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Experimental Cyclic Interconversion between Coherence and Quantum Correlations

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Quantum resource theories seek to quantify sources of nonclassicality that bestow quantum technologies their operational advantage. Chief among these are studies of quantum correlations and quantum coherence. The former isolates nonclassicality in the correlations between systems, and the latter captures nonclassicality of quantum superpositions within a single physical system. Here, we present a scheme that cyclically interconverts between these resources without loss. The first stage converts coherence present in an input system into correlations with an ancilla. The second stage harnesses these correlations to restore coherence on the input system by measurement of the ancilla. We experimentally demonstrate this interconversion process using linear optics. Our experiment highlights the connection between nonclassicality of correlations and nonclassicality within local quantum systems and provides potential flexibilities in exploiting one resource to perform tasks normally associated with the other.

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In quantum science, there is continuing interest in isolating resources that quantify features of nonclassicality and thus underly advantaged quantum information processing. Entanglement is an iconic example, representing correlations in multipartite systems with no classical counterpart. The subsequent discovery that quantum advantage can persist in entanglement-breaking regimes propelled interest in more general forms of nonclassicality. Quantum discord became a prominent candidate, quantifying quantum correlations that may persist in unentangled systems [1–3]. Resource theoretic perspectives also motivated revisiting long-standing notions of nonclassicality in localized systems, where quantum superposition states that Schrödinger's cat stand as key examples. This resulted in the resource theory of quantum coherence, where one identifies a natural classical basis (e.g., alive and dead states of the cat), and a state is said to contain coherence if it cannot be expressed as a mixture of such classical states [4–6]. These studies proved invaluable for isolating how nonclassical resources beyond entanglement can potentially empower quantum technologies [7–15].

Recently, there has been growing evidence that in certain settings these resources can be interconverted, allowing us to consume local nonclassicality to create quantum correlations with an ancillary system and vice

versa [16–21]. These studies field dual benefits. They can provide ways of validating potential new resources in the context of more established resource theories and inspire fresh perspectives on how such resources can lead to practical advantage.

Here, we leverage these ideas by designing a quantum circuit that cyclically interconverts between coherence and discord and implement it using discrete photonics. The first half cycle experimentally realizes a recently proposed protocol for converting coherence to discord [18], where coherence on one input system is converted to discordant correlations between it and a suitable ancilla. The second adapts theoretical and experimental techniques in coherence distillation and steering [19,20,22], whereby we restore coherence in the original input system via measurement of the correlated ancilla. In principle, this cycle can be completed without any loss of resource and operates on any input state with nonzero coherence. Experimentally, we implement this for the case where the input and ancilla are single qubits and demonstrate that up to 80% of the initial coherence is retained within a single cycle. Our work illustrates that under appropriate conditions coherence and discord behave analogously to different forms of energy, exchangeable from one form to another.

Background.—We first review coherence and discord. The resource theory of coherence formalizes the intuition that quantum superpositions are nonclassical [4]. In this framework, some orthogonal basis of states, referred to as the reference basis, $\{|i\rangle\}$ are considered classical, usually motivated by physical grounds of being easy to synthesize or store. For qubits, this basis is usually denoted $\{|0\rangle, |1\rangle\}$ by convention, as they are often considered analogous to the two states of a classical bit. Any mixture of such states, $\chi = \sum_i p_i |i\rangle\langle i|$ with $\sum_i p_i = 1$ and $p_i \geq 0$, is considered classical and termed incoherent. For bipartite systems partitioned by A and B , each with respective reference basis $\{|i\rangle\}$ and $\{|j\rangle\}$, the incoherent states take the form $\chi_{AB} = \sum_{ij} p_{ij} |i\rangle\langle i| \otimes |j\rangle\langle j|$ with $\sum_{ij} p_{ij} = 1$ and $p_{ij} \geq 0$. The rationale being that such states have a 1–1 map to classical probability distributions on classical states. States lying outside this set contain coherence.

Incoherent operations define the set of operations that take incoherent states to incoherent states, representing “free operations” that cannot create nonclassicality and thus can be simulated by classical stochastic maps [4]. Each measure of coherence is then a real valued function on quantum states that cannot increase under incoherent operations [4,10,23]. Here, we adopt the relative entropy of coherence $C(\rho) = \min_{\chi \in \mathcal{I}} S(\rho||\chi)$ that captures the minimal relative entropy $S(\rho||\chi) = \text{Tr} \rho \log \rho - \text{Tr} \rho \log \chi$ between ρ to the closest incoherent state.

Quantum discord captures quantum correlations beyond entanglement in bipartite systems [2,3,24] and represents unavoidable disturbance induced by local measurement. For a bipartite system partitioned by A and B , a state without discord takes the form $\sigma_{AB} = \sum_i p_{ij} |e_i\rangle\langle e_i|_A \otimes |r_j\rangle\langle r_j|_B$, where $\{p_{ij}\} \geq 0$, $\sum_{ij} p_{ij} = 1$ and $\{|e_i\rangle_A\}$, $\{|r_j\rangle_B\}$ are any orthogonal basis for subsystems A and B , respectively. Such states are referred to as being classically correlated (CC), and any other bipartite state is defined to have discord. There are several measures of discord in the literature, among which we adopt the relative entropy of discord defined as $D(\rho_{AB}) = \min_{\sigma_{AB}} S(\rho_{AB}||\sigma_{AB})$, where the minimum is taken over classically correlated σ_{AB} [3].

Framework.—Our scheme for cyclic conversion between coherence and discord is illustrated in Fig. 1. We begin with a system, denoted A in some arbitrary state ρ_A , with coherence $C(\rho_A)$. We then introduce a suitable ancilla B . The cycle is divided into two halves. The first half consumes the initial coherence in A to generate discord between A and B ; the second destroys these correlations by measuring B and uses the measurement results to steer A into a state with coherence.

The first half-cycle adopts a recent proposal for converting coherence to discord. Using system A as the only source of coherence, the proposal considers how much quantum correlations can be generated between A and some initially incoherent ancilla B using only incoherent operations. The amount of coherence initially possessed by

FIG. 1. (i) Quantum circuit and (ii) conceptual diagram for the cyclic interconversion process. This scheme has two stages. Stage (a) takes a coherent state ρ_A as input (system A), along with an incoherent ancilla τ_B (system B). Coherence in A is converted into discord between A and B using incoherent operations, yielding a state $\rho_{AB}^{I \max}$ when the conversion is maximal (such that all coherence is consumed, and the resulting marginal $\rho_A^{I \max}$ is incoherent). In (b), the coherence in A is restored by application of LQICC operations on the output from stage (a). This involves first measuring on B (M_B) and then applying an appropriate incoherence operation (Δ_{A^i}) on A conditioned on the resulting outcome. The ancilla can then be reset to its initial state via incoherent operations (Δ_{B^i}).

A then bounds the discord that can be induced between input and ancilla [18]. Formally, let Δ_{AB} be an arbitrary incoherent operation, and $\rho_{AB}^I = \Delta_{AB}(\rho_A \otimes \tau_B)$, then,

$$D(\rho_{AB}^I) \leq C(\rho_A). \quad (1)$$

Our scheme employs a circuit where this conversion is maximally efficient, such that all coherence on A is consumed and transformed into discord. The resulting transformed state $\rho_{AB}^{I \max}$ satisfies $D(\rho_{AB}^{I \max}) = C(\rho_A)$ and $C(\rho_A^{I \max}) = 0$, where $\rho_A^{I \max} = \text{tr}_B \rho_{AB}^{I \max}$. This is always possible for any input ρ_A , using appropriate choice of ancilla and the application of a generalized CNOT gate [25].

The second half-cycle employs $\rho_{AB}^{I \max}$ to restore coherence in A by suitable local measurements on B . To do so meaningfully, we forbid operations that create discord or are able to spontaneously generate coherence in A . Specifically, we consider the class of operations—known as local quantum incoherent operations and classical communication (LQICC)—that involve measurement on B and apply some incoherent operation to A conditioned on the resulting outcome. Such a framework arose in the context of coherence distillation [19,20,32], where it was motivated by the question of how correlations between A and B can be harnessed to steer A into a more coherent state. In the Supplemental Material [25], we prove that when the initial state is $\rho_{AB}^{I \max}$,

$$C(\rho_A^{\text{LQICC}}) \leq D(\rho_{AB}^{\text{I max}}) = C(\rho_A), \quad (2)$$

where ρ_A^{LQICC} is the state of A after any possible LQICC operation. Thus, the amount of coherence that can be restored to A never exceeds the initial coherence in A . Meanwhile, the measurement on B destroys all discord between A and B . In the Supplemental Material (Sec. S1) [25], we show this bound can be exactly saturated, in which case $C(\rho_A^{\text{LQICC}})$ becomes equal to the coherence of collaboration $C_d^{B|A}(\rho_{AB})$ —the number of copies of $|+\rangle$ we can distill per copy of ρ_{AB} in the independent identically distributed limit [19]. Combining the two subprotocols, we obtain a cyclic procedure that interconverts between coherence and discord which can be repeated *ad infinitum*.

Note that the above results assume all coherence in A is converted to discord in the first half-cycle. In such scenarios, the relative entropy of entanglement is equal to that of discord for $\rho_{AB}^{\text{I max}}$. Thus, the protocol can also be regarded as an interconversion between coherence and entanglement. In less optimal scenarios, this conversion process may not be lossless. Nonoptimal conversions may, for example, partially convert coherence into discord, while generating no entanglement [18]. One example is the conversion of $|+\rangle\langle+| \otimes |0\rangle\langle 0|$ with operation $\Lambda(\rho) = pU_{\text{CNOT}}\rho U_{\text{CNOT}}^\dagger + (1-p)I/4$, where U_{CNOT} denotes the CNOT gate. The resulting state ρ_{AB}^{I} is a Werner state, which has zero entanglement but nonzero discord when $0 < p \leq 1/3$. In this case, the coherence is not maximally converted to discord. Then, in the second half-cycle,

FIG. 2. Experimental setup. The setup divides into three modules: (a) state preparation, (b) coherence to discord conversion, and (c) coherence restoration. Module (a) initializes one photon in some arbitrary state ρ_A (named control) and a second photon in state $|0\rangle\langle 0|_B$ (named target), in particular, sandwichlike type II beamlike phase-matching β -barium borate (BBO) crystals are used to generate two photon entangled sources (ES), while the YVO4 and LiNO3 crystals in each arm are used for temporal and spatial compensation, respectively. Module (b) implements a CNOT gate between control and target photons. This results in a discordant state $\rho_{AB}^{\text{I max}}$. Module (c) implements a von Neumann measurement on the target photon using QWP2 and HWP8 together with a PBS and two SPDs. The final coherence on A is then detected by quantum state tomography using a combination of QWP1, HWP9, PBS, and two SPDs. Note that at the end of module (b), we can also measure the discord in $\rho_{AB}^{\text{I max}}$ via state tomography by using the aforementioned measurement apparatus. Key elements include half-wave plate (HWP), quarter-wave plate (QWP), partially polarizing beam splitter (PPBS), polarizing beam splitter (PBS), single photon detector (SPD), entangled source (ES), fiber coupler (FC), interference filter (IF), quartz plate (QP).

coherence distillation can be used to restore some of the initial coherence in A . Here, we are primarily focused on experimental realization with the purpose of creating the maximal amount of discord during cyclic operation.

Protocol.—Our experiment implements such a cycle for the case where both A and B are qubits, and the basis $\{|0\rangle, |1\rangle\}$ is considered classical. Here, A is initialized in state ρ_A with coherence $C(\rho_A)$, while B is initialized in state $|0\rangle$. The first stage converts the coherence in A into discordant correlations between A and B . This is achieved by a CNOT gate. The resulting state $\rho_{AB}^{\text{I max}}$ has zero coherence on A and discord $C(\rho_A)$, representing complete conversion. The second stage adopts techniques in coherence distillation to restore the coherence in A by taking advantage of the discordant correlations created in the previous stage. This is achieved by measuring B in a basis that is mutually unbiased with the Pauli Z basis (actually, we chose Pauli Y basis in our experiment), with measurement outcomes $m \in \{0, 1\}$. Knowledge of this outcome collapses system A into a state with coherence $C(\rho_A)$ under ideal conditions.

We realize this procedure using linear optics, where the horizontal and vertical polarizations of a single photon denote the basis $\{|0\rangle, |1\rangle\}$. The experimental schematic is outlined in Fig. 2, where we have divided the protocol into three self-contained modules. The first module (green) represents state preparation. The second module (cyan) converts coherence into discord, while the final module (purple) applies coherence distillation to restore initial coherence. For further details, see [25].

Results.—We test the cyclic interconversion for both pure and mixed inputs ρ_A . Figure 3 illustrates the results when A is initialized in some pure state $|\phi\rangle_A = \cos 2\theta|0\rangle + \sin 2\theta|1\rangle$, with initial coherence as depicted by the solid brown line. After application of CNOT, the discord of the resulting state $\rho_{AB}^{\text{I max}}$ can be retrieved by density matrix reconstruction (see the Supplemental Material [25] for details). We see that the vast majority of this coherence is converted into discord (blue squares). The next stage of the experiment restores the coherence of system A by measurement of B . This involves a variant of experimental techniques developed for coherence distillation [22], where we retrieve most of the coherence originally in ρ_A (see red triangles).

Note that under ideal scenarios, this conversion process would be lossless. In our experiment, we experienced a loss of approximately 20%. To understand this divergence, we performed quantum process tomography (QPT) [33] to ascertain the process fidelity of the CNOT gate used during the conversion protocol [25]. Once the achieved fidelity of 0.885 is taken into account, theoretical predictions and experimental results agree to within reasonable accuracy (see red and blue lines in Fig. 3).

We also tested the interconversion of coherence and discord for mixed inputs of the form $\rho_A = \frac{1}{2}(I + a|0\rangle$

FIG. 3. Discord generated and coherence restored for various pure state inputs. We conducted the interconversion protocol for various pure state inputs of the form $|\phi\rangle_{AB} = (\cos 2\theta|0\rangle + \sin 2\theta|1\rangle)|0\rangle$, for various values of θ between 0° and 45° . The coherence of this input state is given by $h(\cos^2 2\theta)$, where $h(p) = -p \log p - (1-p) \log(1-p)$ is the binary entropy (brown line). The first stage of the experiment converts this coherent into discord (blue squares). After the second stage of the experiment, the amount of coherence restored in the input photon is given by the red triangles. The discrepancy from theoretical ideals (brown line) is due to the imperfect fidelity of the CNOT gate (of approximately 0.885) employed in the conversion process. These imperfections are fully characterized by quantum process tomography (see the Supplemental Material [25]). The resulting predictions—using models that take this tomographic data into account—agree well with observed results (blue and red lines).

$\langle 1| + a^*|1\rangle\langle 0|)$ for various values of a . This involves significant modifications to the state preparation module, including the use of quartz crystals of different thicknesses to dephase an initially maximally coherent state. The resulting ρ_A is then determined through quantum state tomography [25]. The initial coherence can then be tuned from 0 to 1 by adjusting the thickness of the quartz crystal (see Fig. 2). Experimental results are illustrated in Fig. 4. The amount of discord generated and the coherence restored after running one full cycle are depicted, respectively, by blue squares and red triangles. The qualitative behavior matches that of the pure state scenario, where the amount of discord and subsequent coherence are both degraded due to experimental imperfections. Numerical simulations taking the fidelity of our CNOT gate into account agrees well with the experimental data [25].

Discussion.—Here, we illustrated a cyclic scheme where coherence initially in a quantum system A is consumed locally to synthesize an identical amount of discordant correlations with some ancilla B . These correlations are then harnessed to restore coherence in A . Under ideal conditions, this cycle is lossless, and can be repeated *ad infinitum*. We realized one round of this cycle using linear optics, showing explicitly how coherence encoded within a photonic qubit can be converted to discord between it and

FIG. 4. Discord generated and coherence restored for various mixed state inputs. Input states of various purity are generated by subjecting a pure maximally coherent input $|+\rangle$ to quartz crystals of different thicknesses, resulting in mixed states ρ_A with varying levels of initial coherence. The exact values are determined by quantum state tomography. For each crystal thickness, we plot the amount of discord successfully generate through the conversion process (blue squares) and the amount of coherence restored after one cycle (red triangle). Theoretical curves taking into account the imperfect fidelity of the CNOT gate (blue and red line) are plotted for comparison. Meanwhile, the brown line represents the amount of coherence we would have achieved in the ideal case of perfect unitary gates (this, of course, aligns with the initial coherence).

an ancilla via incoherent operations. By measurement of the ancillary photon, we restored up to 80% of the coherence within the original qubit. Our experiment corroborates growing evidence of nonclassicality in correlations and nonclassicality within singular quantum systems are closely connected.

A full understanding of these connections is still in progress. While discord and coherence are popular quantifiers of nonclassicality, there exists many other important variants. Ultimately, what constitutes a free state depends heavily on context. In continuous variable quantum optics, coherent states (not to be confused with resource theory of coherence) are generally considered to be classical as they are easily synthesized—despite being a superposition of energy eigenstates [34,35]. Meanwhile, in resource theories of quantum thermodynamics, thermal states are considered free, and anything else is a potential resource [36,37]. Current research indicates these more diverse forms of nonclassicality can also be interconverted to nonclassical correlations. For example, any state that is not a mixture of coherent states is a resource for generating entanglement using beam splitters [16,38]. Meanwhile, conditional thermal operations were recently introduced to understand how measurement of suitably correlated ancilla can generate thermal resources [39]. Could these results be unified in an overarching framework, that describes the interconversion between a general quantifier of local non-classicality and an associated form of non-classical correlations?

Another promising line of research is the role of such conversion processes in computation. Indeed, conversion of coherence to quantum correlations takes place in prominent quantum algorithms including both deterministic quantum computation with one quantum bit (DQC1) and factoring [18,40]. Meanwhile, the use of correlated resources, together with measurement feed-forward, presents a strategy for implementing otherwise difficult to synthesize gates in measurement based computation [41]. If the interconversion of various quantum resources could be related to certain operational properties of such protocols, it could suggest that operational benefits can emerge when one form of nonclassicality is transformed into another.

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