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Witnessing Quantum Resource Conversion within Deterministic Quantum Computation Using One Pure Superconducting Qubit

W. Wang,^{1,‡} J. Han,^{1,‡} B. Yadin,² Y. Ma,¹ J. Ma,¹ W. Cai,¹ Y. Xu,¹ L. Hu,¹ H. Wang,¹ Y. P. Song,¹ Mile Gu,^{3,4,5,*} and L. Sun^{1,†}

¹*Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing 100084, China*

²*Atomic and Laser Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom*

³*School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 639673, Republic of Singapore*

⁴*Complexity Institute, Nanyang Technological University, Singapore 639673, Republic of Singapore*

⁵*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Republic of Singapore*

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Deterministic quantum computation with one qubit (DQC1) is iconic in highlighting that exponential quantum speedup may be achieved with negligible entanglement. Its discovery catalyzed a heated study of general quantum resources, and various conjectures regarding their role in DQC1's performance advantage. Coherence and discord are prominent candidates, respectively, characterizing nonclassicality within localized and correlated systems. Here we realize DQC1 within a superconducting system, engineered such that the dynamics of coherence and discord can be tracked throughout its execution. We experimentally confirm that DQC1 acts as a resource converter, consuming coherence to generate discord during its operation. Our results highlight superconducting circuits as a promising platform for both realizing DQC1 and related algorithms, and experimentally characterizing resource dynamics within quantum protocols.

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Quantum technologies promise to deliver a wide range of information processing tasks from secure communication [1,2], solving classically intractable problems [3,4] to the simulation of complex systems [5–7]. The historical view held that entanglement enabled this quantum advantage, a quantum resource that plays pivotal roles in many quantum-enhanced protocols [8]. However, this picture is incomplete. For example, universal quantum computation has been shown to be achievable with little entanglement [9]. The deterministic quantum computation with one qubit (DQC1) model of computation provides another noteworthy counterpoint [10]. The protocol enables potential exponential quantum speedup in evaluating the normalized trace of unitary matrices [11,12], and its outputs are hard to sample classically [13,14], yet contains little or no entanglement. This motivated a heated search for alternative explanations regarding its source of quantum advantage [15], and catalyzed the recognition that nonclassicality comes in many forms.

Iconic among such developments was discord [16], capturing a more robust form of correlations that can persist in environments where entanglement vanishes. Quantum resources were also proposed to describe nonclassical properties to individual systems. This resulted in a framework for quantifying nonclassicality within coherent quantum superpositions [17] that has since undergone extensive study [18–33]. Meanwhile, different resources were shown to be convertible into each other, a key example being the use of coherence as a resource for generating quantum correlations [24–26,34]. The manipulation and

interplay of these resources is considered a crucial element for understanding the origin of the power of quantum protocols. Indeed, current propositions of how DQC1 gains its operation power include the build-up of discord [15] and, more recently, the conversion of coherence to quantum correlations [25].

Here we realize the DQC1 algorithm within a superconducting system with a circuit quantum electrodynamics (QED) architecture [35–37], and monitor the interplay between coherence and discord in the DQC1 model. We implement the algorithm by coherent control and quantum nondemolition (QND) projective measurements on a single pure superconducting qubit dispersively coupled to a harmonic oscillator that can potentially provide a maximally mixed state with arbitrary dimension. In particular, in our experiment the maximally mixed state with a dimension of eight is generated with repeated application of Kraus rank-2 channels in an adaptive fashion [38] and we perform full joint state tomography on the combined system to characterize the behavior of coherence and discord in the algorithm. Even in the presence of experimental imperfections, we verify that, as theoretically predicted in Ref. [25], the amount of discord generated during the computation is upper bounded by the consumption of the initial coherence of the system. Our work provides the first experimental characterization of resource conversion dynamics within DQC1, and extends previous experimental realizations of DQC1 in linear optics [39] and liquid-state nuclear magnetic resonance [40] to a new technological medium.

FIG. 1. DQC1 model. Initially the ancilla qubit is prepared in a pure ground state and the register qubits are prepared in a maximally mixed state. Coherence in the quantum system is then prepared in the ancilla qubit by a Hadamard gate and converted into discord by a controlled operation U . Measurements of $\langle\sigma_x\rangle$ and $\langle\sigma_y\rangle$ on the ancilla qubit give the real and imaginary parts of $\text{Tr}(U)/2^n$, respectively.

Coherence is taken to mean the superposition of states in some basis set $\{|i\rangle\}$ [17,41,42]. In this work, we focus on one measure: the relative entropy of coherence [17],

$$C(\rho) = S(\rho^{\text{diag}}) - S(\rho), \quad (1)$$

where $S(\cdot)$ is the von Neumann entropy and ρ^{diag} is the state obtained by removing the off-diagonal elements of ρ in the reference basis $\{|i\rangle\}$.

In a multipartite system, the quantumness of correlations between subsystems $A_1, \dots, A_n$ may be quantified with the global quantum discord $D(\rho_{A_1, \dots, A_n})$ [43]. This is defined as the excess of coherence in the global state $\rho_{A_1, \dots, A_n}$ over the local states $\rho_{A_1}, \dots, \rho_{A_n}$, minimized over all basis choices for each subsystem (see the Supplemental Material [44] for details).

The DQC1 protocol is illustrated in Fig. 1. The quantum circuit is fed with $n + 1$ qubits, consisting of one pure ancilla qubit and n maximally mixed register qubits. As noted in Ref. [25], coherence-to-discord conversion takes place in this algorithm. Specifically, coherence is initially generated in the ancilla qubit by a Hadamard gate. Then a controlled- U gate is performed to correlate the ancilla and the register qubits, and thus create discord between the ancilla and register qubits at the cost of the coherence in the ancilla qubit. Note that the control basis of the gate is taken to be the reference basis for which there is no coherence. This process is encapsulated in the following inequality:

$$D(\tilde{\rho}_{AR}) \leq \Delta C(\rho_A), \quad (2)$$

where $\tilde{\rho}_{AR}$ is the joint state of the $n + 1$ qubits after the controlled- U gate, $\Delta C(\rho_A) = C(\rho_A) - C(\tilde{\rho}_A)$ is the coherence consumption during the controlled- U gate, with ρ_A and $\tilde{\rho}_A$ the states of the ancilla qubit before and after the controlled- U gate, respectively.

We realize the DQC1 algorithm using a superconducting transmon qubit dispersively coupled to two waveguide cavity resonators [36,52–56], as shown in Fig. 2(a). The transmon qubit has an energy relaxation time $T_1 = 30 \mu\text{s}$ and a pure dephasing time $T_\phi = 120 \mu\text{s}$. One of the cavities

FIG. 2. Experimental quantum circuit to measure the conversion between coherence and quantum correlations with a DQC1 model. (a) The whole process can be divided into three parts: state preparation, DQC1 algorithm, and joint tomography measurement. The maximally mixed state $(\sum_{k=0}^7 |k\rangle\langle k|)$ of the initial registers is deterministically generated through a quantum channel construction based on QND measurements of the ancilla and adaptive control of the ancilla-register system. The $R_y^{\pi/2}$ operation to create input coherence in the DQC1 algorithm and the following $R_{x(y)}^{\pi/2}$ operations before M_1 in the joint tomography are all generated by GRAPE to compensate the extra phases corresponding to different register states due to the dispersive interaction during these gates, such that the gate operations are independent of the states of the register qubits. The controlled- U gate is realized through an appropriate ancilla-register interaction time and is used to convert coherence to discord. To characterize the ancilla-register system, joint tomography is performed by correlating the ancilla tomography and subsequent register Wigner tomography. In the joint tomography, the two $\pi/2$ rotations $R_{un,y}^{\pi/2}$ before and after the controlled π phase gate C_π are unconditional gates with a Gaussian envelope of $\sigma = 5$ ns. (b) Real part of the reconstructed density matrix (truncated to maximum photon number state $N_{\text{max}} = 9$) of the initial register qubits with a fidelity of 0.977.

(storage cavity) has a long photon lifetime of $\tau_s = 143 \mu\text{s}$. The Fock states in this storage cavity (composing the register qubits) and the transmon qubit (as the ancilla) constitute the bipartite parts of the DQC1 circuit [16]. The other short-lived cavity with a photon lifetime $\tau_r = 44$ ns is used to readout the ancilla qubit. High fidelity and QND single-shot measurements of the ancilla can be achieved with the help of a phase-sensitive Josephson bifurcation amplifier [57–60]. Each readout measurement throughout our experiment returns a digitized value of the qubit state. The experimental apparatus and readout properties are similar to earlier reports in Refs. [61] and [62].

The ancilla qubit and storage cavity are well described by the dispersive Hamiltonian (omitting small high-order nonlinearities)

$$H/\hbar = \omega_s a^\dagger a + \omega_a |e\rangle\langle e| - \chi a^\dagger a |e\rangle\langle e|, \quad (3)$$

where $a^\dagger(a)$ is the creation (annihilation) operator of the storage cavity, $|e\rangle$ is the excited state of the ancilla qubit, and $\chi/2\pi = 1.90$ MHz is the dispersive interaction strength between the qubit and the storage cavity. This strong dispersive coupling gives rise to the ancilla-register entangling operation, allowing for the controlled- U operation in the DQC1 algorithm. The readout cavity has been neglected since it remains in vacuum unless a measurement is performed.

Harmonic oscillators play important roles in quantum information processing [61,63–66] largely due to their infinite dimension and long coherence times. Here we take advantage of these characteristics to use multiple excitations of a harmonic cavity oscillator as register qubit states. In our experiment, we choose the lowest eight Fock states $\{|0\rangle, |1\rangle, \dots, |7\rangle\}$ in the cavity field whose computational space is equivalent to that of three register qubits, namely, $\{|000\rangle, |001\rangle, \dots, |111\rangle\}$, respectively. This gives the DQC1 model in our experiment with $n = 3$ register qubits.

Our experimental sequence is depicted in Fig. 2(a). The whole process can be divided into three parts: state preparation, DQC1 algorithm, and joint tomography measurement. The state preparation starts with a pure ancilla qubit ground state $|g\rangle\langle g|$ by postselection. The maximally mixed state as required by the DQC1 model is deterministically generated through a quantum channel construction based on QND measurements of the ancilla and adaptive control of the ancilla-register system [38]. All the adaptive control pulses are numerically calculated with the Gradient Ascent Pulse Engineering (GRAPE) method [50,51] and the generated maximally mixed state has a fidelity of 0.977, whose reconstructed density matrix based on the measured Wigner function is shown in Fig. 2(b). The state fidelity is defined as $F(\rho_{\text{exp}}, \rho_{\text{ideal}}) = \text{tr} \sqrt{\sqrt{\rho_{\text{ideal}}} \rho_{\text{exp}} \sqrt{\rho_{\text{ideal}}}}$. The protocol for the realization of the maximally mixed state is shown in Ref. [44]. Note that the register qubits do not contribute any coherence to the combined system.

In the following DQC1 algorithm, coherence preparation is performed by an ancilla qubit operation $R_y^{\pi/2}$ corresponding to a $\pi/2$ rotation around the y axis on the Bloch sphere, having the same action here as a Hadamard gate. Note that this $R_y^{\pi/2}$ operation and the following $R_{x(y)}^{\pi/2}$ operations before M_1 in the joint tomography are also generated by GRAPE to compensate for the extra phases during these “Hadamard” gates, such that the gate operations are independent of the states of the register qubits (see Ref. [44]). Consequently, the system is prepared in a product state $\rho_{AR} = (|g\rangle + |e\rangle)(\langle g| + \langle e|) \otimes \sum_{k=0}^7 |k\rangle\langle k|$ (ignoring normalization). A conditional cavity phase shift

$C_\varphi = |g\rangle\langle g| \otimes \mathbf{1} + |e\rangle\langle e| \otimes e^{i\varphi a^\dagger a}$ is the mechanism of the controlled- U gate, where $\varphi = \chi t$ is acquired from the free evolution of the dispersive Hamiltonian Eq. (3) for a time interval t . As a result, the controlled- U gate can be described as $|g\rangle\langle g| \otimes \mathbf{1} + |e\rangle\langle e| \otimes U$, where

$$U = \begin{pmatrix} 1 & 0 & \dots & 0 \\ 0 & e^{i\varphi} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & e^{i7\varphi} \end{pmatrix} \quad (4)$$

in the computational Hilbert space. Note that in the Fock state basis, the controlled U is an incoherent operation. After the controlled- U gate, the system evolves to $\tilde{\rho}_{AR}$.

To observe the bipartite system, we finally perform a joint measurement of the coupled ancilla-register system with two sequential QND measurements of the ancilla qubit and the register qubits, following a technique similar to that previously demonstrated in Ref. [67]. As shown in Fig. 2(a), the ancilla qubit detections along one of the three basis vectors X , Y , and Z are first performed with or without an appropriate prerotation $R_{x(y)}^{\pi/2}$ followed by a z -basis measurement M_1 . These measurements alone can give a full tomography of the ancilla. Then a Wigner tomography of the register qubit is performed by measuring the cavity observable $P(\beta)$ which is a combination of the cavity’s displacement operation $D_{-\beta}$ and a parity measurement P of the cavity. The parity measurement is realized in a Ramsey-type experiment of the ancilla qubit, where a conditional cavity π phase shift C_π is sandwiched in between two unconditional qubit rotations $R_{un,y}^{\pi/2}$ (a Gaussian envelope with $\sigma = 5$ ns) followed by another z -basis measurement M_2 [53,54,68,69]. After the qubit tomography measurement M_1 , the qubit is at a specific known state and the correlation of M_1 and M_2 determines the parity of the register. Multiplication of the ancilla qubit detection σ_i (in the qubit Pauli set $\{I, X, Y, Z\}$) and the register Wigner tomography $W(\beta) = (2/\pi)\langle P(\beta) \rangle$ shot by shot gives the joint Wigner function [67], defined as

$$W_i(\beta) = \frac{2}{\pi} \langle \sigma_i P(\beta) \rangle. \quad (5)$$

The joint Wigner functions are a complete representation of the combined ancilla-register quantum system. From these functions we reconstruct the combined ancilla-register density matrix $\tilde{\rho}_{AR}$ in a 16-dimensional Hilbert space by a least squares regression using maximum likelihood estimation with the only constraints that the reconstructed density matrix is positive semidefinite with trace equal to 1 [67,70]. Based on the obtained density matrix $\tilde{\rho}_{AR}$, we can derive the remaining coherence $C(\tilde{\rho}_A)$ and the created

FIG. 3. DQC1 algorithm output. The real and imaginary parts of the normalized trace $\text{Tr}(U)/8$ are measured for different φ . All data (points) are averaged with over 10^7 measurements and error bars correspond to 1 standard deviation. The solid lines show theoretical expectations. Crosses present the simulated results including all decoherence channels. Experimental results agree well with both theory and simulation even with the presence of decoherence processes from both ancilla and register qubits.

discord $D(\tilde{\rho}_{AR})$ [44], where $\tilde{\rho}_A$ is the partial trace of $\tilde{\rho}_{AR}$ over the registers.

The initial coherence is generated by the ancilla qubit operation $R_y^{\pi/2}$ and is first characterized to be $C(\rho_A) = 0.894$ by a qubit tomography immediately after this coherent operation, while the ancilla qubit state fidelity is 0.993 (see Ref. [44]). The reduction is mainly due to a qubit decay process during the tomography measurement and the imperfection of $R_y^{\pi/2}$ in the presence of the maximally mixed state. This initial coherence built in the ancilla state is then to be consumed in order to correlate the ancilla and the register qubits, and thus is used as a reference for the coherence consumption. We next show the results after applying the controlled- U gate in the DQC1 model. The normalized trace of U is encoded in the ancilla qubit and can be recovered from the result of M_1 , as shown in Fig. 3. Although there are decoherence processes with both ancilla and register qubits, the experimental results (dots) agree well with the exact theoretical expectation (lines) and the numerical simulation (crosses) that involves all imperfection channels, suggesting the robustness of the protocol.

We finally show in Fig. 4 the coherence consumption $\Delta C(\rho_A)$ and discord production $D(\tilde{\rho}_{AR})$ in the DQC1 model as a function of phase φ in the controlled- U gate which varies over the range $0 \leq \varphi \leq 2\pi$. Theoretical expectations of $\Delta C(\rho_A)$ and $D(\tilde{\rho}_{AR})$ for an ideal system without any decoherence are shown as solid lines for comparison. Both curves are symmetric around $\varphi = \pi$. At $\varphi = \pi$, the controlled- U gate is expected to transform the qubit-register system into a classically correlated state without any discord. At $\varphi = \pi/2, \pi, 3\pi/2$, after tracing out the register state the ancilla qubit is in a maximally mixed state. In these cases, the original coherence is completely consumed by the controlled- U operation. The gap between the expected solid lines means that, even theoretically,

FIG. 4. The coherence consumption $\Delta C(\rho_A)$ and discord production $D(\tilde{\rho}_{AR})$ as a function of phase φ in the DQC1 model. (a) Theoretical expectations are shown with solid lines. Dots give the experimental results. In the experiment, each point in the joint Wigner functions has been averaged over 3000 single-shot joint ancilla and register measurements, and the standard deviation in $\Delta C(\rho_A)$ and $D(\tilde{\rho}_{AR})$ are estimated by bootstrapping on the measured joint Wigner functions [67]. Crosses present the simulated data including all decoherence channels with both the ancilla and register qubits. The measured $\Delta C(\rho_A)$ agrees fairly well with the theoretical one with a small gap at the middle plateau. This gap comes from the imperfect generation and measurement of the initial coherence $C(\rho_A) = 0.894$ while the ancilla state fidelity is 0.993 to the ideal state $(|g\rangle + |e\rangle)/\sqrt{2}$ after the $R_y^{\pi/2}$ operation. The measured produced discord agrees extremely well with the theoretical expectation, captures all the important features as in the theoretical curve and is unambiguously lower than $\Delta C(\rho_A)$ as expected. (b) The fidelity of the measured $\tilde{\rho}_{AR}$ compared to the ideal ones with an average of 0.96.

coherence cannot be fully converted to discord. The non-monotonic oscillations in the theoretical curves are not fully understood yet and need further investigation.

The experimental results for both $\Delta C(\rho_A)$ and $D(\tilde{\rho}_{AR})$ are depicted as dots and are indeed quite symmetric around $\varphi = \pi$, and capture all the important features in the theoretical curves. The measured coherence consumption agrees fairly well with theory. The small gap at the middle plateau comes from the imperfect generation and measurement of the initial coherence $C(\rho_A) = 0.894$. The measured produced discord agrees extremely well with the theoretical expectation. All measured $D(\tilde{\rho}_{AR})$ are indeed significantly lower than the measured $\Delta C(\rho_A)$, successfully demonstrating Eq. (2). Figure 4(b) shows the state fidelity of the ancilla-register system at each φ based on the measured $\tilde{\rho}_{AR}$. All fidelities are above 0.92,

demonstrating the good control of our system throughout the process.

We note that in Eq. (3) the higher order corrections to the dispersive term, such as $(\chi'/2)a^\dagger a^\dagger aa|e\rangle\langle e|$ (χ' is typically more than 2 orders of magnitude smaller than χ), have been ignored because of their small contribution to φ compared to the dispersive term in the small photon number limit. However, these higher order nonlinear terms in principle allow for generating arbitrary controlled U by repeated applications of appropriate cavity displacements followed by appropriate waiting, provided the system has enough coherence [71–74].

In summary, we have experimentally demonstrated and quantified quantum resource conversion in the DQC1 model. We show that coherence is converted into the quantum discord that is considered as the resource in DQC1 [15]. The produced discord is unambiguously demonstrated to be lower than the coherence consumption. This experiment reveals the potential of superconducting circuits as a versatile platform for investigating and even deepening our understanding of resource dynamics in quantum information.

A natural extension of the present work is to chain multiple DQC1 circuits together. Provided the register qubits are not reset between iterations, the resulting circuit enables a variant of Shor’s algorithm [75,76]. Here, each iteration converts an additional bit of coherence into quantum correlations, enabling study of resource conversion dynamics within the iconic quantum factoring protocol. Our architecture is also suitable for the “power of one pure qumode” protocol—in which the control qubit in DQC1 is replaced with a continuous variable mode to form a hybrid model of computation that combines discrete and continuous variables [77]. Its realization could enable hybrid factoring algorithms, and aid the study of how continuous and discrete notions of nonclassicality interact. Each of these developments would provide a promising experimental platform for studying quantum resource dynamics within more complex settings.

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*mgu@quantumcomplexity.org

†luyansun@tsinghua.edu.cn

‡W. W. and J. H. contributed equally to this work.

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