Verification of a resetting protocol for an uncontrolled superconducting qubit

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(Dated: 2nd December 2019)

We experimentally verify the simplest non-trivial case of a quantum resetting protocol with five superconducting qubits, testing it with different types of free evolutions and target-probe interactions. After post-selection, we obtained a reset state fidelity as high as 0.951, and the process fidelity was found to be 0.792. We also implemented 100 randomly-chosen interactions and demonstrated an average success probability of 0.323, experimentally confirmed the non-zeros probability of success for unknown interactions; the numerical simulated value is 0.384. We anticipate this protocol will have widespread applications in quantum information processing science, since it is able to combat any form of free evolution.

Removing an unwanted free evolution of a quantum system is a key technical challenge in fields of quantum information processing science like quantum error correction[1], quantum metrology[2], quantum memory[3], and quantum communication[4]. Efforts to address this challenge such as spin echo[9] and dynamical decoupling[6–9] have been well investigated, but these refocusing techniques need prior knowledge of the decoherence channels to construct effective control pulses. Recently, a new protocol has been published which can probabilistically reset a target quantum system of arbitrary dimension to a state in its past by making external probing systems interact with unknown dynamics after an unknown time-independent evolution of the target [10]. The power of this quantum resetting protocol is that, unlike the previous refocusing techniques, it can reset an uncontrolled system, thus making it able to combat any form of free evolution.

In this letter, we tested the simplest non-trivial quantum resetting protocol: a 2D quantum system interacting with four 2D probes, known as the \( V_4 \) protocol [10]. Fig. 1A represents the protocol schematically. After being set to an initial state, the target qubit interacts with each of the four probes, which form two pairs of entangled states. Then, measurement of the probes affects the target qubit, sending it back to its initial state with a given probability.

The general gate sequence of the quantum circuit used to implement the five-qubit protocol is pictured in Fig. 1B. We divide the circuit into four parts: state preparation, free evolution, interaction and tomographic readout. Before the circuit begins, all qubits are initialized in the state \( \lvert 0 \rangle \). During state preparation, the gate \( G_1 \) is applied to the target qubit to bring it to \( \lvert \psi(0) \rangle \), and each pair of neighboring probes is set to the singlet state \( \lvert \Psi^- \rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}} \). After state preparation, we apply the gate \( R \), which simulates the free evolution with Hamiltonian \( H_0 = \sum_{j=x,y,z}^3 h_j \sigma_j \), where \{\sigma_j\} are the Pauli operators and \( h_j \) is the coupling strength on the \( j \)-axis. After the first \( R \) gate is applied to the target, the first probe interacts with the target via a bipartite unitary operator \( U \), which varies according to the experimental case. This process of free evolution followed by target-probe interaction is repeated three more times on the target and different probes. Once the interaction process is complete, a five-qubit state tomography is performed to obtain the final state with density matrix \( \rho_f \). A successful reset has occurred in the portion of the state that overlaps with the success subspace spanned by the following six vectors \( S \).

\[
S = \left\{ \lvert 0000 \rangle, \lvert 1111 \rangle, \frac{1}{\sqrt{2}} (\lvert 0111 \rangle + \lvert 1100 \rangle), \right. \\
\left. \frac{1}{2} (\lvert 1000 \rangle + \lvert 0100 \rangle + \lvert 0010 \rangle + \lvert 0001 \rangle), \right. \\
\left. \frac{1}{2} (\lvert 0111 \rangle + \lvert 1011 \rangle + \lvert 1101 \rangle + \lvert 1110 \rangle), \right. \\
\left. \frac{1}{2} (\lvert 1010 \rangle + \lvert 0101 \rangle + \lvert 0011 \rangle + \lvert 0110 \rangle) \right\}
\]

Projecting the probe subspace onto this success subspace post-selects for a successful reset. The trace overlap between the measured state and the post-selected state is defined as the success probability, \( P_s = \text{Tr}(\rho_f \rho_{ps}) \), where \( \rho_{ps} \) is the density matrix of the post-selected state. The reset state of the target qubit can be extracted from the post-selected state by tracing out the probes[11], \( \rho = \text{Tr}_{\text{probes}}(\rho_{ps}) \), where \( \rho \) is the density matrix of the reset state. Once the reset state has been obtained, we also evaluate the quality of the reset state. The reset state fidelity is defined as the trace overlap between the reset state and the initial state of the target qubit, \( \mathcal{F} = \text{Tr}(\rho \lvert \psi(0) \rangle \langle \psi(0) \rvert) \). Note that for the deterministic cases of our experiment, success subspace is reduced to the space spanned by the first three vectors in \( S \).

This protocol lies on the vanguard of what is currently experimentally feasible. Even for protocols with five qubits, cor-

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rectly performing a quantum resetting protocol requires extremely high quality single- and double-qubit gates to model all possible interactions and free evolutions that make up the protocol. Quantum processors with superconducting qubits, which have undergone great progress over recent years, have reached a level of technical achievement that makes it possible to implement the long sequences of arbitrary operations in a multi-qubit system [1, 4, 6, 13–25, 27]. However, increasing the depth of circuits remains a significant challenge. Through extensive calibration and optimization of our system, we were able to successfully implement quantum circuits with up to 47 layers, 35 of which contained totally 119 single-qubit gates and the rest contained 12 entangling gates. The detail of the 47-layer circuits is shown in the Supplementary Material. Our results push the limits of the depth of superconducting quantum circuits.

Table 1: Table of different experimental cases. The initial state of the target qubit is $|\psi(0)\rangle$; $\mathcal{H}_0$ is the free-evolution Hamiltonian; $U$ is the target-probe interaction operator. Case 1a, 1b, and 1c (Fig. 2) test deterministic unitaries. Case 2 (Fig. 3) tests six different initial states and uses four of them to perform quantum process tomography. Case 3 (Fig. 4) tests random target-probe interactions.

| Case | $|\psi(0)\rangle$ | $\mathcal{H}_0$ | $U$ |
|------|-----------------|----------------|-----|
| 1a   | $|\bar{\psi}\rangle$ | $(X \otimes Z + iY \otimes X)/\sqrt{2}$ |
| 1b   | $|\psi\rangle$ | $(X \otimes Z + iY \otimes X)/\sqrt{2}$ |
| 1c   | $\sum_i p_i |i\rangle \langle i|$, $\text{Tr}(\rho^2) < 1$ | $h_x\sigma_x$ | $(X \otimes Z + iY \otimes X)/\sqrt{2}$ |
| 2    | $|0\rangle, |1\rangle, |\pm\rangle, |\mp\rangle$ | $I$ | $(X \otimes Z + iY \otimes X)/\sqrt{2}$ |
| 3    | $|1\rangle$ | $I$ | Random |

To verify the $\mathcal{W}_4$ protocol, we performed different variations of the resetting experiments, which we divide into three cases (Table 1). Case 1 (Fig. 2) tested interactions with a theoretical success probability of 1, i.e. deterministic interactions, varying the initial target states and free evolutions. Case 2 (Fig. 3) fully characterized the resetting process with...
Figure 2: **Resetting the target qubit after a free evolution.** Red dots mark the state before and after a successful reset. Blue dots mark a free evolution without resetting for comparison. Bloch spheres also mark the red and blue dots and show the state during three important phases of the resetting protocol: After state preparation (A, E, I), after free evolution (B, F, J), and after resetting (C, G, K). From top to bottom, each row shows a different version of the resetting protocol in case 1, demonstrated the resetting process for a superposition state $|{-}\rangle$, a classical state $|1\rangle$, and a mixed state, respectively. In D, H, and L, the state fidelities after the application of resetting protocol are observed jumping from 0.690(5), 0.679(5), and 0.662(2), to 0.809(4), 0.764(3), and 0.783(3), respectively. The green and blue phases correspond to the free evolution and interaction process in Fig. 1(B). The uncertainties are estimated via bootstrapping.

For case 1, we experimentally proved that the protocol can successfully reset the target with high fidelity using theoretically predicted deterministic unitaries. The success probabilities are not as high as theoretical prediction: for case 1a, we obtained $P_s = 0.544$. The results for case 1b and 1c are similar (see SM). We attribute this difference to the fidelity of the measured 5-qubit state, which was found to be 0.399 in comparison with an ideal state. Actually, considering the length of these circuits—for case 1a 39 layers in total, including 12 entangling-gates layers and 27 single-qubit-gate layers—these results push the limits of superconducting quantum processor technology. In context of these long quantum circuits, state fidelities of reset target, as shown in Fig. 2D, H, L, in the range of 0.76 − 0.81 really stand out. As the ability to implement long circuits increases, it will be possible to combine these types of protocols with other meaningful operations.

Once we confirmed that the protocol can reset the target qubit, we decided to characterize the resetting process more closely. Setting $R = I$ and $U = (X \otimes Z + iY \otimes X)/\sqrt{2}$, we initialized the target qubit to the six axes of the Bloch sphere $\varphi = 3\pi/8$, in which all fidelities of the reset states can be seen jumping above those without resetting. More results verifying the protocol for other rotation angles are listed in SM.
Figure 3: **Quantum state and process tomography of a successful reset.** The free-evolution Hamiltonian is $I$, and the deterministic interaction is $U = (X \otimes Z + iY \otimes X)/\sqrt{2}$. **A-F.** The density matrices of target qubit after resetting with initialization to each axis of the Bloch sphere: Alphabetically, $|0\rangle$, $|1\rangle$, $|+\rangle$, $|i\rangle$, $|-\rangle$ and $|-i\rangle$. The corresponding fidelities are 0.946(1), 0.951(1), 0.840(2), 0.815(2), 0.823(2), and 0.829(2), respectively. **G.** The process tomography of the resetting protocol determined from **A-D.** The process fidelity is 0.792(4). Solid lines correspond to ideal density matrices $\rho$ and the ideal $\chi_i$ matrix. The uncertainties are estimated via bootstrapping.

and performed quantum process tomography. The density matrices $\rho$ of the reset target obtained with state tomography has significant variations in fidelity depending on the initialization (**Figure 3A-F**). The states $|0\rangle$ and $|1\rangle$ are not sensitive to dephasing, and have higher reset fidelities – close to 0.95. But the four other initializations are located on the equator of the Bloch sphere, so they are sensitive to dephasing and accordingly, have lower fidelities, ranging from 0.81 – 0.84. These different initialization are important because they can be used to fully characterize the resetting process. By combining final states $|0\rangle$, $|1\rangle$, $|+\rangle$ and $|i\rangle$, we can obtain the $\chi$ matrix (**Fig. 3G**) with quantum process tomography[11]. We define the process fidelity as the trace overlap between the ideal process $\chi_i$, which only contains the identity operation $I$, and the measured $\chi$, as $F_\chi = Tr(\chi_i\chi)$, and is determined to be above 0.79. The comparison between the reset fidelities of phase-sensitive and phase-insensitive initial states shows the important role dephasing plays in our experiment, leaving room for further improvement.

The most remarkable advantage of this resetting protocol is that the interaction need not to be controlled or known. Our interpretation of the word ‘known’ simply means that the in-
teraction dynamics can not be adjusted according to the free evolution of the target system. To simulate these sorts of situations, we investigate the effects of random target-probe interactions. Specifically, we tested the success probability of random unitaries ($U_r$), generated by rotating the target qubit and its interaction probe before and after a $CZ$ gate (Fig. 1D). Each random rotation is implemented as a sequence of $R_x(\alpha_i)$, $R_y(\beta_i)$, and $R_z(\gamma_i)$ gates, with angles $\alpha_i$, $\beta_i$, and $\gamma_i$ all chosen randomly. As shown in Table I case 3, we set $|\psi(0)\rangle = |1\rangle$ and $R = I$, and tested 100 different random unitaries. To compare the experimental and theoretical results, we numerically simulated the circuit with ideal quantum gates. Experimental success probabilities for the random unitaries are in good agreement with numerical simulation (Fig. 4). When the results for the random unitaries are combined, the cumulative average of success probability converges towards 0.323, which is close to the simulated value of 0.384. The average reset state fidelity is 0.684. We attribute the low fidelities and the discrepancy between the experimental and simulated values mainly to gate errors and decoherence from energy relaxation and dephasing. Similar to our other results, we expect these blemishes to become less pronounced as the quality of quantum processors is improved.

We have successfully verified the quantum resetting protocol for known and unknown interactions. Even when the interactions are not known, we still have an average success probability of 0.323. This probability can be significantly improved by an ‘undoing failure’ protocol presented by Navascués[10]. Upon failure, it is possible to send more probes to interact with the target, and measure the new probes for another chance of a successful reset. Although practical difficulties in implementing additional layers of circuit to correct failed resets may outweigh the potential benefits, since the ‘undoing failure’ protocol may not increase the fidelity of the reset state.

Another result of Navascués [10], is that the resetting protocol can reset a target system of any dimension. In a photonic system, our colleagues have demonstrated that a qubit can be reset to its past entangled state[29], and also here we showed that a mixed state can be reset, giving the experimental verification that the protocol can work on a target qubit which is a part of higher-dimensional systems. Given the speed of progress with superconducting processors, it is expected that the realization of resetting higher-dimensional systems is achievable in the near term, opening the door for applications in quantum memory[3]. It is also possible that higher-dimensional versions of the resetting protocol will be useful in quantum error correction[1]. But the result of Navascués only proved the existence of higher-dimensional protocols, and provided some heuristic methods for finding deterministic unitaries. Theoretical tools for easily finding deterministic interactions in higher dimensions are urgently needed. We expect that theoretical and experimental development of this protocol will have great potential to advance many areas of quantum information processing.

The authors thank the USTC Center for Micro- and Nanoscale Research and Fabrication, Institute of Physics CAS and National Center for Nanoscience and Technology for supporting the sample fabrication. The authors also thank QuantumCTek Co., Ltd. for supporting the fabrication and the maintenance of room temperature electronics. This research was supported by the National Key Research and Development Program of China (Grants No. 2017YFA0304300, No. 2018YFA0306703), the Chinese Academy of Sciences, and Science and Technology Committee of Shanghai Municipality (Grants No. 16DZ2260100). This research was also supported by NSFC (Grants No. 11574380, No. 11905217) and Anhui Initiative in Quantum Information Technologies.

Figure 4: Success probability of random unitaries. The random unitaries are realized as $U_r$ shown in Fig. 1(d), where 12 random single-qubit gates are applied before and after a $CZ$ gate. As shown in case 3 of Table. I, the prepared initial state of the target qubit is $|1\rangle$, and the free-evolution Hamiltonian is $I$. Experimental results are shown in blue; simulated values are in brown. The numerical simulations are realized by direct product of the circuits with standard quantum gates, thus neither gate error nor decoherence effect are considered, corresponding to ideal processes. We leave the results with the target qubit prepared in $|-\rangle$ state in Supplementary Materials. A. Success probabilities for each of the 100 random unitaries tested in the experiment. B. Cumulative average of success probabilities, showing convergence to 0.323 in experiment and 0.384 in simulation.

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I. PERFORMANCE OF QUBITS

The superconducting processor used in this work is a 12 qubits processor[1]. We chose five adjacent qubits to perform the present experiment. Table. S1 shows the performance of the qubits in our experiment.

| Qubit | $f_0$ (GHz) | $\eta$ (MHz) | $T_1$ (\mu s) | $T_2^*$ (\mu s) | Readout Fidelity (%) | X/2 gate fidelity (%) | CZ gate fidelity (%) |
|-------|-------------|--------------|--------------|----------------|---------------------|---------------------|---------------------|
|       | 4.901       | -246.9       | 47.9         | 4.6            | 87.1                | 99.93               | 98.7               |
|       | 4.227       | -201.5       | 41.3         | 3.2            | 79.2                | 99.86               | 98.1               |
|       | 4.998       | -245.8       | 35.8         | 5.4            | 84.2                | 99.86               | 98.2               |
|       | 4.119       | -203.0       | 48.2         | 2.5            | 80.4                | 99.85               | 96.1               |
|       | 4.870       | -243.5       | 36.9         | 2.9            | 88.8                | 99.92               | 98.2               |
|       | -          | -            | 42.0         | 3.7            | 83.9                | 99.88               | 98.3               |

Table S1: Performance of qubits. $f_0$ is working points of the qubits. $\eta$ is the anharmonicity. $T_1$ is the energy relaxation time. $T_2^*$ is the dephasing time determined from Ramsey fringe experiment. Readout Fidelity is the possibility of error in readout of qubit state. X/2 gate fidelity and CZ gate fidelity are single- and two-qubit gate fidelity determined with randomized benchmarking (RB).

II. MORE DETAILS IN CASE 1 OF THE MAIN TEXT

In Table S2 we presented the detailed data in three subcases, i.e., case 1a, 1b, and 1c. Fore case 1a, 8 rotation angles are tested and all reset-state fidelities are above 0.80. In case 1b, 4 rotation angles are tested, and the reset-state fidelities are above 0.73. We note that the difference in reset-state fidelity between case 1a and 1b mostly comes from the depth. The interaction unitary between case 1a and 1b are different, thus the final circuits to perform the tests have different depths. In case 1b, 8 more single-qubit-gate layers are applied, introducing more gate errors and decoherence effect. In case 1c, the target is initialized in $|\psi\rangle$ and decohered for $1\mu s$ before the other parts of state preparation. Before the application of free evolution, the fidelity of the target is measured to be around 0.90, indicating that the initial state has already been a mixed state. In this subcase, we measure 4 different rotation angles and obtained the reset-state fidelities above 0.77.

III. RANDOM UNITARIES WITH TARGET PREPARED IN $|\psi\rangle$

In the main text, we present the resetting protocol with random unitaries in case 3. The target is prepared in a classical state $|\psi\rangle$, and the probabilities with the target successfully reset to its original state is determined. Here we present another similar test. The only difference is that the target is prepared in state $|\psi\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$, a superposition state. As shown in Fig. S1, we measured 100 success probabilities with the interaction randomly chosen as in Fig. 1D in main text. We compared the experimental success probabilities with the numerically simulated results, finding out a similar pattern in it. The cumulative average of the 100 success probabilities is 0.292, close to the simulated value 0.304. The difference of the cumulative average between different target states comes from the limited number of random unitaries.

IV. GATE IMPLEMENTATION

Only single-qubit gates and controlled-phase (CZ) gates are used in our experiment. Single-qubit gates are implemented as microwave pulses. We realize CZ gates by implementing DC wave sequences on two neighbouring qubits to tune the $|11\rangle$ state close to the avoided crossing generated by the states $|11\rangle$ and $|02\rangle$ following a “fast adiabatic” trajectory [2–5].

CZ gates can only be implemented on neighbouring qubits, so to generate interactions between distant qubits, a SWAP gate is required. For example, to generate an interaction between $Q_1$ and $Q_3$, we first apply $U$ between $Q_2$ and $Q_3$ and then apply a SWAP gate between $Q_2$ and $Q_1$. Likewise with $Q_2$ and $Q_3$. The SWAP gate is realized by combining single-qubit gates and CZ gates as $SWAP = (I \otimes -\mathbf{Y}/2)CZ(-\mathbf{Y}/2 \otimes \mathbf{Y}/2)CZ(Y/2 \otimes -\mathbf{Y}/2)CZ(I \otimes \mathbf{Y}/2)$ [4], where $\mathbf{Y}/2$ is $R_y(\pi/2)$ ($R_y(-\pi/2)$), representing the rotation by an angle $\pi/2$ ($-\pi/2$) about the y axis.

The total depth of the sequences for the implementation of case 1a and 2 in the main text is 39, including 12 double-qubit-gate layers and 27 single-qubit-gate layers. For case 1b and case 3 in the main text, the total depths are 47, both including 12 double-qubit-gate layers and 35 single-qubit-gate layers. An example of the gate sequences for case 3 is shown in Fig. S2.
| Initial target state | Initial state fidelity | Circuit depth | $U$ | $R$ | $\varphi/\pi$ | Reset state fidelity | Success probability |
|----------------------|-----------------------|---------------|-----|-----|----------------|---------------------|-------------------|
| $|\rightarrow\rangle$ | 0.998(4) | 27 (single-qubit) 12 (double-qubit) | $X\otimes Z + iY \otimes X$ | $R_z(\varphi)$ | 1/16 | 0.845(4) | 0.518(3) |
|                      |          |               | $\sqrt{2}$ | | 2/16 | 0.844(4) | 0.525(3) |
|                      |          |               |               | | 3/16 | 0.845(3) | 0.527(4) |
|                      |          |               |               | | 4/16 | 0.834(2) | 0.520(4) |
|                      |          |               |               | | 5/16 | 0.805(4) | 0.534(3) |
|                      |          |               |               | | 6/16 | 0.809(4) | 0.544(4) |
|                      |          |               |               | | 7/16 | 0.835(2) | 0.557(5) |
|                      |          |               |               | | 8/16 | 0.837(2) | 0.544(4) |
| $|1\rangle$ | 0.988(1) | 35 (single-qubit) 12 (double-qubit) | $-Z\otimes Z + iY \otimes X$ | $R_x(\varphi)$ | 5/16 | 0.760(4) | 0.455(3) |
|                      |          |               | $\sqrt{2}$ | | 6/16 | 0.764(3) | 0.467(3) |
|                      |          |               |               | | 7/16 | 0.759(4) | 0.442(3) |
|                      |          |               |               | | 8/16 | 0.739(4) | 0.451(3) |
| $\sum_i p_i |i\rangle \langle i|, \rho^2 < 1$ | 0.907(2) | 29 (single-qubit) 12 (double-qubit) | $X\otimes Z + iY \otimes X$ | $R_z(\varphi)$ | 5/16 | 0.778(3) | 0.453(3) |
|                      |          |               | $\sqrt{2}$ | | 6/16 | 0.783(3) | 0.458(3) |
|                      |          |               |               | | 7/16 | 0.7983(3) | 0.449(3) |
|                      |          |               |               | | 8/16 | 0.793(3) | 0.451(4) |

Table S2: Detailed data in case 1 in the main text. Three parts from top to bottom correspond to case 1a, 1b, and 1c, respectively. The uncertainties are estimated via bootstrapping.

V. GATE OPTIMIZATION

Calibrations and optimizations is a necessary step to successfully realize the theoretical circuits. Cross-talk on the Z control line [6] is a source of error that needs to be firstly addressed. When CZ gate is applied, because of the 1% – 2% Z cross-talk, it induces a frequency shift on other qubits, and leads unwanted dynamical phases. We correct these phase shifts by adding corresponding phase gates to each of them. Meanwhile, CZ gates must be applied in while all other qubits are idling. Secondly, due to the finite bandwidth and imperfection of the impedance matching in the route from the DAC channels to the qubit control lines, there is a pulse distortion after an applied pulse [5–8]. We use the deconvolution method to correct this kind of pulse distortion[6, 8]. Last, to mitigate the effects of dephasing, which produce more errors than energy relaxation in our experiment, we apply Hahn spin echoes [4, 9–12] to idling elements of the circuit.

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Figure S1: **Success resetting probabilities with 100 random unitaries.** The qubit is initialized in $|\cdash\rangle$ state. A. Direct comparison of experimentally determined and theoretically simulated success resetting probabilities. The simulation is performed by gate model without consideration of neither gate error nor decoherence effect. B. Cumulative average of success probability. The experimentally determined cumulative average for 100 random unitaries is 0.292, while the simulated value is 0.304.

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Figure S2: Gate sequences for the test of random unitaries. The total depth is 47, including 12 double-qubit gates and 119 single-qubit gates.