Sudden death and robustness of quantum discord and entanglement in cavity QED

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Abstract. - The quantum dynamics of two entangled two-level atoms is studied. Each of the two atoms is located within an isolated and dissipative cavity. If the interaction time of atoms and cavities is not very long, the amount of quantum discord and entanglement between two atoms decreases as the system evolves. The sudden death of quantum discord and entanglement of two atoms occurs within a short interaction time. However, after a long interaction time, quantum discord and entanglement of two atoms could be partially preserved due to the long-lived nature of quantum discord and entanglement. Surprisingly, we find the amount of long-lived quantum discord could be smaller than that of long-lived entanglement. Thus, entanglement may be more robust than quantum discord against decoherence.

Introduction. – Quantum entanglement is at the heart of quantum information processing and quantum computation [1–3]. In recent years, many efforts have been invested in the study of the evolution of joint systems formed by two subsystems (each system locally interacts with its environment) [4–9]. In particular, the entanglement of a two-qubit system may disappear for a finite time during the dynamics evolution. The nonsmooth finite-time disappearance of entanglement is called “entanglement sudden death” (ESD). Experimentally, the ESD phenomenon has been observed in the laboratory by several groups for optical setups [10,11] and atomic ensembles [12].

One the other hand, quantum entanglement is not the only kind of quantum correlation useful for quantum information processing [13–15]. In fact, it was shown both theoretically [16–23] and experimentally [24] that some tasks can be sped up over their classical counterparts using fully separable and highly mixed states. These results clearly show that separable states with quantum discord can be used to implement quantum information processing such as deterministic quantum computation with one qubit [24]. Quantum discord introduced in [25,26] is another kind of quantum correlation different from entanglement. Very recently, quantum discord has been investigated widely [27–30]. Note that all the previous studies [27–30] have shown that, for several quantum systems, there is no quantum discord sudden death (DSD). However, quantum discord is a kind of quantum correlation in composite quantum systems. Since entanglement of quantum systems can stay zero for a finite time (ESD), a natural question is whether there is DSD in quantum systems with ESD. Here, we present a quantum system where there exists DSD as well as ESD. We also explain why there is no DSD in [30]. Furthermore, we find that there is also long-lived quantum discord. In recent years, many efforts has been devoted to the study of the long-lived entanglement in cavity QED [31,34] or solid state systems [35]. To the best of our knowledge, there is few study on the long-term behavior of quantum discord. Thus, an investigation of quantum discord of a quantum system in the presence of decoherence in the limit \(t \to \infty\) is highly desired. This question is also addressed in the present work.

In the present paper, we investigate the dynamics of
quantum discord and entanglement of a quantum system formed by two two-level atoms within two spatially separated and dissipative cavities in the dispersive limit using the results of [39]. The two atoms are initially prepared in the Werner states [6] and the cavities are initially prepared in coherent states. We show that both DSD and ESD can appear in the present system. The amount of quantum discord and entanglement of two atoms decreases with time in the short-term. However, the long-term behavior is very different since a long survival of quantum discord and entanglement of two atoms could be partially preserved even they are put into dissipative cavities. Unlike the results in [27,30], our results show that the amount of long-lived quantum discord could be smaller than that of long-lived entanglement. In other words, quantum entanglement may be more robust than quantum discord in the present model.

The model. — We first consider a quantum system consisting of a two-level atom interacting with a single-mode cavity. Under the electric dipole and rotating wave approximation, the Hamiltonian of the present system is (\(\hbar = 1\)) [37]

\[
H = \omega a^\dagger a + \frac{\omega_0}{2} \sigma_z + g(a^\dagger \sigma_+ + a \sigma_-),
\]

(1)

where \(g\) is the atom-field coupling constant, \(\sigma_z\) are the atomic spin flip operators characterizing the effective two-level atom with frequency \(\omega_0\), and \(\sigma_\pm = |e\rangle\langle e| - |g\rangle\langle g|\). Note that the symbols \(|e\rangle\) and \(|g\rangle\) refer to the excited and ground states for the two-level atom. Here, \(a^\dagger\) and \(a\) are the creation and annihilation operators of the field with frequency \(\omega\), respectively. The dispersive limit is obtained when the condition \(|\Delta| = |\omega_0 - \omega| \gg \sqrt{n + 1}\gamma\) is satisfied for any relevant \(n\). Then, the interaction Hamiltonian \(g(a^\dagger \sigma_+ + a \sigma_-)\) can be regarded as a small perturbation. Hence the effective Hamiltonian of the present model can be rewritten as [38]

\[
H_e = \omega a^\dagger a + \frac{\omega_0}{2} \sigma_z + \Omega [(a^\dagger a + 1)|e\rangle\langle e| - a^\dagger a|g\rangle\langle g|],
\]

(2)

with \(\Omega = g^2/\Delta\). In the interaction picture, the interaction Hamiltonian is

\[
V = \Omega [(a^\dagger a + 1)|e\rangle\langle e| - a^\dagger a|g\rangle\langle g|].
\]

(3)

We assume the two-level atom interacting with a coherent field in a dissipative environment. This interaction causes the losses in the cavity which is presented by the superoperator \(D = \gamma (2a \cdot a^\dagger - a^\dagger a \cdot a^\dagger a)\), where \(\gamma\) is the decay constant. For the sake of simplicity, we confine our consideration in the case of zero temperature cavity. Then, the master equation that governs the dynamics of the system can be written as follows

\[
\frac{d\bar{\rho}}{dt} = -i[V, \bar{\rho}] + D\bar{\rho},
\]

(4)

where \(\bar{\rho}\) is the density matrix of the atom-field system.

If the initial state of the two-level atom is \(\left(\begin{array}{c} \zeta_a \\ \zeta_c \\ \zeta_c^* \\ \zeta_b \end{array}\right)\) and the field is initially prepared in a coherent state \(|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle\) with \(\alpha\) being a complex number. Here, \(|n\rangle\) is the Fock state with \(a^\dagger a|n\rangle = n|n\rangle\). Then, the reduced density matrix of the atom is obtained by tracing out the variables of the field from the atom-field density matrix [39]

\[
\bar{\rho}_{atom}(t) = \zeta_a|e\rangle\langle e| + \zeta_b|g\rangle\langle g| + [\zeta_c f(t)|e\rangle\langle g| + h.c],
\]

\[
f(t) = \exp \{-i\Omega t + |\alpha|^2 (e^{-2\gamma t} - 1)\} 
\]

\[
\times \exp \left\{ \frac{|\alpha|^2 \gamma}{\gamma + i \Omega} [1 - e^{-2(\gamma + \Omega)t}] \right\} 
\]

\[
\times \exp \left\{ \frac{|\alpha|^2 e^{-2\gamma t} (e^{-2\Omega t} - 1)}{1} \right\},
\]

(5)

where \(h.c\) denotes the Hermitian conjugate.

Then, we consider a quantum system consisting of two noninteracting atoms each locally interacts with its own coherent field of a dissipative cavity. The interactions between each atom and its own dissipative cavity is described by Eq. (4). We assume the two atoms are initially prepared in Werner states defined by [6]

\[
\rho_{\Phi} = p|\Phi\rangle\langle \Phi| + \frac{1 - p}{4} I,
\]

\[
\rho_{\Psi} = p|\Psi\rangle\langle \Psi| + \frac{1 - p}{4} I,
\]

\[
|\Phi\rangle = \frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle),
\]

\[
|\Psi\rangle = \frac{1}{\sqrt{2}}(|ee\rangle + |gg\rangle),
\]

(6)

where \(p\) is a real number which indicates the purity of initial states, \(I\) is a \(4 \times 4\) identity matrix. The parameter \(p = 1\) for pure states and 0 for completely mixed states. The two fields are prepared in coherent states \(|\alpha_1\rangle\) and \(|\alpha_2\rangle\). For the sake of simplicity, we assume \(\alpha_1 = \alpha_2 = \alpha\), the decay rates of the two cavities are equal, and the atom-field coupling constants are the same. Using the method introduced in [6], we can obtain the reduced density matrix of two atoms conveniently.

The reduced density matrix of two atoms can be obtained by using the superoperator method [39,41]. As one can see below, the quantum discord and entanglement of the present system can be calculated conveniently by employing the results of [39]. We assume the initial state of the two atoms is \(\rho_0\). Using the results of [39] and Eq. (6), we obtain the density matrix of two atoms \(\rho(t)\) as follow

\[
\left(\begin{array}{cccc} \frac{1-p}{4} & 0 & 0 & 0 \\ 0 & \frac{1+p}{4} - |f(t)|^2 & \frac{|f(t)|^2}{4} & 0 \\ 0 & \frac{|f(t)|^2}{4} & \frac{1+p}{4} & 0 \\ 0 & 0 & 0 & \frac{1-p}{4} \end{array}\right),
\]

(7)

where \(f(t)\) is given by Eq. (5).
Quantum discord and entanglement. – In general, a composite quantum system contains both quantum and classical correlations, the total amount of which are quantified by quantum mutual information. Precisely, the quantum mutual information of a composite bipartite system $\rho^{AB}$ is defined as

$$I(\rho^{AB}) = S(\rho^A) + S(\rho^B) - S(\rho^{AB}), \quad (8)$$

where $S(\rho) = -Tr(\log_2 \rho)$ is the von Neumann entropy of density matrix $\rho$, $\gamma_i$ being the eigenvalues of density matrix $\rho$. We note that 0 log 2 0 is defined to be 0 and $\rho^i(\rho^{AB})$ is the reduced density matrix of $\rho^{AB}$ by tracing out system $B(A)$.

Quantum discord [25, 26] is another kind of quantum correlation different from entanglement. In order to quantify quantum discord, the authors of [25] proposed to use the von Neumann type measurements consisting of one-dimensional projector $\{B_i\}$ (acts on system $B$ only), such that $\sum_i B_i = 1$. The conditional density matrix of the total system after the von Neumann type measurements is [25]

$$\rho_{B_i}^{AB} = \frac{1}{p_i} (I \otimes B_i) \rho^{AB} (I \otimes B_i), \quad p_i = Tr((I \otimes B_i) \rho^{AB} (I \otimes B_i)), \quad (9)$$

where $p_i$ is the probability of the corresponding measurement. The quantum conditional entropy with respect to this kind of measurement is defined as

$$S(\rho^{AB} \mid \{B_i\}) = \sum_i p_i S(\rho_{B_i}^{AB}), \quad (10)$$

and the corresponding quantum mutual information with respect to the measurement is defined by

$$I(\rho^{AB} \mid \{B_i\}) = S(\rho^A) - S(\rho^{AB} \mid \{B_i\}). \quad (11)$$

The quantity $I(\rho^{AB} \mid \{B_i\})$ is the information gained about system $A$ if one performs measurement $B_i$ on system $B$. The resulting classical correlation according to [25, 26] is defined as

$$J(\rho^{AB}) = \sup_{\{B_i\}} I(\rho^{AB} \mid \{B_i\}) = S(\rho^A) - \min_{\{B_i\}} [S(\rho^{AB} \mid \{B_i\})]. \quad (12)$$

The quantum discord is obtained by subtracting $J$ from the quantum mutual information $I$

$$D(\rho^{AB}) = I(\rho^{AB}) - J(\rho^{AB}). \quad (13)$$

As one can see from the above equations, the minimization procedure should be done over all possible von Neumann measurements $B_i$ on system $B$. Thus, the main difficulty of calculating quantum discord lies in the elaborate minimization process in the term $\min_{\{B_i\}} [S(\rho^{AB} \mid \{B_i\})]$. Fortunately, the quantum discord of Eq. (13) can be calculated with the help of the results of [30]

$$D(\rho^{AB}) = \frac{1}{4} [(1 - d_1 - d_2 - d_3) \log_2 (1 - d_1 - d_2 - d_3) + (1 - d_1 + d_2 + d_3) \log_2 (1 - d_1 + d_2 + d_3) + (1 + d_1 - d_2 + d_3) \log_2 (1 + d_1 - d_2 + d_3) + (1 + d_1 + d_2 - d_3) \log_2 (1 + d_1 + d_2 - d_3)] - \frac{1 - d}{2} \log_2 \frac{1 - d}{2} - \frac{1 + d}{2} \log_2 \frac{1 + d}{2},$$

where

$$d_1 = d_2 = p[f(t)]^2, \quad d_3 = -p,$$

$$d = \max \{\{d_1, \{d_2, \{d_3\}\}\}\}. \quad (14)$$

In order to investigate the entanglement of two-qubit systems, we adopt the entanglement measure concurrence introduced in [12]

$$C = \max \{0, \chi_1 - \chi_2 - \chi_3 - \chi_4\}. \quad (15)$$

where $\chi_i (i = 1, 2, 3, 4)$ are the square roots of the eigenvalues in decreasing order of the magnitude of the “spin-flipped” density matrix operator $R = \rho(\sigma_y \otimes \sigma_y) \rho^*(\sigma_y \otimes \sigma_y)$ and $\sigma_y$ is the Pauli Y matrix, i.e., $\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$. Concurrence of a quantum state ranges from 0, which corresponds to an unentangled state, to 1, which corresponds to a maximally entangled state. The concurrence of the above state is

$$C(t) = \max \{0, p[f(t)]^2 - \frac{1 - p}{2} \}. \quad (16)$$

We will use this equation to calculate the entanglement of the quantum system presented in this work.

Results and discussions. –

Sudden death of quantum discord and entanglement.

We now want to investigate the dynamics of quantum discord and entanglement. In Fig. 1, quantum discord and entanglement are plotted as functions of the dimensionless scaled time $\Omega t$ for $\alpha = 0.5$ (upper panel) and $\alpha = 1$ (lower panel). Clearly, there is ESD in the present model as one can see from Fig. 1. From the upper panel of Fig. 1, one may conclude that there is no DSD, which is consistent with the results of [27, 30]. However, this is not always correct. As one can easily observe from the lower panel of Fig. 1 if we increase the intensity of the coherent fields that is proportional to $|\alpha|^2$, there is DSD. We note that in this figure, quantum discord is larger than entanglement, which is coincidence with the observations of [27, 30]. However, this is not a general result since quantum discord and entanglement are two different quantities and there is no simple relative ordering between them. For example, for the Werner states defined by $\rho = p|\psi_-\rangle \langle \psi_-| + \frac{1 - p}{4}$, where $|\psi_-\rangle = (|eg\rangle - |ge\rangle)/\sqrt{2}$, quantum discord may be larger or smaller than entanglement [36].

We now want to explain why there is no DSD in the case of dephasing channel in [30]. At first sight, the elements of the density matrix of the dephasing case is very similar.
The influence of the purity of the initial state of atoms quantum discord and entanglement in the present model. We consider the question of whether there is long-lived to long-lived quantum discord even though lots of work have pointed out previously, little attention has been paid to the matrix elements of Eq. (7). Let us focus on the off-diagonal elements $\rho_{23}(t)$ of \([30]\), i.e., $\rho_{23}(t) = e^{-\Gamma t} \rho_{23}(0)$, where $\Gamma$ is the decay rate. Obviously, the term $e^{-\Gamma t}$ becomes zero only in the asymptotic limit $t \rightarrow \infty$. Quantum discord vanishes only in the asymptotic limit, which behaves similarly to decoherence of each atom \([30]\). In the present work, the off-diagonal element $\rho_{23}(t)$ is much more complicated than that of \([30]\) and it is possible for quantum discord to stay zero for a finite time. Physically, the influence of the interactions between atoms and cavities, and the mean photon number and decay rate of dissipative cavities upon quantum discord has not bee considered in \([30]\). Here, all the above influence upon the dynamics of quantum discord and entanglement is taken into accounted. In this sense, the results of \([30]\) can only reveal parts of the properties of quantum discord (no DSD), which is consistent with the upper panel of Fig. 1. However, the lower panel of Fig. 1 which indicates the existence of DSD, can not appear in \([30]\).

**Long-lived quantum discord and entanglement.** As we have pointed out previously, little attention has been paid to long-lived quantum discord even though lots of work has been made on long-lived entanglement \([31,35]\). Here, we consider the question of whether there is long-lived quantum discord and entanglement in the present model. The influence of the purity of the initial state of atoms upon the long-time behavior of quantum discord and entanglement is also discussed.

In Fig. 2 quantum discord and entanglement as functions of the dimensionless scaled time $\Omega t$ with $\gamma/\Omega = 0.01$ and $p = 0.4$. Upper panel: $\alpha = 0.5$. Lower panel: $\alpha = 1$. There is no DSD in the upper panel with $\alpha = 0.5$. However, the lower panel clearly shows the existence of DSD in the case of $\alpha = 1$. With the increase of the parameter $p$. The relative ordering of quantum discord and entanglement depends heavily on the purity $p$. For example, in the case of $p = 0.5$, long-lived quantum discord is larger than long-lived entanglement. However, in the case of $p = 0.8$, we find that, in contrast to the results of [27,30], the amount of long-lived quantum discord could be smaller than that of long-lived entanglement. In other words, quantum entanglement could be more robust than discord against decoherence. Thus, it is difficult for us to make a general statement whether or not quantum discord is more robust against decoherence than entanglement. Intuitively, quantum discord is different from entanglement and it is difficult to make a general conclusion about the relative ordering of the amount of quantum discord and entanglement in the presence of decoherence. In order to show the influence of decoherence of cavities upon the quantum discord of two atoms, we plot the quantum discord of two atoms in Fig. 3. Note that it has been proved that white noise of cavity fields can play a constructive role in the generation of entanglement in cavity QED systems \([13]\). Here, Fig. 3 demonstrates that the dissipation of cavity fields may also play a constructive role in the generation of quantum discord. Note that in Figs. 4-5, we have assumed the atoms are initially prepared in $\rho_0$. One can also consider the dynamics of quantum discord and entanglement if the initial state of atoms is $\rho_0$ and the results are similar.

**Conclusions.** In the present work, we have studied the dynamics of quantum discord and entanglement of two two-level atoms without direct interactions. Each atom is put into a spatially separated and dissipative cav-
Fig. 3: Quantum discord of two atoms are plotted as functions of the dimensionless scaled time \( \Omega t \) and parameter \( \gamma/\Omega \) with \( \alpha = 1 \) and \( p = 0.8 \).

ity in the dispersive limit. We first investigated the short-
time behavior of quantum discord and entanglement in
the presence of dissipation. The amount of quantum dis-
cord and entanglement of two atoms decreases with time if
the interaction time is not very long. Particularly, we
have shown that both DSD and ESD could appear simulta-
neously in the present system. This is different from the
results of \([27, 30]\). Then, we discussed the long-time be-
tavior of quantum discord and entanglement of two atoms.
We show there is long-lived quantum discord and entan-
glement in the presence of the dissipation of cavities. Our
results show that quantum entanglement may be more ro-

bust against decoherence than quantum discord. Finally,
we would like to point out that it could be possible to
study quantum discord of any dimensional bipartite states
from a geometrical point of view \([44]\). It is also interesting
to compare the results of any dimensional bipartite states
in the presence of decoherence with our work.

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