Environment-induced sudden change of coherence in quantum systems

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Manipulating dynamical evolution is an important task in quantum information. The sudden death phenomenon (SDP), which is predicted to be unattainable beyond entanglement [T. Yu and J. H. Eberly, Sudden death of entanglement, Science **323**, 598 (2009)], would be an especially surprising feature in quantum coherence. In this paper, we modulate the spatial modes of photons and build a spatially inclined channel using a series of specially made quartz plate pairs. Within this channel, sudden changes in coherence occur in open-quantum systems. We, then, describe the SDP within a general theoretical framework of sudden quantum-coherence changes and by defining the *n*th-order sudden coherence change. Moreover, by adding non-Markovian noise, we find that coherence can rebirth after a sudden death. We further compare the sudden change features in coherence and quantum entanglement. We find that both coherence and entanglement perform identical dynamical processes upon Bell diagonal states, although their dynamical characteristics change when the initial state is partially entangled. Our results provide insights into the sudden change phenomena of quantum correlations beyond entanglement along with intriguing perspectives on quantum coherence dynamics.

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I. INTRODUCTION

Such as sudden change of coherence and other correlations from protein folding in biological systems [1,2] to financial transactions in the stock market [3]. Sudden change phenomena (SCPs) are also observed in the quantum realm [4–29]. In the pioneering days of quantum mechanics, Heisenberg applied the term "wave-function reduction" to describe features [4] undergoing a sudden wave-function change that does not obey the Schrödinger equation [5]. Such measurements also induce a jump that can be regarded as a sudden change of knowledge of the quantum system [6,7]. During the development of quantum mechanics, SCPs were observed in many other quantum systems, such as abrupt potential changes in a system with infrared divergence [8], phase transitions in quantum chaos [9] and topological insulators [11], and sudden changes of electrical characteristics in a multiquantum well [12].

In recent years, SCPs have been frequently discovered in various kinds of quantum resources [13–29]. For example, a sudden transition between the quantum and the classical correlations has been reported [14–17], and a sudden change in quantum discord occurs when two noninteracting qubits subjected the action of Pauli maps in certain conditions [17,18]. The most dazzling SCP is surely the sudden death of entanglement [19–23], which is regarded as a new form of decay [20] *only* encountered by quantum entanglement [1]. The sudden death of entanglement has been observed in many situations, such as influence by an independent environment on a system [21], during redistribution of the entanglement under decoherence channels [23], and during decay of storage time in atomic ensembles [24]. The antisudden death phenomenon, i.e., sudden birth, has also been observed in an all-optical setup in a non-Markovian environment [25].

When seeking the mechanism behind the above-mentioned SCP, we found that different phenomena are induced in different ways. The sudden reduction in the wave function is caused by measurement with a classical observable, whereas the sudden changes in potential or electrical characteristics are induced by the material properties. The SCPs in quantum correlations strongly depend on their measures. The main causes are the emergence of a pointer basis [26] or the compulsive selection of the maximal value in a group [25]. Naturally, such a definitive sudden change cannot be a universal phenomenon in general quantum correlations but is peculiar to some defined physical quantity. Therefore, to observe an SCP (including sudden death) beyond entanglement, discord, or correlation as discussed above, we must conclude that such a phenomenon is created by a distinctly general mechanism.

The environment of the quantum system can induce sudden changes in many general physical resources, especially,

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in quantum coherence [30–34]. Environment-induced mechanisms that create entanglement sudden death (ESD) [21] and sudden transitions in quantum discord dynamics [18] have been recently reported. However, such environmentally induced SCPs in quantum coherence have not been studied in detail. Inspired by the above works, we choose coherence as a major research theme for investigating SCPs, and provide a general theoretical framework of SCPs. In an experimental study, we also compare and attempt to relate the sudden change behaviors of coherence with entanglement. We realize the SCP in quantum coherence by manipulating the spatial environment into a particular shape using digital mirror device (DMD). The DMD contains spatial light modulators that realize an arbitrary spatial distribution of the photons. We, then, construct a spatially inclined channel for the corresponding evolution in which arbitrary decoherence occurs. This spatial environment-induced method opens up a novel way of regulating the quantum environment, as also discussed in Ref. [35].

II. A GENERAL THEORETICAL FRAMEWORK FOR SUDDEN CHANGE OF QUANTUM COHERENCE

Before discussing the experimental setting of the coherence sudden change (CSC), let us examine the CSC within the context of SCPs.

The framework of quantum resource theory embraces several quantum resource theories of coherence [30]. Here, we adopt the theory developed in Ref. [31], which defines coherence as follows. For a given complete orthonormal basis $\{|i\rangle\}_{i=1}^{n}$ in a fixed Hilbert space $\mathbb{H}$, referred to as an incoherent basis, we define the complete dephasing map $\Delta(\cdot) := \sum_i |i\rangle\langle i|(\cdot)|i\rangle\langle i|$. A state $\rho \in B(\mathcal{H})$ is called incoherent (free) if

$$\Delta(\rho) = \rho. \tag{1}$$

We denote the set of all incoherent states in $\mathcal{H}$ as $\mathcal{I}(\mathcal{H})$. Suppose that $\Lambda \in \mathcal{L}(B(\mathcal{H}), B(\mathcal{K}))$ is a quantum channel with Kraus operators $\{K_j\}_j$. Channel Λ is called free or incoherent (mapping an incoherent state into an incoherent state) if

$$K_j \Delta(\rho) K_j^\dagger = \Delta(K_j \rho K_j^\dagger), \quad \forall\, j. \tag{2}$$

It is easily checked that the Kraus operators of a free operation are of the form

$$K_j = \sum_k a_{jk} |\sigma(k)\rangle\langle k|, \tag{3}$$

where σ is a function mapping $\mathbb{N}_n = \{1, \dots, n\}$ to itself.

Now, consider a situation in which a dynamical system with state $\rho[t, \tau(t)]$ interacts with the environment. We denote by $\tau(t)$ the effect of the environment on the system, which is usually a time-dependent coupling constant. As $\tau(t)$ varies, the property of the state may change from coherent to incoherent. At some change points, this transition is smooth, but at other points, the coherence change is sudden. To define the smoothness, we introduce a quantifier or measure of the coherence. Baumgratz *et al.* [31] formulated a set of physical requirements that should be satisfied by any valid quantifier C of quantum coherence. The details are given in the Appendix.

The coherence of a dynamical state $\rho[t, \tau(t)]$ is, thus, given by $C[t, \tau(t)] = C\{\rho[t, \tau(t)]\}$. We say that the coherence undergoes a sudden change at $\tau(t) = \tau_s$ if $\partial_\tau C(\tau)$ is discontinuous at that point. If τ_s is a CSC point, $C(\tau_s - \varepsilon) \neq 0$ and $C(\tau_s + \varepsilon) = 0$ for arbitrarily small $\varepsilon > 0$, the change is referred to as sudden death; alternatively, if τ_s is a CSC point, $C(\tau_s - \varepsilon) = 0$ and $C(\tau_s + \varepsilon) \neq 0$ for arbitrarily small $\varepsilon > 0$, the change is a sudden rebirth.

Why is the SCP crucial for understanding the physics of a system? A main reason is the potential applicability of SCPs in statistical physics. In a statistical system characterized by a set of parameters $\tau = (\tau_1, \dots, \tau_n)$, the system state is described by a density operator $\rho(\tau)$ (classically, a probability density over the parameter space). Thermodynamical observables such as free energy $F(\tau) = F[\rho(\tau)]$ are functions of density operators $\rho(\tau)$. A phase transition is characterized by smooth changes in the thermodynamical observables [36–39]. If the first-order derivative of a thermodynamical observable is discontinuous at a point $\tau = \tau_s$, the system undergoes a first-order phase transition at τ. Similarly, if the derivatives of the thermodynamical observables up to the $(n-1)$th order are continuous at $\tau = \tau_s$ but the nth-order derivative is discontinuous at $\tau = \tau_s$, we say that the system undergoes a nth order phase transition [36–38].

Motivated by the above discussion, we define the nth-order sudden change of the coherence. The coherence quantifiers are analogous in the role to thermodynamical observables. For a quantum state $\rho(\tau)$, we can calculate the degree of coherence by an appropriate quantifier C as $C[\rho(\tau)]$. This system undergoes a nth-order sudden change in coherence when the nth-order derivative of the coherence (defined in terms of quantifier C) becomes discontinuous whereas all $(n-1)$th, ..., 1st-order derivatives are continuous at the same time. This definition is generalizable to other quantum correlations, such as quantum entanglement and quantum nonlocality. Under this definition, we can seek the sudden change points of other quantum resources, such as correlation and CSCs.

A nth-order sudden change of quantum correlations (such as coherence) is not merely analogous to a phase transition. In fact, we have gradually understood the important role of quantum resources in quantum information theory [14–24,27,40], quantum phases [9,41–43], and quantum field theory [44,45]. Typical examples are topological ordering [46,47] and discrete anti-de Sitter/conformational field theory [48]. As the different phases (macroscopic physical states) of a system are characterized by different correlation patterns of the degrees of freedom of the system, understanding their SCPs may shed new light on these diverse fields.

III. AN EXAMPLE OF QUANTUM-COHERENCE SUDDEN CHANGE IN QUANTUM OPTICS

Inspired by the above studies, we experimentally investigate the CSC in an all-optical setup. More precisely, we choose the polarization of the photons as the system and the spatial degree of freedom as the environment. By regulating the spatial mode, we can induce a sudden drop in coherence during the evolution of the dephasing channel. The initial state is the product of the polarization and spatial mode, which can be expressed as

$$|\Psi\rangle = (c_1|H\rangle + c_2|V\rangle) \otimes \int f(\mathbf{r})|\mathbf{r}\rangle d\mathbf{r}, \tag{4}$$

where we have omitted the constant phase. $|H\rangle$ ($|V\rangle$) denotes the horizontal (vertical) polarization and $f(\mathbf{r})$ is the amplitude at spatial position $\mathbf{r}$. The state is normalized as $|c_1|^2+|c_2|^2=1$ and $\int |f(\mathbf{r})|^2 d\mathbf{r} = 1$. For simplicity and without loss of generality, we focus on the one-dimensional case in which $\mathbf{r}$ reduces to x (the coordinate the coordinate along the horizontal direction). As an example, we generate the spatial mode $f(x) = \mathrm{sinc}(\pi x)$ using a digital mirror device (see the next section for details), but it is worth noting that many other spatial modes can generate SCPs. Decoherence in such an open system is determined by the differently evolved phases at every spatial position, namely, coherence dynamics occur when the system (polarization) and environmental (spatial modes) interact in a series of inclined birefringent media. The evolution of the total state is governed by the Hamiltonian,

$$H = (n_H |H\rangle\langle H| + n_V |V\rangle\langle V|) \otimes \int \frac{\omega_0}{c} x |x\rangle\langle x| dx, \tag{5}$$

where n_H (n_V) is the refractive index of the medium in the direction H (V), $\omega_0 = 2\pi \times c/\lambda_0$, $\lambda_0 = 808$ nm, and c denotes the light speed.

Tracing out the environmental state, the system (polarization state) undergoes the following dynamical process:

$$\rho(\alpha) = |c_1|^2 |H\rangle\langle H| + |c_2|^2 |V\rangle\langle V| + \chi^*(\alpha)|c_1||c_2||H\rangle\langle V| + \chi(\alpha)|c_1||c_2||V\rangle\langle H|. \tag{6}$$

The decoherence function $\chi(\alpha)$ is given by

$$\chi(\alpha) = \int |f(x)|^2 e^{i(\omega_0/c)x\,\Delta n\alpha} dx. \tag{7}$$

Here, $\Delta n = n_H - n_V$, x is the spatial position, and α is the angle corresponding to the evolution length in the dephasing channel. α determines the phase difference between the horizontal and the vertical polarizations at every position x, i.e., the degree decoherence. In a way, $\chi(\alpha)$ is decided by the length of the dephasing channel α and the distribution of $f(x)$ in the engineered environment (here, designed for creating SCPs). Thus, by tuning the graphics of the environment, we can observe the sudden death phenomenon.

Unlike the irreversible decoherence process in a Markovian environment, non-Markovian noise $\mathcal{N}(x)$ has a memory effect that can contribute to the rebirth of coherence that has fallen to zero [1,22,25,49,50]. The same phenomenon has been observed in quantum entanglement [25]. To modulate the environment as a non-Markovian environment $|f'(x)|^2 = |f(x)|^2\mathcal{N}(x)$, we add a comb function on the environment that reproduces a dead coherence. This sudden rebirth of quantum coherence extends its lifetime and can be exploited in practical applications.

IV. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The photon pairs were generated by a spontaneous parametric down-conversion (SPDC) process in two 1-mm-thick beam-like-cut β barium borate crystals pumped by a 404-nm laser [51]. Then, the photons (of the wavelength $\lambda = 808$ nm) passed through a filter (3-nm full width at half maximum) and were coupled into single-mode fibers. The polarization state of the photon through path A represents the open system. As the

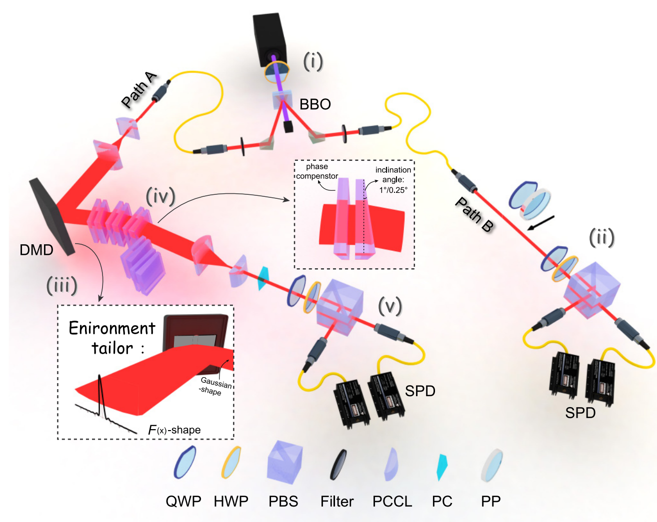

FIG. 1. Experimental setup. The whole experimental setup is divided into five parts: (i) generation of entangled photon pairs; (ii) remote preparation of the system state on path B; (iii) modulation of the spatial (environment) mode; (iv) dephasing through a channel composed of inclined quartz plates; (v) measurement of the system state. The initial environmental state is a spatial mode with a Gaussian-shaped facula, which can be tailored by the DMD into a $|f(x)|^2$-shaped mode. Along the series of inclined quartz plates, the polarization and spatial degrees of freedom are coupled, and the inclination angle is varied to simulate the evolution time. The photons are, then, detected by a single-photon detector (SPD), and the value of the coherence (or entanglement is obtained by quantum state tomography.

photon pairs were generated in a Bell maximally entangled state, the initial state at path A $|\psi\rangle = 1/\sqrt{2}(|H\rangle + |V\rangle)$ could be remotely prepared by projecting the photons on path B to the corresponding basis ($|H\rangle + |V\rangle$). As discussed above, we reduced the spatial modes to the one-dimensional case $f(x)$. Experimentally, the spatial modes were initialized by a pair of planoconvex cylindrical lenses (PCCLs) and tailored by the DMD (V-9501 VIS, Texas Instruments DLP Technology) with 768 pixels in the horizontal direction. Each pixel is a micromirror of size (13.7×13.7) μm^2. The spatial-inclined channel was simulated by a series of quartz plate pairs, and the decoherence strength was determined by the total angle of inclination α. Each plate pair constituted a quartz plate inclined at 1° or 0.25°, and a matched normal quartz plate whose optical axis was orthogonal to the inclined one and which compensated the decoherence in the frequency degree of freedom.

By inserting or removing the inclined quartz plates, we could tune the total inclination angle α, and, thus, control the decoherence strength. After the channel, we traced out the system from the spatial environment by another pair of PCCLs and measured the coherence resource in the final state using quantum state tomography. To simulate the non-Markovian noise $\mathcal{N}(x)$, we created a grating on the spatial optical field by periodically switching the pixels on the DMD screen on and off, as shown in Fig. 2.

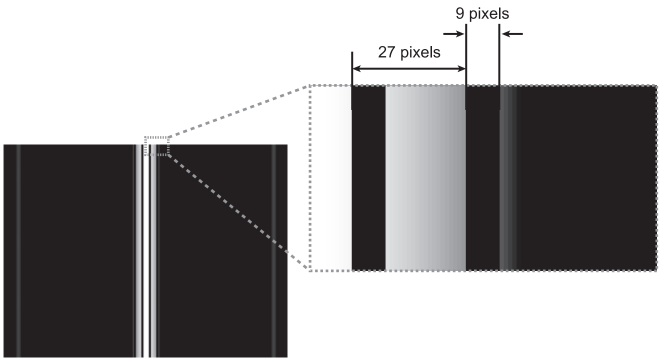

FIG. 2. Simulation the non-Markovian noise on the DMD screen [the experimental results are shown in Fig. 3(e)]. The enlarged image (right) highlights the periodic attributes. The grating constant ($d = 27$ pixels) and the width of each seam ($a = 18$ pixels) are clearly discernible. Here, 1 pixel = 13.7 μm.

V. RESULTS

A. Coherence sudden death and rebirth

Figure 3 shows the results when the initial state was prepared as $|\psi\rangle = 1/\sqrt{2}(|H\rangle + |V\rangle)$. The coherences based on the quantifiers l_1 norm and relative entropy, respectively, are calculated as

$$\mathcal{C}_{l_1}[\rho(\alpha)] = |\chi(\alpha)|,$$

and

$$\mathcal{C}_{re}[\rho(\alpha)] = 1 - \frac{1}{2}\left[[1 + |\chi(\alpha)|]\log_2\frac{2}{1+|\chi(\alpha)|} + [1 - |\chi(\alpha)|]\log_2\frac{2}{1-|\chi(\alpha)|}\right]. \quad (8)$$

The coherences based on both quantifiers were completely consumed at the critical point $\alpha = 0.090$ rad in our specially engineered environment [see Fig. 3(a)]. By measuring the first- and second-order derivatives of the coherences [see Figs. 3(b)–3(d)], we demonstrated the sudden death feature in the dynamical evolution. However, the different coherence quantifiers determined different orders of the sudden change. For instance, the discontinuous feature appeared in the first-order derivative of $\mathcal{C}_{l_1}$ quantified by the l_1 norm [Fig. 3(b)], but in the second-order derivative of $\mathcal{C}_{re}$ quantified by the relative entropy [Figs. 3(c) and 3(d)]. We conclude that, in this case, coherence undergoes a first-order sudden change when quantified by the l_1 norm and a second-order sudden change when measured by the relative entropy.

The corresponding results of coherence sudden death under non-Markovian noise are shown in Fig. 3(e). After coherence sudden death (CSD), the coherence rebirthed at another critical point $\alpha = 0.160$ rad.

To exhibit the sudden feature of the coherence sudden birth (CSB) in Fig. 3(e), we also measured the first- and second-order derivatives of the coherences defined by the l_1 norm and entropy, and the results are shown in Fig. 4. The discontinuous feature appearing in the first-order derivative (second-order derivative) of the l_1-norm definition (relative entropy definition) exactly demonstrates the sudden rebirth of the coherence.

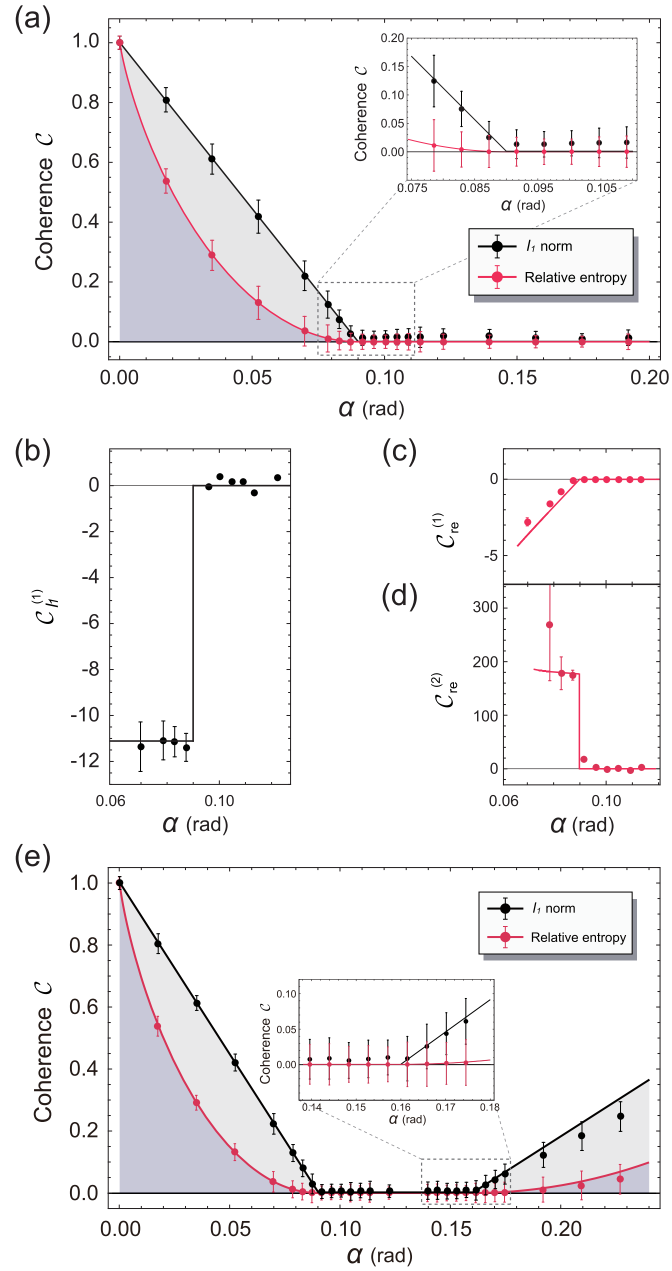

FIG. 3. Results of coherence sudden death and rebirth. (a) Evolution of coherence quantified by the l_1 norm and relative entropy (inset is an enlargement of the sudden death behavior). (b) Coherence measured by the l_1 norm, showing the discontinuous feature in the first-order derivative. (c) and (d) Coherence measured by the relative entropy, showing a continuous first-order derivative but a jump (sudden change) in the second-order derivative. (e) After adding a non-Markovian noise on the spatial mode, we observe a sudden birth (at $\alpha = 0.160$ rad) after the sudden death (inset is an enlargement of the sudden birth feature). The errors (and those in subsequent figures) were derived using the Monte Carlo method.

The gap between the theoretical and experimental values after the CSB in Fig. 3(e) is caused by the inclined-quartz-plates-constituted channel. The small inclination angle induces a tiny spatial walk-off between the horizontal and vertical polarizations, which, in turn, causes a tiny decoherence.

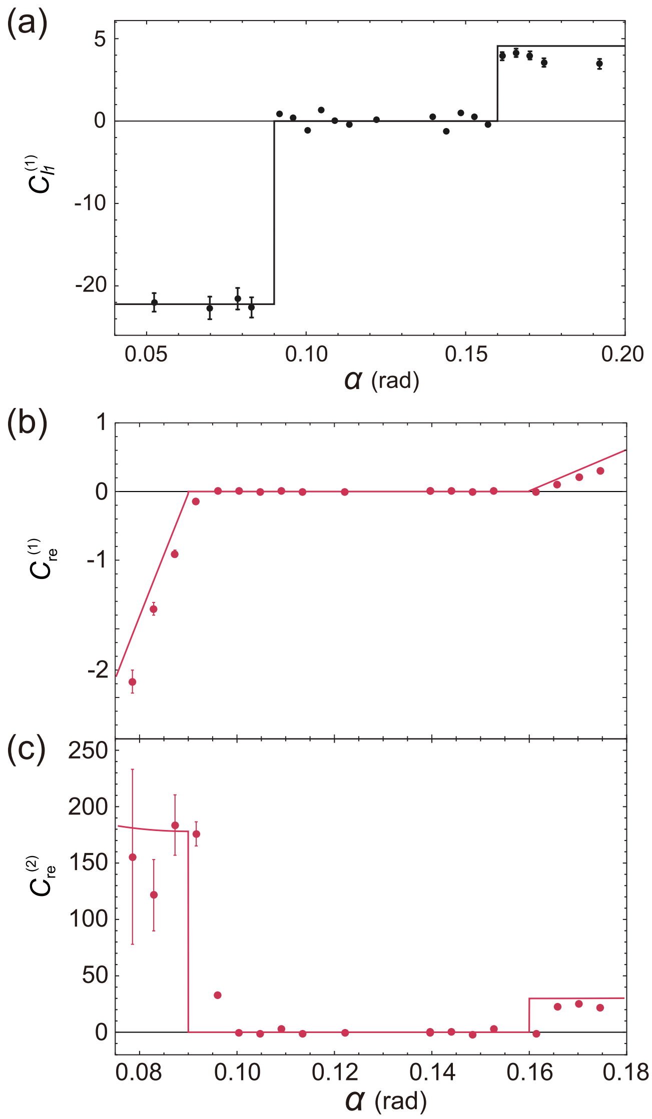

FIG. 4. Derivative of coherence defined by the l_1 norm and relative entropy. (a) After adding the non-Markovian noise $\mathcal{N}(x)$, the discontinuous feature is detected at $\alpha = 0.160$ rad in the first-order derivative, showing a first-order sudden rebirth of coherence. (b) and (c) In the coherence defined by the relative entropy, the first-order derivative is continuous but a jump at $\alpha = 0.160$ rad appears in the second-order derivative, indicating a sudden change in the rebirth of coherence.

In a long channel, this feature gains prominence, and the result deviates from the theoretical result. Meanwhile, as the area of the DMD screen is limited, we limited the spatial state to $x = -7.5$–7.5 mm (placing $x = 0$ at the center of the screen), thus, bringing another tiny error into the experimental results.

B. Sudden change of coherence and entanglement in two-qubit states

Given the strong relationship between coherence and entanglement [30], we are naturally driven to explore the effect of an environmentally induced sudden-change mechanism on the entanglement (or other quantum correlations). The ESD phenomenon was uncovered a decade ago, but the same experiences cannot be assumed for the CSD phenomenon in the coherence regime [1]. The previously proposed and demonstrated ESD mainly depends on its defined concurrence $\mathcal{E}$ [23,25,52,53]. However, the coherence quantifiers themselves cannot provide the sudden change feature because almost all of them are continuous and (unlike concurrence) the sudden change feature is not the maximum among a group of values. Here, we choose the l_1 norm as the coherence measure and the concurrence $\mathcal{E}$ as the entanglement and investigate how the sudden changes of coherence and entanglement are influenced by their different inducements.

The two-qubit maximally entangled polarization state $|\psi\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$ was prepared in the above experimental setup by removing the remote projection process on path B. One of the photons (on path A), then, passed through the dephasing channel in the introduced environment (the same equipment used in Fig. 3). After calculating the values of the l_1-norm coherence and the concurrence quantifier, we determined their relationship as

$$\mathcal{C}_{l_1}[\rho(\alpha)] = \mathcal{E}[\rho(\alpha)] = |\chi(\alpha)|. \tag{9}$$

The theoretical and experimental results are compared in Fig. 5(a). On this occasion, the coherence and entanglement disappeared simultaneously, and both were caused by the specifically structured spatial state $|f(x)|^2$.

C. Sudden change of coherence and entanglement in partially entangled states

We, then, investigated the coherence and entanglement dynamics in a partially entangled initial state, prepared by implementing a σ_x operation and dephasing in H/V bases on path B. In our experiment, the photon pairs generated by the SPDC process were created as a Bell maximally entangled state, $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$, with fidelity 0.982. The σ_x operation was then implemented on the photon at path B by inserting an HWP at 22.5°. The photons were dephased by inserting a 50λ phase plate on the H/V bases [25]. After evolution from this partially entangled state, the biphoton state can be expressed as the following density matrix:

$$\rho(\alpha) = \frac{1}{4}\begin{pmatrix} 1 & \chi(\alpha)^* & \chi_0^* & -\chi_0^*\chi(\alpha)^* \\ \chi(\alpha) & 1 & \chi_0^*\chi(\alpha) & -\chi_0^* \\ \chi_0 & \chi_0\chi(\alpha)^* & 1 & -\chi(\alpha)^* \\ -\chi_0\chi(\alpha) & -\chi_0 & -\chi(\alpha) & 1 \end{pmatrix},$$

where $\chi(\alpha)$ is the decoherence parameter of the system as mentioned previously, and χ_0 is the decoherence constant of the photon at path B. In the situation of no dynamic evolution of photon A, χ_0 was measured as 0.722.

The coherence and entanglement, respectively, of the quantifier were determined as

$$\mathcal{E}[\rho(\alpha)] = \max\left\{0, \tfrac{1}{2}[|\chi_0| + |\chi_0||\chi(\alpha)| + |\chi(\alpha)| - 1]\right\}, \tag{10}$$

where $\chi(\alpha)$ is the decoherence parameter of the above-mentioned system and $\chi_0 = 0.722$ is the decoherence constant of the dephasing process on path B.

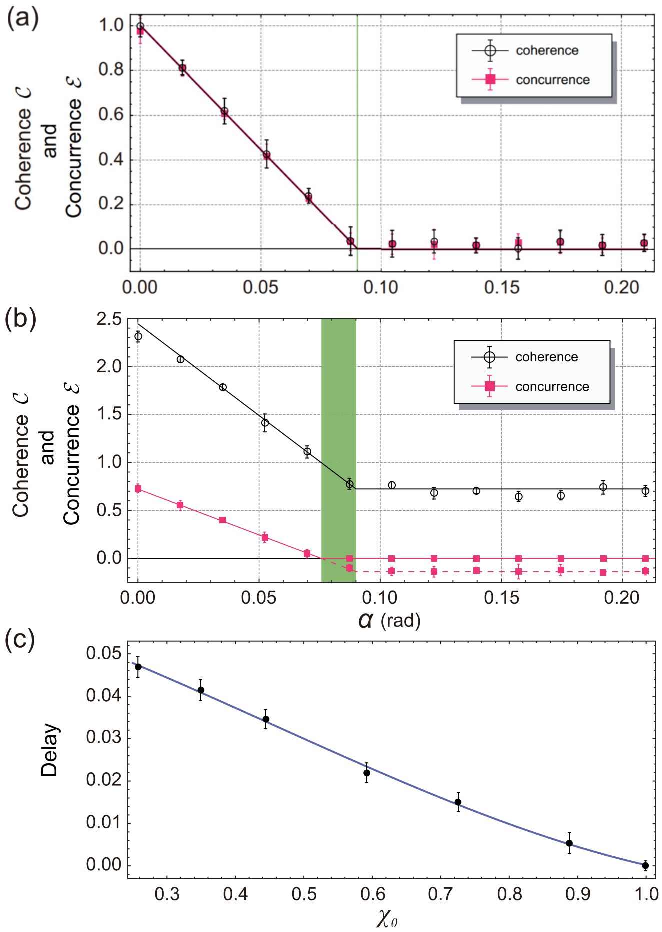

FIG. 5. Sudden change in coherence and entanglement. (a) Maximally entangled state situation. The coherence (black circles) and concurrence (red squares) simultaneously disappear at $\alpha = 0.090$ rad (green line). (b) Partially entangled state situation. The concurrence (red squares) is consumed completely, but the coherence decays up to $\alpha = 0.090$ rad (this period is shadowed in green). The red dashed line corresponding to the negative Γ [53]. (c) Interval between the sudden changes in entanglement and coherence. The interval is extended when the mixing of the state increases (χ_0 reduces).

The corresponding results are shown in Fig. 5(b). The ESD at $\alpha = 0.0755$ rad was caused by the concurrence (which performs as a max function [53]). In contrast, the coherence exhibited no sudden death feature at $\alpha = 0.0755$ rad but was maintained at $\alpha \geqslant 0.090$ rad; that is, the sudden change was not a sudden death. Interestingly, over a short period [green region in Fig. 5(b)], the entanglement was already dead, but the coherence continued to decay. As is well known, entanglement is independent of the chosen concurrence basis. Therefore, this phenomenon occurs with a different decoherence constant from that of ESD. Furthermore, the previously observed ESD phenomenon, which was almost completely caused by the concurrence measurement, was a first-order SCP. However, as observed for coherence, the order of the sudden change depends on its quantifiers.

VI. CONCLUSIONS

We demonstrated an experimental method for investigating the coherence sudden-change phenomenon in an inclined-quartz-plates-constituted dephasing channel, which is sensitive to the spatial modes of photons. First, we devised a general theoretical framework for the sudden change in quantum coherence, and defined the nth-order sudden change as the discontinuous feature in the nth-order derivatives of the coherence $\mathcal{C}$. Next, we experimentally demonstrated that when the environment (the spatial state) was modulated into a particular shape by the DMD, the coherence was completely consumed in finite time under a dephasing channel. When defined in terms of the l_1 norm and relative entropy, the coherence underwent a first-order and second-order sudden change, respectively. After adding a non-Markovian noise to the environment, we discovered a sudden rebirth phenomenon after the CSD. Finally, we compared the different mechanisms of sudden change between coherence and another quantum correlation (namely, entanglement). Evolving the Bell diagonal initial state in the same modulated environment, CSD and ESD occurred simultaneously and exhibited the same dynamical behavior when quantified by the l_1 norm and concurrence. However, when the partial entangled initial state was rotated, CSD was prevented, but the entanglement resource was completely consumed until the coherence became invariant. This behavior was mainly induced by the concurrence quantifier and exhibited a first-order sudden change.

In conclusion, we have presented a distinctive mechanism for creating coherence sudden changes (sudden death and rebirth) in an open quantum system. We demonstrated some intriguing traits of coherence and other quantum correlations. Our paper enriches the understanding of sudden change features and fosters insight into other quantum correlations that are previously predicted to exhibit no sudden change phenomena [1,19–21]. coherence and other quantum correlations. Our paper enriches our understanding of sudden change features and fosters insight into other quantum correlations that were previously predicted to exhibit no sudden change phenomena.

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APPENDIX: BRIEF INTRODUCTION TO QUANTUM COHERENCE AND ITS QUANTIFERS

Coherence can be regarded as a resource that cannot be generated or increased under a restricted class of incoherent quantum channels Λ. Such channels, which always map the incoherent states ($\mathcal{I}$) to themselves, are given by the Kraus expression $\Lambda(\rho_i) = \Sigma_i K_i \rho K_i^\dagger$ with $\Sigma_i K_i K_i^\dagger = \mathbb{I}$ and $K_i \mathcal{I} K_i^\dagger \subseteq \mathcal{I}$.

Baumgratz *et al.* [31] formulated a set of physical requirements that should be satisfied by any valid measure of quantum coherence C:

(i) For any state ρ, $C(\rho) \geqslant 0$; $C(\rho) = 0$ iff $\rho \in \mathcal{I}$.

(iia) C is nonincreasing under an incoherent channel Λ, i.e., $C(\rho) \geqslant C[\Lambda(\rho)]$.

(iib) On average C is nonincreasing under selective measurements, i.e., $C(\rho) \geqslant \Sigma_i k_i C(\rho_i)$, where $k_i = \mathrm{Tr}(K_i \rho K_i^\dagger)$ and $\rho_i = K_i \rho K_i^\dagger / k_i$.

(iii) C is convex, i.e., $C(\Sigma_i k_i \rho_i) \leqslant \Sigma_i k_i C(\rho_i)$. After measuring the coherence, quantifying the coherence is the logical next step [31]. Given a fixed reference basis $|i\rangle$, the relative entropy of coherence can be expressed as $C_{re}(\rho) = S(\rho_{\mathrm{diag}}) - S(\rho)$ where $S(\cdot)$ is the von Neumann entropy and ρ_{diag} denotes the state obtained by removing all off-diagonal elements from ρ. The intuitive l_1 norm of coherence is $C_{l_1} = \Sigma_{i,j(i\neq j)} |\rho_{i,j}|$.

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