interaction of qubits in solid physical systems, nuclear spin systems [30], quantum dots [31, 32] systems but also have useful applications.

However, in practical realization,every quantum system is open and unavoidable interaction with the surrounding environment which leads to decoherence. As a result, it is more challenging to store quantum correlation in two atoms. In recent years, there has been an ongoing effort applied to solve the decoherence. One of approaches is to modify the Schrodinger equation in such a way that the quantum coherence is automatically destroyed as the quantum system evolves. This effect is called intrinsic decoherence proposed by Miburn [33]. The master equation describing the intrinsic decoherence under Markovian approximations is given

$$\frac{d\rho_t}{dt} = -i[H,\rho] - \frac{\gamma}{2}\big[H,\big[H,\rho(t)\big]\big] \tag{1}$$

γ is the intrinsic decoherence rate. The formal solution of the above master equation can be described as [34]

$$\rho(t) = \sum_{k=0}^{\infty} \frac{(\gamma t)^k}{k!} M^k(t)\rho(0)M^{\dagger k}(t) \tag{2}$$

where $\rho(0)$ is the density operators of the initial system and $M^k(t)$ is defined by

$$M^k(t) = H^k \exp(-iHt)\exp\left(-\frac{\gamma t}{2\gamma}H^2\right) \tag{3}$$

Motivated by these, in this paper, we are concerned with the quantum correlation in a two-qubit Heisenberg XYZ chain with intrinsic decoherence in the presence of an uniform and inhomogeneous magnetic field. This paper is organized as follows. In Sect. 2 we define the anisotropic XYZ model, and give the eigenvalues and eigenvectors. In Sect. 3, recall the definition of QD, obtain the evolution of density matrix with different initial states, and investigate the QD and SQD dynamics in detail. Finally Sect. 4 is devoted to conclusions.

2 Description of the Model

Consider now for a two-qubit anisotropic Heisenberg XYZ chain with inhomogeneous magnetic field, the Hamiltonian can be described as

$$H = J\left(\sigma_1^+\sigma_2^- + \sigma_1^-\sigma_2^+\right) + J\Delta\left(\sigma_1^+\sigma_2^+ + \sigma_1^-\sigma_2^-\right) + \frac{J_z}{2}\sigma_1^z\sigma_2^z + \frac{(B+b)}{2}\sigma_1^z + \frac{(B-b)}{2}\sigma_2^z, \tag{4}$$

where $J = \frac{J_x+J_y}{2}$, $\Delta = \frac{J_x-J_y}{J_x+J_y}$ and $\sigma^\pm = \frac{1}{2}(\sigma^x \pm i\sigma^y)$, J_x and J_y are the coupling constants along the X and Y axis, respectively; $\sigma\pm$ are rasing and lowering operators, and Δ ($0 < \Delta < 1$) measures the anisotropy in the XY plane. The magnetic field on the two-qubit are $B+b$ and $B-b$, the value of b controls the degree of inhomogeneity [35]. Without loss of generality, through solving the eigenvalues and eigenstates of H in the standard basis of $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$, the four eigenvalues and the corresponding four eigenstates can be explained as

$$\begin{aligned}
&E_{1,2} = \left(-\frac{J_z}{2} \pm \xi\right), \qquad E_{3,4} = \left(\frac{J_z}{2} \pm \eta\right),\\
&|\psi_{1,2}\rangle = N^\pm\left[\frac{(b\pm\xi)}{J}|01\rangle + |10\rangle\right],\\
&|\psi_{3,4}\rangle = M^\pm\left[\frac{(B\pm\eta)}{J\Delta}|00\rangle + |11\rangle\right],
\end{aligned} \tag{5}$$

where the parameters $\eta = \sqrt{B^2 + J^2\Delta^2}$ and $\xi = \sqrt{b^2 + J^2}$, the normalization constants $N^\pm = 1/\sqrt{\frac{1+(b\pm\xi)^2}{J^2}}$ and $M^\pm = 1/\sqrt{\frac{1+(B\pm\eta)^2}{J^2\gamma^2}}$, respectively.

3 QD and SQD Between Two Qubits for Different Initial States

Based on knowing the spectrum of H, we now introduce the decoherence of Milburn's model. When the intrinsic decoherence is considered, and inserting the complete relation $\sum_n |\psi_n\rangle\langle\psi_n|$ in Eq. (2), the evolution of the elements of density matrix can be expressed as

$$\begin{aligned}
\rho(t) = \sum_{mn} &\exp\left[-\frac{\gamma t}{2}(E_m - E_n)^2 - i(E_m - E_n)t\right]\\
&\times \langle\psi_m|\rho(0)|\psi_n\rangle|\psi_m\rangle\langle\psi_n|,
\end{aligned} \tag{6}$$

where $E_{m,n}$ and $\psi_{m,n}$ are the eigenvalues and the corresponding eigenvectors of H given in Eq. (5), $\rho(0)$ is the initial state about this spin system. With different initial states, one can obtain corresponding different evolution density matrix elements, however our tendency is to investigate the effects of those parameters on QD and SQD, such as the parameters Δ, external uniform or nonuniform magnetic field, and intrinsic decoherence. From the spectrum of H in Eq. (5) and the evolution density matrix shown in Eq. (6), one can conclude that when the initial state is $|00\rangle$, $|11\rangle$ or the superposition states between them (such as the bell state: $\frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$), only the external uniform field B, the anisotropic parameter Δ and intrinsic decoherence effect the evolution density matrix. While with the case of initial superposition states between $|01\rangle$ and $|10\rangle$, we can investigate the effect of parameter b on QD and SQD, for this case the parameters B and Δ cannot influence the quantum correlation. We also know that for a two qubits system, the density matrix contains nonzero elements usually along the main diagonal and anti-diagonal, such as the X-state form

$$\rho = \begin{pmatrix} \rho_{11} & 0 & 0 & \rho_{14} \\ 0 & \rho_{22} & \rho_{23} & 0 \\ 0 & \rho_{23^*} & \rho_{33} & 0 \\ \rho_{14^*} & 0 & 0 & \rho_{44} \end{pmatrix} \tag{7}$$

for this two qubits system, prepared in an initial quantum state determined by the X-state form initial density matrix $\rho(0)$, after some time the evolution state density matrix $\rho(t)$ remain preserve the X structure.

By knowing the evolution density matrix, one can use the QD to examine the effects of those parameters on the quantum correlations. In classical information theory, the total correlations in a bipartite quantum system are measured by the total quantum mutual information $I(\rho_{AB})$ defined as

$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB}) = \mathrm{QD}(\rho_{AB}) + C(\rho_{AB}) \tag{8}$$

where $S(\rho) = -\mathrm{Tr}(\rho \log_2 \rho)$is the Von Neumann extropy of density matrix, ρ_A and ρ_B are the reduced density matrices of the subsystem A and B, respectively; ρ_{AB} is the total density matrix. $\mathrm{QD}(\rho_{AB})$ denotes the QD which provides information about the nature quantum correlation. It is a measure of pure quantum correlations called quantum discord (QD) [8]. $C(\rho_{AB})$ is the classical correlation which is defined as the maximum information about one subsystem ρ_i, the value of $C(\rho_{AB})$ is depends on the type of measurement performed on the other subsystem. In this paper, we limit ourselves to projective measurement $\Pi_k = |k\rangle\langle k|$ $(k = \pm)$ performed only on the subsystem B, the two orthogonal states $|+\rangle$ and $|-\rangle$ can be represented as a unitary vector on the Bloch sphere $|+\rangle = \cos\theta|1\rangle + e^{i\phi}\sin\theta|0\rangle$ and $|-\rangle = e^{-i\phi}\sin\theta|1\rangle - \cos\theta|0\rangle$ with $0 \le \theta \le \pi/2$ and $0 \le \phi \le 2\pi$. Then the classical correlation can be defined as

$$C(\rho_{AB}) = S(\rho_A) - \min_{\{\Pi_k\}}\left[\sum_k p_k S\big(\rho_A^{(k)}\big)\right]. \tag{9}$$

The minimum is taken over the complete set of orthogonal projectors Π_k, where $\rho_A^{(k)} = \frac{1}{p_k}\mathrm{Tr}_B[(\mathrm{I}_A \otimes \Pi_k)\rho_{AB}(\mathrm{I}_A \otimes \Pi_k)]$ is the reduced matrix of subsystem A after obtaining the measurement outcome k, where $p_k = \mathrm{Tr}_{AB}[(\mathrm{I}_A \otimes \Pi_k)\rho_{AB}(\mathrm{I}_A \otimes \Pi_k)]$. Usually the classical correlation is somewhat difficult to calculate and we cannot get the analytical solutions. While for the X state density matrix (8), we can obtain the exact expression of classical correlation

$$\begin{aligned} C(\rho_{AB}) &= S(\rho_A) - \min(C_1, C_2) \\ C_1 &= -\bigg[\rho_{11}\log_2\left(\frac{\rho_{11}}{\rho_{11}+\rho_{33}}\right) + \rho_{22}\log_2\left(\frac{\rho_{22}}{\rho_{22}+\rho_{44}}\right) + \rho_{33}\log_2\left(\frac{\rho_{33}}{\rho_{33}+\rho_{11}}\right) \\ &\quad + \rho_{44}\log_2\left(\frac{\rho_{44}}{\rho_{44}+\rho_{22}}\right)\bigg] \\ C_2 &= -\left[\frac{1+\Xi}{2}\log_2\left(\frac{1+\Xi}{2}\right) + \frac{1-\Xi}{2}\log_2\left(\frac{1-\Xi}{2}\right)\right], \end{aligned} \tag{10}$$

where $\Xi = [(\rho_{11} - \rho_{14} + \rho_{23} - \rho_{33})^2 + 4(|\rho_{14}| + |\rho_{23}|)^2]^{\frac{1}{2}}$. Based on the equations above we can define QD as

$$\mathrm{QD}(\rho_{AB}) = I(\rho_{AB}) - C(\rho_{AB}) = S(\rho_B) - S(\rho_{AB}) + \min(C_1, C_2). \tag{11}$$

In the following, we use above formalisms to study the dynamical character of those parameters on the quantum correlation about this two qubits system for several different initial states.

(1) Consider this two qubits system is initially in the state $|\varphi_1\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, then $\rho(0) = |\varphi_1\rangle\langle\varphi_1|$, substituting $\rho(0)$ into Eq. (6). For this initial state we can examine the effects of parameters Δ, uniform magnetic field B and the intrinsic decoherence γ on quantum correlation. Those nonzero matrix elements of the evolution density matrix are following

$$\begin{aligned}
\rho_{11} &= \frac{1}{2} + \frac{BJ\Delta}{2\eta^2}\bigl[1 - \exp\bigl(-2\eta^2\gamma t\bigr)\cos(2\eta t)\bigr], \\
\rho_{14} &= \frac{J^2\Delta^2}{2\eta^2} + \frac{B}{2\eta^2}\exp\bigl(-2\eta^2\gamma t\bigr)\bigl[B\cos(2\eta t) - i\eta\sin(2\eta t)\bigr], \\
\rho_{44} &= \frac{1}{2} - \frac{BJ\Delta}{2\eta^2}\bigl[1 - \exp\bigl(-2\eta^2\gamma t\bigr)\cos(2\eta t)\bigr]
\end{aligned} \tag{12}$$

the others matrix elements are zero. According to Eq. (12), it is easy to see that there is no QD when anisotropic parameter $\Delta = 0$ and $B = 0$, with this case the matrix element ρ_{14} equals to zero at any time. To clear see the effects of parameters B and Δ on QD behavior, in Fig. 1, we plot the evolution of QD as a function of the decoherence time with different values of the anisotropic parameter Δ for external field B is fixed. It is shown us that the QD is initially to be the maximum value 1, the reason is that this spin system is initially in the maximum entangled pure state. When the decoherence time increases the value of QD is decreased, which is reasonable, decoherence comes from environment usually destroy the quantum correlation, and the larger the intrinsic decoherence rate γ is, the more quickly QD collapses. However, one point we must mention is that this Milburn's decoherence cannot entirely destroy the quantum correlation, there exists a SQD value with the time is infinity. From the figure, we also know that this SQD value is increased with increasing anisotropic parameter Δ, which concludes us that one can weaken the effects of intrinsic decoherence and obtain ideal SQD value by adjusting Δ. This phenomenon also can be understood by

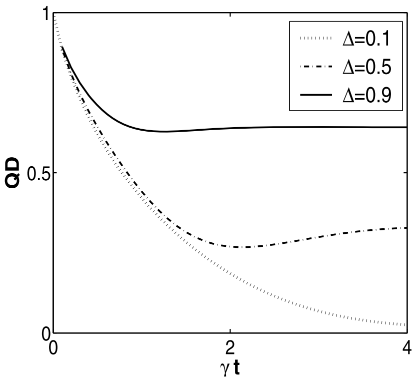

Fig. 1 The QD behavior as a function of the decoherence time γt with different values of the anisotropic parameter Δ. For the *dotted line*: $\Delta = 0.1$, the *dash-dotted line*: $\Delta = 0.5$ and the *black line*: $\Delta = 0.9$, where we set $J = 1$, $B = 0.4$

Eq. (12), with time t is larger enough, the off-diagonal density matrix element ρ_{14} is not zero. According to the Eq. (12) and the definition of QD, in the limit case of $t \to \infty$, we can obtain the value of SQD reads as

$$\lim_{t\to\infty} \mathrm{SQD} = \log_2 \frac{\eta B}{\delta} + \frac{J\Delta}{\eta} \log_2 \frac{\eta + J\Delta}{B} + \frac{J\Delta B}{\eta^2} \log_2 \frac{\eta^2 - J\Delta B}{\delta}, \tag{13}$$

where $\delta = \sqrt{\eta^4 - J^2\Delta^2 B^2}$. It notes us that the magnitude of the SQD value is strongly dependent on the anisotropic parameter Δ and external field B. From Eq. (12), the off-diagonal density matrix element $\rho_{14} = \frac{J^2\Delta^2}{2\eta^2}$ with time t is infinity, which imply us that the value of SQD is increased with improving the anisotropic parameter Δ. While increasing B, SQD value is decreased. Therefore, one can obtain the stronger quantum correlation and steady quantum correlation by tuning the anisotropic parameter and external field, such as increasing Δ or decreasing the external field. Most interested thing is that when $\Delta = 0$, there is no steady quantum correlation whatever value of B (the value of SQD is zero), so when $J \neq 0$ the anisotropic parameter Δ decided the existence of SQD, $J \neq 0$ and $\Delta \neq 0$ are the conditions about the existence of SQD phenomenon.

(2) Consider the initial state $|\varphi_2\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$, for this initial state one can examine the effects of nonuniform field b on evolution QD. substituting $\rho(0) = |\varphi_2\rangle\langle\varphi_2|$ into Eq. (6), the detailed expressions of nonzero evolution density matrix elements as follows

$$\begin{aligned}
\rho_{22} &= \frac{1}{2} + \frac{Jb}{2\xi^2}\big[1 - \exp\big(-2\gamma\xi^2 t\big)\cos(2\xi t)\big], \\
\rho_{23} &= \frac{J^2}{2\xi^2} + \frac{b}{2\xi^2}\exp\big(-2\gamma\xi^2 t\big)\big[b\cos(2\xi t) - i\xi\sin(2\xi t)\big], \\
\rho_{33} &= \frac{1}{2} - \frac{Jb}{2\xi^2}\big[1 - \exp\big(-2\gamma\xi^2 t\big)\cos(2\xi t)\big].
\end{aligned} \tag{14}$$

Then we can obtain the quantum correlation behavior by the definition of QD, the effects of the nonuniform field parameter on the QD dynamics is shown in Fig. 2, where we have plotted the time evolution of QD with different values of b. From Fig. 2 we can see that the value of QD will decay with the time, and this decaying behavior becomes more evidently when increasing b, which concludes us that one can weaken the effects of intrinsic decoherence by decreasing b. We can also see that the minimal value of QD is not equal to zero, the SQD

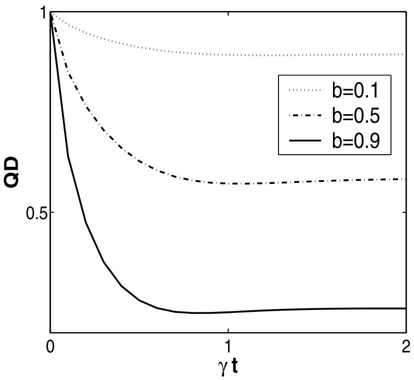

Fig. 2 The QD behavior as a function of time t with different values of b. For the *dash-dotted line*: $b = 0.5$, *black line*: $b = 0.9$ and *dotted line*: $b = 0.1$. We set $J = 1$

phenomenon is exists, and the SQD value is improved with decreasing b. Now, we proceed further to study the reason of SQD phenomenon. With $t \to \infty$, according to Eq. (14) and the definition of QD, we can obtain the value of SQD as follows

$$\lim_{t\to\infty} \mathrm{SQD} = \log_2 \frac{\xi b}{\epsilon} + \frac{J}{\xi} \log_2 \frac{\xi + J}{b} + \frac{Jb}{\xi^2} \log_2 \frac{\xi^2 - Jb}{\epsilon} \tag{15}$$

where $\epsilon = \sqrt{\xi^4 - J^2 b^2}$. When t is infinity, the off-diagonal matrix element $\rho_{23} = \frac{J^2}{2\xi^2}$, it concludes us that the SQD value is mainly dependent the coupling parameter J and nonuniform field b. $J \neq 0$ is the condition about the existence of SQD for this initial state or some kindred superposition states.

(3) We assume the two qubits are initial in a class of states with maximally mixed marginals, which is described by the X-structured density operator

$$\rho(0) = \frac{1}{4}\left(I_{AB} + \sum_{j=1}^{3} c_j \sigma_A^j \otimes \sigma_B^j\right) \tag{16}$$

after some calculations, the nonzero density matrix elements of two qubits at time t has the following analytical expression

$$\begin{aligned}
\rho_{11,44} &= A \pm \frac{BJ\Delta C}{\eta^2}\left[1 - \exp\left(-2\eta^2\gamma t\right)\cos(2\eta t)\right] \\
\rho_{22,33} &= D \pm \frac{JbF}{\xi^2}\left[1 - \exp\left(-2\gamma\xi^2 t\right)\cos(2\xi t)\right] \\
\rho_{14} &= \frac{J^2\Delta^2 C}{\eta^2} + \frac{BC}{\eta^2}\exp\left(-2\eta^2\gamma t\right)\left[B\cos(2\eta t) - i\eta\sin(2\eta t)\right] \\
\rho_{23} &= \frac{J^2 F}{\xi^2} + \frac{bF}{\xi^2}\exp\left(-2\gamma\xi^2 t\right)\left[b\cos(2\xi t) - i\xi\sin(2\xi t)\right]
\end{aligned} \tag{17}$$

where $A = \frac{1}{4}(1 + c_3)$, $D = \frac{1}{4}(1 - c_3)$, $C = \frac{1}{4}(c_1 - c_2)$, and $F = \frac{1}{4}(c_1 + c_2)$. Figure 3 shows the effects of anisotropic parameter Δ and nonuniform field b on QD dynamics with arbitrary initial state. From Fig. 3(a) we can see clearly that QD is initially increased and then decreased with time because of the intrinsic decoherence. The SQD value is exists, which is increased with increasing Δ. While increasing b, the value of SQD is decreased, which

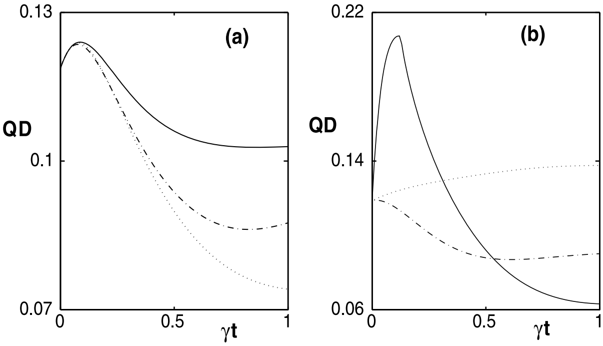

Fig. 3 (**a**) with $B = 0.5$ and $b = 1$, the evolution QD with different values of Δ, the *dotted line*, *dash-dotted line* and *black line* corresponding to $\Delta = 0.1, 0.5$ and 0.9. (**b**) with $B = 0.8$ and $\Delta = 0.8$, the evolution QD with different values of b: $b = 1$ (*dotted line*), $b = 2$ (*dash-dotted line*), and $b = 3$ (*black line*). We set $c_1 = 1$, $c_2 = -c_3 = 0.4$ and $J = 1$

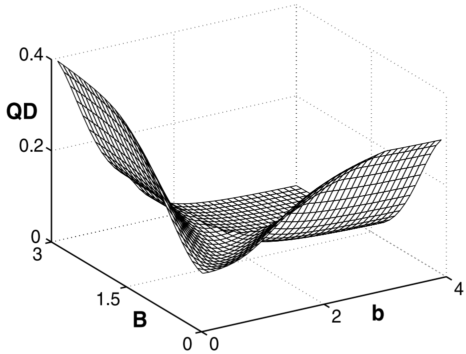

Fig. 4 The QD behavior as a function of B and b with $\gamma t = 0.4$, where we set $J = 1$, $\Delta = 0.8$, $c_1 = 1$ and $c_2 = -c_3 = 0.4$

can be seen in Fig. 3(b). These phenomenon can be understood by the Eq. (17), when t is infinity, four off-diagonal density matrix elements are survived as $\rho_{14} = \rho_{41} = \frac{J^2\Delta^2 C}{\eta^2}$, $\rho_{23} = \rho_{32} = \frac{J^2 F}{\xi^2}$ which imply us that increasing Δ, decreasing b or B, the off-diagonal matrix element can be improved, the quantum coherence and the SQD value are both increased. Therefore one can obtain the stronger steady quantum correlation and weaken the effect of intrinsic decoherence by tuning Δ, external fields b and B, such as improving Δ, decreasing b or B. We also conclude that when $c_1 = -c_2$, anisotropic parameter $\Delta \neq 0$ is the condition about the existence of SQD phenomenon. While when $c_1 \neq -c_2$ SQD phenomenon is exists whatever value of Δ. From Fig. 3(b), we also know that the value of QD with larger b can be larger than the case of lower b at the initial time, so in the region of initial time, QD dynamics is complicated. In order to see clearly the effects of b, in Fig. 4, we plot the QD as a function of B and b at decoherence time $\gamma t = 0.4$ with finite $\Delta = 0.8$ for arbitrary initial state. It shows us that quantum correlation is increased with increasing b when B is lower. While the value of QD is decreased through improving b in the case of larger B. One can obtain a larger QD value by tuning B and b.

4 Conclusion

In conclusion, it is analyzed the QD dynamics about a Two-qubit Heisenberg XYZ system with intrinsic decoherence under an external nonuniform magnetic field. We studied in detail about the effects of external and self parameters on the QD behavior with different initial states. The results derived show that not only the QD value can be increased but also can weaken the effects of decoherence by properly tuning the external fields and the anisotropic parameter. Through analyzing the physical about the SQD phenomenon, The conditions about the existence of SQD phenomenon are obtained with different initial states. We also found that the SQD value is increased with increasing anisotropic parameter, and decreased with improving B or b, it means that one can weaken the effects of decoherence by improving Δ, decreasing B or b. For arbitrary initial state, quantum correlation is increased with increasing b when B is lower, but decreased with larger B. Thus the value of QD and SQD can be controlled by varying the external and self parameters such as the anisotropic parameter Δ, external fields B and b, one can obtain a larger value of QD and SQD by tuning these parameters.

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