Atomic entanglement sudden death in a strongly driven cavity QED system

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Abstract

We study the entanglement dynamics of strongly driven atoms off-resonantly coupled with cavity fields. We consider conditions characterized not only by the atom–field coupling but also by the atom–field detuning. By studying two different models within the framework of cavity QED, we show that the so-called atomic entanglement sudden death (ESD) always occurs if the atom–field coupling is larger than the atom–field detuning, and is independent of the type of initial atomic state.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Entanglement plays a crucial role in quantum information processing [1]. Quantum algorithms (particularly, in Shor’s algorithm, to find the prime factors of an \(n\)-bit integer) exploit entanglement to speed up computation. Entanglement dynamics is a difficult subject and has attracted extensive interest recently ranging from two-qubit systems [2–5], to continuous variables [6, 7], spin systems [8, 9, 10] and multi-partite systems [11–14]. The entanglement of open quantum systems also has attracted considerable attention due to its significance for both fundamentals and applications of quantum information processing [15, 16]. For example, [15] gives us the non-Markovian entanglement evolution of two uncoupled qubits which are coupled to their own independent environments. The origination and survival of entanglement for two independent qubits dephasingly coupled to a common zero-temperature, super-Ohmic, bosonic environment is studied in [16]. Moreover, in closed systems, proposals [17, 18] have been made for the direct measurement of finite-time disentanglement in cavity QED, and real-time detection of entanglement sudden death (ESD) has been reported very recently [19, 20, 21].

The interaction of a two-level atom with a quantized single mode of a harmonic oscillator, is called the Jaynes–Cummings (JC) model [22]. The JC model has found its natural playground in the field of cavity quantum electrodynamics (CQED), and extensions of the JC model to more atoms and more modes, externally driven or not, have been developed. Currently, we enjoy a vast number of theoretical and experimental developments. In [19], the authors dealt with a double JC model in which two initially entangled two-level atoms \(A\) and \(B\) are independently coupled with separate cavity fields \(a\) and \(b\), respectively, but there are no interactions at all between the subsystems \(Aa\) and \(Bb\). Focusing on the atomic subsystem they found that depending on the type of initial state of atoms \(AB\), their entanglement may or may not exhibit ESD. From [19], we can acquire that the authors have taken Bell-like states as the initial state of atoms and assumed the initial cavity field to be in vacuum. As a consequence, ESD was found to be sensitive to the initial atomic state. That is to say, ESD may occur for a certain type of initial atomic state but does not appear for another type.

In this paper, we consider a system consisting of a two-level atom trapped inside a single mode cavity. The atom is additionally driven by a strong classical field. The experimental implementation seems to be feasible due to the recent advances in deterministic trapping of atoms in the optical cavities [23, 24]. We show that undertaking atomic pure Bell-like states \(|\Phi_{AB}\rangle = \cos \theta |e_A, e_B\rangle + \sin \theta e^{i\phi} |g_A, g_B\rangle\) or \(|\Psi_{AB}\rangle = \cos \theta |e_A, g_B\rangle + \sin \theta e^{i\phi} |g_A, e_B\rangle\) (with \(0 \leq \theta \leq 2\pi\) and \(0 \leq \phi \leq \pi\)) as the initial state of atoms and assuming the initial cavity field to be in vacuum, ESD can occur for two types of initial atomic states. In order to study entanglement we will use the negativity \((N)\), which can be defined for two

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qubits as twice the modulus of the negative eigenvalue of the partial transposition of the state $\rho$, $\rho^{T_A}$ [25, 26], if it exists. For short

$$N(\rho) = 2 \max \{0, -\lambda_{\min}\},$$

where $\lambda_{\min}$ is the lowest eigenvalue of $\rho^{T_A}$. Our choice is motivated by the fact that the negativity is easy to calculate and provides full entanglement information for a two-qubit system. We also need to quantify three-party entanglement in the three-qubit state $|\Psi_{ABa}\rangle$; the three-tangle $\tau_3(\Psi_{ABa})$ has been introduced in [27]. It can be expressed by using the wavefunction coefficients $\{\psi_{000}, \psi_{001}, \ldots, \psi_{111}\}$ as

$$\tau_3 = 4|d_1 - 2d_2 + 4d_3|,$$

$$d_1 = \psi_{000}^2 \psi_{111}^2 + \psi_{001}^2 \psi_{110}^2 + \psi_{010}^2 \psi_{101}^2 + \psi_{100}^2 \psi_{011}^2,$$

$$d_2 = \psi_{000} \psi_{011} \psi_{100} \psi_{111} \psi_{010}^2 + \psi_{001} \psi_{010} \psi_{101} \psi_{111} \psi_{010}^2 + \psi_{011} \psi_{010} \psi_{101} \psi_{111} \psi_{010}^2,$$

$$d_3 = \psi_{000} \psi_{110} \psi_{101} \psi_{011} \psi_{010} \psi_{100}.$$

To figure out general conditions for the possible negativity of atomic ESD, we shall study two different atom–cavity models, which we refer to as model 1 and model 2. Model 1 is considered in section 2; in model one of two atoms is trapped in a single cavity, off-resonantly coupled to this cavity, and driven by a classic strong coherent field, while the others remain outside the cavity and have no environment. In section 3 we consider model 2 which deals with a double driven JCM: each of the two strongly driven atoms interacts with its own cavity in the absence of any coupling between the atom–field subsystems. A generic result we have found is that the atomic ESD always occurs in the conditions of the atom–field coupling being larger than the atom–field detuning. We conclude in section 4.

2. Model 1

In this section we show a model in which a strongly driven atom $A$ is off-resonantly coupled to a single cavity mode $a$, while the other atom $B$ is isolated from all environment. The Hamiltonian of the system can be described by

$$H = \hbar \omega_a \sigma_A^+ \sigma_A^0 + \hbar \omega_0 a^\dagger a + \hbar \Omega (e^{-i\omega_D t} \sigma_A^+ + e^{i\omega_D t} \sigma_A^0),$$

where $\Omega$ is the Rabi frequency associated with the coherent driving field amplitude, $\omega$ is the atom–cavity mode coupling constant, $\omega_D$ is the field annihilation (creation) operator, $\sigma_A^0 = |g_A\rangle \langle e_A|, \sigma_A^+ = |e_A\rangle \langle g_A|$ the atomic lowering (raising) operator and $\sigma_A^0 = |e_A\rangle \langle e_A|-|g_A\rangle \langle g_A|$ the inversion operator. Considering the strong-driving regime for the interaction between the atom and the external coherent field $\hbar \Omega \gg |g|, |\delta|$ and making $\omega_0 = \omega_D$, we can use the rotating-wave approximation (RWA) obtaining the effective Hamiltonian [28]

$$H_{\text{eff}} = \hbar \delta \sigma_A^+ \sigma_A^0 (a e^{i\theta} + a^\dagger e^{-i\theta}),$$

where $\delta = \omega_D - \omega_0$ is the atom–cavity detuning.
The negativity $N(\rho_{AB}^\Psi(t))$ has been calculated, as shown in figures 1 and 2 for different $g/\delta$. Obviously the negativity is fluctuating with dimensionless time $gt$ and the mixing angle $\theta$, and it can be zero in a finite amount of time (the so-called entanglement sudden death). An important point is that ESD is sensitive to the value of $g/\delta$ as displayed in figures 1 and 2. For $g/\delta > 1$, ESD happens readily (figure 1), and the larger the value of $g/\delta$, the more easily the ESD appears. When $g/\delta \leq 1$, ESD will not appear at any time (figure 2). This phenomenon shows that ESD is related to $g/\delta$ completely in this model. Moreover, as we study entanglement dynamics under a closed system, figure 1 also shows that the sudden death and resurrection of atomic entanglement can occur periodically as well as alternately. After entanglement of two atoms gives rise to sudden death for a finite time, atomic entanglement can revive again gradually. We have verified that when the ratio $g/\delta$ is larger than that used in figure 1, the region of ESD and entanglement revivals increases, and they last for a longer time. On the other hand, when we decrease $g/\delta$, the ESD regions shrink and the period of the entanglement oscillations becomes smaller.

The character revealed by figure 3 is that $\delta$ influences the period of the ESD and $g$ is related to the velocity of the $AB$ subsystem’s disentanglement. If we want to acquire a long-time ESD, then we can choose a smaller atom–field detuning $\delta$ (figure 3(a)). While $\delta$ is a constant, the $AB$ subsystem can rapidly disentangle with the larger $g$ (figure 3(b)). A physical interpretation of the result is that the more the atom couples to the cavity mode, the easier the initial entanglement decays. Then we consider the atom and the cavity under resonance condition ($\delta = 0$) or the large detuning regime ($\delta \gg g$). First, in the resonant regime the negativity $N(\rho_{AB}^\Psi(t))$ decreases at the beginning, and then vanishes at any time and resurrection of atomic entanglement cannot happen forever under this condition (figure 4), so the strongly driven model under the resonant regime can be considered as an information eraser. Second, entangled states are generally very fragile against interaction with environments, but in our present scheme, the energy exchange between the atom and cavity does not exist under the atom–cavity large detuning regime, so the initial entanglement of atoms can be preserved during system evolution, which is shown in figure 5. That is to say, the strongly driven and large detuning model can be used to preserve the information (entanglement) in quantum processing and quantum computing.
Figure 4. $N(\rho_{\Psi}^{A}(t))$ as a function of $\theta$ and the dimensionless time $gt$ for $\delta = 0$ in model 1.

Figure 5. $N(\rho_{\Psi}^{A}(t))$ as a function of $\theta$ and the dimensionless time $gt$ for $\delta = 10g$, in the large detuning regime in model 1.

Now we move to the negativity $N(\rho_{\Psi}^{A}(t))$ and $N(\rho_{\Psi}^{B}(t))$ and the three-tangle $\tau(\rho_{\Psi}^{A\Psi}(t))$, and we acquire the following:

\[ N(\rho_{\Psi}^{A}(t)) = 2\max\{0, Q_{Aa}\}, \]  
\[ N(\rho_{\Psi}^{B}(t)) = 2\max\{0, Q_{Ba}\}, \]  
\[ \tau(\rho_{\Psi}^{A\Psi}(t)) = \frac{1}{2}(1 - P^2)(1 - \cos 4\theta), \]

if $0 < \cos 2\theta < 1$, then $Q_{Aa} = -\frac{1}{8}(2 - 2\cos 2\theta - \sqrt{2}/3 + (4 - 8P^2)\cos 2\theta + \cos 4\theta)$ and $Q_{Ba} = -\frac{1}{8}(1 - P\cos 2\theta)$, and if $-1 < \cos 2\theta < 0$, then $Q_{Aa} = -\frac{1}{8}(2 + 2\cos 2\theta - \sqrt{2}/3 + (8P^2 - 4)\cos 2\theta + \cos 4\theta)$ and $Q_{Ba} = -\frac{1}{8}(1 + P\cos 2\theta)$. Due to $0 < P < 1$, then $Q_{Ba} < 0$, the negativity $N(\rho_{\Psi}^{B}(t)) = 0$. In the strongly driven regime, $B$ is isolated from all environment, and the strong classical field that drives the atom $A$ can be used to enhance the atom(A)–cavity field ($a$) interaction. The entanglement between $A$ and cavity $a$ can appear during the system evolution, but $B$ and cavity $a$ cannot entangle with each other in the strongly driven regime (that is different from the standard JC model [21]). It is interesting to find that while the $AB$ subsystem appears the long-time ESD, the entanglement of the $Aa$ subsystem and the three-tangle of the whole system are all on the long-time invariable entanglement (as shown in figure 6(a)). It is clearly shown that the three-tangle $\tau_{A\Psi}^{A\Psi\Psi}$ can be influenced by the initial state $|\Psi_{AB}(0)\rangle$ in figure 6(b). On the condition $\theta = \pi/4$ (the initial state is on the maximum entanglement), when $AB$ subsystem’s entanglement vanishes for a long time, the three-tangle of the whole system can achieve the maximum value 1 at the same time and the entanglement between $A$ and $a$ cannot appear for any time. That is to say, the $AB$ subsystem’s entanglement is transferred to the whole system’s entanglement thoroughly (figure 6(c)). So, we can acquire the three-partite system’s long-time maximum entanglement in the strongly driven regime (in model 1).

Next, we choose $|\Phi_{AB}\rangle$ to be the initial atomic state. Then the initial total system state is

\[ \Phi_{A\Psi}(0) = (\cos\theta|e_{A}, e_{B}\rangle + \sin\theta e^{i\phi}|g_{A}, g_{B}\rangle) \otimes |\text{Vacuum}\rangle_{a}. \]  

(13)
with $\phi = 0$, and for $\rho^{\Phi}_{A_B}(t)$ we have the expressions as follows:

$$\rho_{11} = \rho_{44} = \left( \frac{\cos \theta + \sin \theta}{2} \right)^2,$$

$$\rho_{22} = \rho_{33} = \left( \frac{\cos \theta - \sin \theta}{2} \right)^2,$$

$$\rho_{14} = \rho_{41} = \left( \frac{\cos \theta + \sin \theta}{2} \right)^2 P,$$

$$\rho_{23} = \rho_{32} = \left( \frac{\cos \theta - \sin \theta}{2} \right)^2 P,$$

$$\rho_{12} = \rho_{21} = \rho_{43} = -\frac{\cos^2 \theta - \sin^2 \theta}{4},$$

$$\rho_{13} = \rho_{31} = \rho_{42} = \rho_{24} = -\frac{\cos^2 \theta - \sin^2 \theta}{4} P.$$

The negativity of $\rho^{\Phi}_{A_B}(t)$ is satisfied with

$$N(\rho^{\Phi}_{A_B}(t)) = N(\rho^{\Psi}_{A_B}(t)).$$

Equation (15) reveals that the behaviour of $N(\rho^{\Phi}_{A_B}(t))$ dependent on $g/\delta$ is equal to that of $N(\rho^{\Psi}_{A_B}(t))$. We also calculate the negativity $N(\rho^{\Phi}_{A_B}(t))$ and $N(\rho^{\Psi}_{A_B}(t))$ and the three-angle $\tau(\rho^{\Phi}_{A_B}(t))$, and find that they are all equal to $N(\rho^{\Phi}_{A_B}(t)), N(\rho^{\Psi}_{A_B}(t))$ and $\tau(\rho^{\Psi}_{A_B}(t))$.

Consequently, for model 1, where only one driven atom interacts with its environment, if the atom is not driven and the cavity field is in the vacuum initially, ESD does not occur either for $\rho^{\Phi}_{A_B}(0)$ or $\rho^{\Psi}_{A_B}(0)$. In contrast, however, if the atom is driven by a strong classical field and both the atom–cavity and the atom–cavity detuning satisfy $g/\delta > 1$, the atomic subsystem $A_B$ always evolves via ESD, independent of the type of initial atomic state (i.e. it never matters if it is $\rho^{\Phi}_{A_B}(0)$ or $\rho^{\Psi}_{A_B}(0)$).

3. Model 2

The double JC, which has been intensively investigated recently [19], has shown that if atoms $A$ and $B$ are prepared in the $|\Phi_{A_B}\rangle$-type Bell-like pure state initially, then the atomic entanglement dies in a finite time and remains dead for some time before reviving itself again, i.e., ESD occurs, whereas the $|\Psi_{A_B}\rangle$-type Bell-like pure state does not exhibit ESD at all. However, these investigations are confined to the atom–field under full resonance conditions. Our purpose here is to focus on the results that may appear under the conditions where the atoms $A$ and $B$ are independently driven by a strongly external classical field and the atom–cavity off resonance.

In model 2, we consider two remote two-level atoms $A$ and $B$ which are first prepared to be in an entangled state, and then let each atom couple with a single-mode cavity, respectively. During the interaction with the single-mode cavity, the two atoms are independently driven by a strong classical field. In the strong-driving regime, the effective Hamiltonian governing model 2 is of the form

$$H_{\text{eff}} = \sum_{k=A,B} H_{\text{eff}}^k,$$

where

$$H_{\text{eff}}^k = \frac{\hbar g_k}{2}(a_k^\dagger + a_k)(a_k e^{i\delta t} + a_k^\dagger e^{-i\delta t}).$$

The total system state at $t = 0$ is of the form

$$|\Psi(0)\rangle_{A_Bab} = (\cos \theta |e_A, g_B\rangle + \sin \theta e^{i\phi} |g_A, e_B\rangle) \otimes |\text{Vacuum}_a\rangle |\text{Vacuum}_b\rangle.$$

Also with $\phi = 0$, then the evolved state in time $t$ will be

$$|\Psi(t)\rangle_{A_Bab} = \exp(-i H_{\text{eff}} t) |\Psi(0)\rangle_{A_Bab} = \cos \theta + \sin \theta e^{i\phi} |a_A, b_B\rangle + \sin \theta e^{-i\phi} |b_A, a_B\rangle$$

where $|\langle i\rangle_{A_Bab} = \{|+A+_B\rangle, \{-A_-B\rangle, \{-A_B+\rangle, \{-A_B-\rangle\}$ is the rotated basis of the atomic Hilbert space. Similar to equation (6), we also define

$$|0_a\rangle = |a_A\rangle, \quad |1_a\rangle = (-a_A - P_A a_A)/\sqrt{1 - P_A^2},$$

$$|0_b\rangle = |-b_B\rangle, \quad |1_b\rangle = (b_B - P_B b_B)/\sqrt{1 - P_B^2},$$

where $P_A = \exp(\frac{\delta A t}{\hbar})(\cos \delta At - 1)$, $P_B = \exp(\frac{\delta B t}{\hbar}) (\cos \delta B t - 1)$. The reduced density matrix $\rho^{\Phi}_{A_B}(t)$ is

$$\rho_{11} = \rho_{44} = \left( \frac{\cos \theta + \sin \theta}{2} \right)^2,$$

$$\rho_{22} = \rho_{33} = \left( \frac{\cos \theta - \sin \theta}{2} \right)^2,$$

$$\rho_{14} = \rho_{41} = \left( \frac{\cos \theta + \sin \theta}{2} \right)^2 P_A P_B,$$

$$\rho_{23} = \rho_{32} = \left( \frac{\cos \theta - \sin \theta}{2} \right)^2 P_A P_B,$$

$$\rho_{12} = \rho_{21} = \rho_{43} = \rho_{34} = \frac{\cos^2 \theta - \sin^2 \theta}{4} P_B,$$

$$\rho_{13} = \rho_{31} = \rho_{42} = \rho_{24} = -\frac{\cos^2 \theta - \sin^2 \theta}{4} P_A.$$

The negativity of $\rho^{\Phi}_{A_B}(t)$ is

$$N(\rho^{\Phi}_{A_B}(t)) = 2 \max \{ 0, -\frac{1}{2} (2 - 2 P_A P_B - \sqrt{2} \times \sqrt{(1 + P_A^2)(1 + P_B^2) + (P_A^2 + P_B^2 - 1 - 4 P_A P_B - P_A^2 P_B^2) \cos 4\theta}) \}.$$
are related to the velocity of the initial state’s disentanglement, and \( \delta_A, \delta_B \) influence the ESD’s period. In addition, the ESD also appears on the condition \( g_A/\delta_A \geq 1, g_B/\delta_B \geq 1, \delta_A \geq g_A, \delta_B \geq g_B \) (but when \( \delta_A > g_A, \delta_B > g_B \) (but \( \delta_A \) and \( \delta_B \) do not correspond to the large detuning regime), and is shown as figures 7 and 8, in which the ESD phenomenon can also occur in the case when \( \delta_A \) and \( \delta_B \) are larger than \( g_A \) and \( g_B \) (but not by too much). As we all know, the larger atom–cavity detuning means that the interaction between the atom and cavity becomes small, for example, in the large detuning regime, the cavity and the atom cannot have energy exchange. So when \( \delta_A \) and \( \delta_B \) are much larger than \( g_A \) and \( g_B \), the ESD will disappear. If we consider the driven atoms and the cavities under resonance condition (\( \delta_A = \delta_B = 0 \)), the negativity of \( \rho_{AB}(t) \) decreases at the beginning, and then vanishes for all time (the same as figure 4). So model 2 under the resonance regime can also be used as an information eraser.

For another type of atomic initial state \( |\Phi_{AB}\rangle \), it can be verified that the negativity \( N(\rho_{AB}(t)) \) is also equal to \( N(\rho_{AB}(0)) \). Through calculating the negativities \( N_{AA}, N_{BB}, N_{AB} \), and \( N_{BA} \) in model 2, we find that the entanglement of \( AA \) and \( BB \) can occur during the system evolution and can be on a long-time invariable entanglement when the \( AB \) subsystem gives rise to the ESD. Because of no existing interaction in the \( Ba \) subsystem (or \( Ab \) subsystem), it is impossible to entangle \( Ab \) (or \( Ba \)) in the strongly driven regime (these results are not similar to the standard double JC model [19]). Hence, our conclusion regarding model 2 is that the driven atomic subsystem \( AB \) always suffers ESD if the atom–cavity coupling and the atom-detuning are satisfied with the condition \( g_A/\delta_A > 1, g_B/\delta_B > 1 \) or \( g_A/\delta_A \geq 1, \delta_B \geq g_B \) or \( g_B/\delta_B \geq 1, \delta_A \geq g_A \), even when \( \delta_A > g_A, \delta_B > g_B \) (but \( \delta_A \) and \( \delta_B \) cannot correspond to the large detuning regime), independent of the type of the atomic initial state which may be either \( \rho_{AA}(0) \) or \( \rho_{BB}(0) \).

4. Conclusion

We have described the entanglement evolution of two two-level atoms off-resonantly coupled to cavity fields. In model 1, one of two atoms is trapped in a single cavity, off-resonantly coupled to this cavity, and driven by a classic strong coherent field, while the other remains outside the cavity and has no environment. However, in model 2, each of the two strongly driven atoms interacts with its own cavity in the absence of any coupling between the atom–field subsystems. There are different available or forthcoming routes to the implementation of our model. In the microwave regime of cavity QED, pairs of atoms excited to Rydberg levels cross a high-Q superconductive cavity with negligible spontaneous emission during the interaction [29]. In the optical regime the application of cooling and trapping techniques in cavity QED [23] allows the deterministic loading of single atoms in a high-finesse cavity, with accurate position control and trapping times of many seconds [24]. In this regime laser-assisted three-level atoms can behave as effective two-level atoms [30]. On the other hand, trapped atomic ions can remain in an optical cavity for an indefinite time in a fixed position, where they can couple to a single mode without coupling rate fluctuations [31]. These systems are quite promising for our purposes and could become almost ideal in the case of achievement of the strong coupling regime.

Under off-resonance conditions and starting from the vacuum state of the cavity fields, for negligible atomic decays and cavity leakage, we solved exactly the system dynamics for two types of initial preparation of the atom pairs (\( |\Phi_{AB}\rangle \) and \( |\Phi_{AB}\rangle \)). Thus we found conditions for the negativity of the so-called atomic ESD. Namely, the initial entanglement of atoms, if any, will eventually suffer a sudden death, if the atom–cavity coupling and the atom–cavity detuning are satisfied with \( g/\delta > 1 \) (in model 1), while in model 2 the system is in accordance to \( g_A/\delta_A \geq 1, g_B/\delta_B \geq 1 \) or \( g_A/\delta_A > 1, \delta_B > g_B \) and/or \( g_B/\delta_B > 1, \delta_A > g_A \) (but \( \delta_A \) and \( \delta_B \) cannot correspond to the large detuning regime). Furthermore, it is interesting to note that such conditions for ESD do not depend on the
coupling. controlling the atom–cavity detuning and atom–cavity entanglement of two atoms can be manipulated through our results in the strongly driven regime manifest that the degree of entanglement at certain time disentangled states in the open systems. From paper [15] can evolve quasiperiodically between the entangled and dynamics [15]. That is to say, non-Markovian entanglement appears to be linked to the non-Markovian character of the bipartite system is a mononically decreasing function of time in the close system. It means that atoms evolve quasiperiodically between the entangled and disentangled states. This result is different from [15, 16]; Dajka et al show that the negativity of the second qubit has no environment [15]. But Dajka et al. also have proposed that in the case when the second qubit is set in a finite and controlling quantum environment, the dynamics of entanglement can oscillate; this nonmonontic behaviour appears to be linked to the non-Markovian character of the dynamics [15]. That is to say, non-Markovian entanglement can evolve quasiperiodically between the entangled and disentangled states in the open systems. From paper [15] we acquire that the degree of entanglement at certain time intervals can be manipulated by means of an appropriate choice of the initial state of the controlling quantum environment. Our results in the strongly driven regime manifest that the entanglement of two atoms can be manipulated through controlling the atom–cavity detuning and atom–cavity coupling.

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