

Hardware-efficient stabilization of entanglement via engineered dissipation in superconducting circuits

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Generation and preservation of quantum entanglement are among the primary tasks in quantum information processing. State stabilization via quantum bath engineering offers a resource-efficient approach to achieve this objective. However, current methods for engineering dissipative channels to stabilize target entangled states often require specialized hardware designs, complicating experimental realization and hindering their compatibility with scalable quantum computation architectures. In this work, we propose and experimentally demonstrate a stabilization protocol readily implementable in the mainstream integrated superconducting quantum circuits. The approach utilizes a Raman process involving a resonant (or nearly resonant) superconducting qubit array and the qubits' dedicated readout resonators to effectively develop nonlocal dissipative channels. Leveraging individual controllability of the qubits and resonators, the protocol stabilizes two-qubit Bell states with a fidelity of 90.7%, marking the highest reported value in solid-state platforms to date. Furthermore, by extending this strategy to include three qubits, an entangled W state is achieved with a fidelity of 86.2%. This demonstrates the protocol's extensibility beyond two-qubit systems. Notably, the protocol is of practical interest since it only utilizes existing hardware common to standard operations in the underlying superconducting circuits, thereby facilitating the exploration of many-body quantum entanglement with dissipative resources.

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Quantum state preparation is typically achieved through coherent unitary operations [1]. However, realistic quantum systems interact with the environment, resulting in decoherence that degrades their quantumness [2–4]. Although decoherence is typically seen as an obstacle to quantum information processing (QIP), it can, if controllable, offer distinct benefits over unitary-only circuits. For example, quantum bath engineering [5] has been shown to enable efficient processing with applications in stabilized state preparation [6–9], quantum error correction (QEC) [10–12], and dissipation-assisted phase transition [13–16]. Consequently, bath engineering has evolved into a fruitful research field, encompassing appli-

cations such as cooling various quantum systems [17–20] and entanglement stabilization in both trapped ions [6,21,22] and superconducting circuits [23–25]. This nonunitary technique for state stabilization is appealing because it directs a driven-dissipative system toward steady states of interest by engineering dissipative channels, making it insensitive to initial states and noise [22]. Engineered dissipation also plays an essential role in various fundamental areas, including non-Hermitian quantum mechanism [13], quantum thermodynamics [5], and nonequilibrium transport [9].

Circuit quantum electrodynamics (cQED), based on superconducting devices, constitutes a promising platform for QIP [26]. In this platform, dissipative resonators coupled with superconducting qubits are employed to realize dispersive readout [27]. Furthermore, when considered as generalized measurement, dissipation serves as a powerful quantum control tool that has been utilized in other QIP tasks within cQED [5,28], including state stabilization and autonomous QEC in both single-qubit [29–36] and two-qubit systems [23–25, 37–40]. This continuous driven-dissipative concept has been further generalized to many-body systems [41–43], and specific eigenstates of a three-qubit array have been prepared

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by Hacoen-Gourgy *et al.* [44], although the quantum coherence of these states has yet to be confirmed. Nevertheless, in all existing experiments involving quantum bath engineering for entangled-state stabilization, superconducting qubits have been coupled to a common dissipative resonator requiring specialized hardware designs, rendering most of them incompatible with mainstream architectures for scalable quantum computation and simulation. Additionally, the stabilized Bell state fidelity achieved in cQED remains relatively low, with the highest reported value up to 84% [25] so far, thus limiting its potential application in QIP. Therefore, a bath engineering scheme that is compatible with scalable architectures and capable of achieving high-fidelity entangled states in superconducting circuits is highly desirable.

In this Letter, we propose and experimentally implement a hardware-efficient scheme for stabilizing entangled states that is compatible with the mainstream and scalable architecture of contemporary superconducting quantum computation. We consider a driven-dissipative system of the transmon qubits [45] with their readout resonators. A Raman process [29] is utilized by applying detuning drives to the resonators to tailor the spectrum of their quantum noise [46], thereby engineering appropriate dissipative channels for generating steady and desired entangled states. Leveraging the individual addressing of qubits and resonators, we are able to stabilize a Bell state of two qubits with a fidelity of 90.7% as determined by quantum state tomography (QST). The protocol is further extended to a three-qubit scenario, stabilizing an entangled W state with a fidelity of 86.2%. While theoretically, these entangled states can be maintained indefinitely, the stabilization period demonstrated in our experiment is finite due to the limited buffer time of the apparatus. Our results demonstrate the potential of harnessing dissipation with hardware efficiency to stabilize multiqubit entangled states.

Our protocol is experimentally implemented on a superconducting quantum processor consisting of a two-dimensional array of 4×4 frequency-tunable transmon qubits, with neighboring qubits coupled via frequency-tunable couplers [47]. The components involved in the protocol are highlighted in Fig. 1(a). Each of the three transmon qubits Q_i , with a frequency of ω_i^q , is dispersively coupled to a dedicated readout resonator R_i with a frequency ω_i^r , via a cross-Kerr coupling of strength χ_i . The exchange coupling strength $J_{i,i+1}$ between Q_i and Q_{i+1} can be modulated by the relevant coupler. For all qubits, a shared low-quality factor Purcell filter is designed to protect them from external environmental noise while providing moderate dissipation rates κ_i for their readout resonators. The effective interaction Hamiltonian of the system, with near-resonant drives applied to both qubits and resonators, can be written as

$$\begin{aligned}
 H/\hbar = & \sum_{i=1}^L \Delta_i^q b_i^\dagger b_i + \frac{\alpha_i}{2} b_i^\dagger b_i^\dagger b_i b_i + \Delta_i^r c_i^\dagger c_i + \chi_i b_i^\dagger b_i c_i^\dagger c_i \\
 & - \sum_{i=1}^{L-1} J_{i,i+1} (b_i^\dagger b_{i+1} + b_{i+1}^\dagger b_i) \\
 & + \sum_{i=1}^L \Omega_i^p b_i^\dagger + \epsilon_i^d c_i^\dagger + \text{H.c.}
 \end{aligned} \quad (1)$$

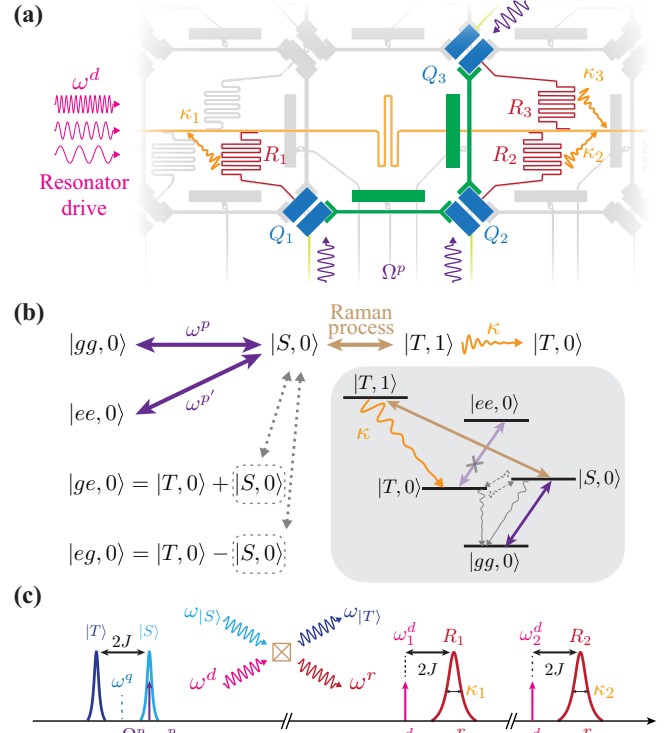


FIG. 1. (a) Schematics of the superconducting circuits employed in the experiment, with the involved components highlighted. Each qubit Q_i is paired with a dedicated readout resonator R_i . The coupling between qubits is adjusted using tunable couplers (green). (b) Main panel: Illustration of the evolution of various initial states to the target Bell state of two qubits, where $\omega^p = \omega^q + 2J$ and $\omega^{p'} = \omega^q - 2J$. The essential component of the flow is a Raman process. Numbers in the Dirac notation indicate Fock states of the resonators. Shaded panel: Energy level diagram of the system showing the Raman process (brown line), pumping drives applied to the qubits (purple line), and decoherence processes (yellow and gray wavy lines). The pumping drives selectively excite the transition $|T\rangle \leftrightarrow |ee\rangle$ due to symmetry of the pumping drives. The combination of the Raman process and rapid energy dissipation in the resonators stabilizes the system into the target Bell state $|T\rangle$. Only the first two energy levels of the resonator are shown for clarity. (c) Frequency landscape of the two resonators and the two Bell states, along with microwave pulses applied to all components. The Raman process is activated by injecting red-detuned ($\omega_i^r - \omega_i^q = 2J$) drives into the resonators. The pumping drive is centered at $\omega_{|S\rangle}$, targeting the state $|T\rangle$. The inset illustrates the Raman process as four-wave mixing.

Here, $b_i^\dagger$ and $c_i^\dagger$ are the creation operators for Q_i and R_i , respectively, and α_i denotes the anharmonicity of Q_i . All qubits are pumped by microwave pulses with the same frequency of ω^p ($\Delta_i^q = \omega_i^q - \omega^p$ denotes the corresponding detuning) but different amplitudes of Ω_i^p . Both ω^p and Ω_i^p can be tuned *in situ*. The Raman process is realized by driving R_i using a microwave pulse with a frequency of ω_i^d ($\Delta_i^r = \omega_i^r - \omega_i^d$) and an amplitude of ϵ_i^d (see Supplemental Material [48] (SM) for experimental parameters).

We first demonstrate the generation of the Bell states of Q_1 and Q_2 using our dissipative scheme, corresponding to $L = 2$

in Eq. (1). Consider the situation where all microwave drives on qubits and resonators are turned off, and the two qubits are tuned into resonance at $\omega^q = \omega_1^q = \omega_2^q$ with a moderate coupling strength of $J/2\pi = J_{12}/2\pi = 5$ MHz. It can then be easily verified that the two Bell states, $|T\rangle = (|ge\rangle + |eg\rangle)/\sqrt{2}$ and $|S\rangle = (|ge\rangle - |eg\rangle)/\sqrt{2}$, become the eigenstates of the single-excitation manifold, with the difference between their eigenenergies satisfying $\omega_{|S\rangle} - \omega_{|T\rangle} = 2J$. Here, $g(e)$ denotes the ground (excited) state of the qubits. The energy level diagram of the system is illustrated in Fig. 1(b). Although these Bell states can be coherently prepared through a combination of single- and two-qubit gates, such unitary processes are prone to noise and control errors. Moreover, the entangled states prepared in this manner are constantly degraded by both T_2 (dephasing) and T_1 (relaxation) processes after preparation. Furthermore, since the conventional method of dealing with noise through measurement-based QEC is resource demanding [37,49–51], quantum bath engineering has been developed to circumvent this issue due to its inherent autonomous feedback loop [5,28].

Figure 1(b) shows an example of our scheme where the $|T\rangle$ state is the target Bell state. The key concept involves properly tuning the energy landscape of the system and applying appropriate microwave drives to design the transitions and dissipation channels to work collaboratively, steering any initial state towards the target Bell state. Moreover, this steering flow dynamically and autonomously stabilizes the Bell state against decoherence. The critical component within this steering flow is a Raman process that drives the $|S, 0\rangle$ state to the $|T, 1\rangle$ state. This process leverages the rapid dissipation in the readout resonators, as exploited in pioneering works on cooling single and multiple qubits in three-dimensional superconducting cavities [29,44]. This Raman scattering can be intuitively understood as a four-wave mixing process involving the transmons and their resonators R_i , as depicted in the inset of Fig. 1(c). With microwave drive(s) applied to one or both resonators at a frequency ω_i^d satisfying $\omega_i^d - \omega_i^r = \omega_{|S\rangle} - \omega_{|T\rangle}$, the input $|S, 0\rangle$ state is scattered into the $|T, 1\rangle$ state, with the gained energy populating the resonator(s) and dissipating efficiently. Consequently, the $|T, 1\rangle$ state rapidly decays into the target $|T, 0\rangle$ state. Evidently, such scattering occurs most efficiently when $\omega_i^r - \omega_i^d = \omega_{|S\rangle} - \omega_{|T\rangle} = 2J$, where the anti-Stokes photons resonate with R_i due to the cross-Kerr coupling $\chi_i b_i^\dagger b_i c_i^\dagger c_i$.

To maintain the system in the target state $|T, 0\rangle$, it is necessary to counterbalance the continuous relaxation from the subspace of $|S, 0\rangle$ and $|T, 0\rangle$ to the ground state $|gg, 0\rangle$. This can be achieved by concurrently driving both qubits with pulses of the same frequency ω^p but opposite amplitudes, i.e., $\Omega_1^p = -\Omega_2^p = \Omega^p$, where $\Omega^p/2\pi = 0.53$ MHz. Here, ω^p is chosen to ensure a resonant transition between $|gg\rangle$ and $|S\rangle$ while strongly suppressing the $|S\rangle \leftrightarrow |ee\rangle$ transition as $\Omega^p \ll 2J$. Meanwhile, the $|T\rangle \leftrightarrow |ee\rangle$ transition is forbidden due to a dynamical symmetry [48]. When these continuous and concurrent drives are applied to the qubits, in combination with the previously discussed Raman process, the state $|T, 0\rangle$ approximates a steady state of the system, even in the presence of decoherence. A similar scheme can be implemented for the other Bell state $|S\rangle$.

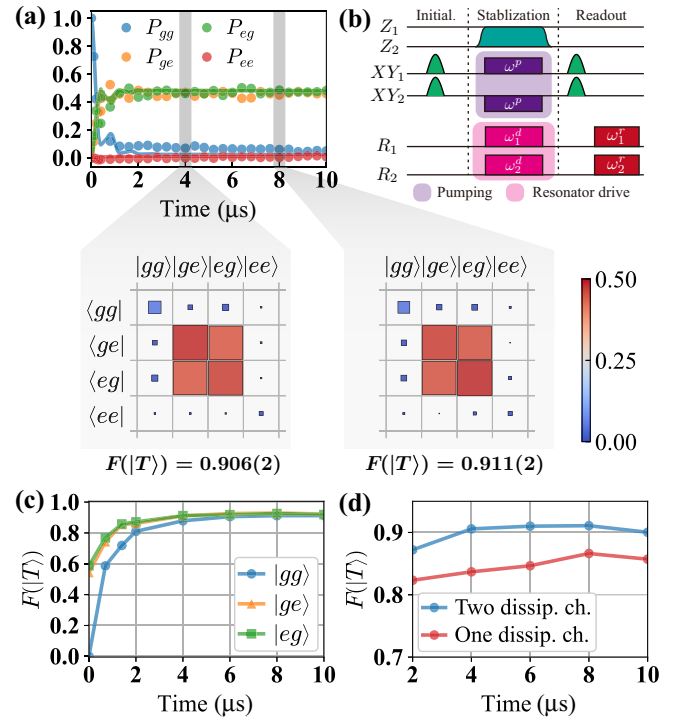


FIG. 2. Stabilization of the Bell state of two qubits. (a) Population dynamics of the four basis states of the two qubits as a function of time, starting from an initial state $|gg\rangle$. Markers represent experimental data, and lines denote numerical simulations with the master equation. Both readout resonators participate in stabilization. Two QST measurements are performed at 4 and 8 μs , with the results depicted in the two callouts. Both the size and the color of the squares in the QST results represent the magnitude of the density matrices, showing that the decay into $|gg\rangle$ and the residual population in $|S\rangle$ account for most of the error. The fidelity values are calculated as described in the main text. (b) Experimental pulse sequence for state preparation, stabilization, and readout. (c) Fidelity of stabilization over time for different initial states. Once the stabilization process commences, all initial states converge towards the target Bell state. (d) Fidelity of stabilization over time when activating one or two dissipative channels (i.e., applying pulses to one or both resonators). With two channels energized, stabilization proceeds more rapidly and achieves a higher fidelity.

Figure 2(a) shows one example of the stabilization process for an initial state $|gg\rangle$. In this measurement, the two qubits are tuned into resonance. After applying all drives to the qubits and resonators, the system initially undergoes a brief period where three of the four basis states are populated but soon become equally populated in the $|eg\rangle$ and $|ge\rangle$ states only. Throughout the entire period, the $|ee\rangle$ state remains almost unpopulated, as it is decoupled from the other states, as previously explained. To verify that the steady state of the stabilization is indeed the target Bell state, two QST measurements are performed at 4 and 8 μs . The fidelity is calculated as $F = \text{Tr}(\langle T | \rho_{\text{exp}} | T \rangle)$, where ρ_{exp} is constructed from QST data [Fig. 2(a)]. $F = 90.6(2)\%$ and $91.1(2)\%$ are obtained for the two measurements without postselection. It is noted that the time span of 10 μs in our measurements is set by the longest buffer time of the electronics, not by any intrinsic limit.

We further demonstrate that the entanglement stabilization is insensitive to the initial state. Figure 2(c) shows the fidelity measured at different phases of the stabilization for three different initial states. In all cases, the fidelity quickly converges and stabilizes. Due to their greater overlap with the target state, both $|ge\rangle$ and $|eg\rangle$ states approach $|T\rangle$ more rapidly than the state $|gg\rangle$. A time constant of $T_s = 0.9 \mu\text{s}$ for the stabilization process can be extracted from the data, corresponding to a stabilization rate of $\Gamma_s = 1/T_s$ ($\sim \kappa/6$, where κ is the average photon decay rate of resonators). Other relevant rates include $\Gamma_1^{(2)} = 1/T_1^{(2)}$ and $\Gamma_\phi = 1/T_\phi^{(S)-|T\rangle}$, which represent the rates at which the $Q_1 Q_2$ system is scattered away from the target state. In this case, $T_1^1 = T_1^2 = 27 \mu\text{s}$ and $T_\phi^{(S)-|T\rangle} = 18 \mu\text{s}$ are determined by the spin-echo time average of the two qubits. Using a rough estimate [48] of $[\Gamma_s - (\Gamma_1^1 + \Gamma_1^2)/2 - \Gamma_\phi]/\Gamma_s = 0.917$, we arrive at a value consistent with the measured fidelities. Note that stabilization from the decoupled state $|ee\rangle$ is also possible with additional coherent Rabi driving to connect $|ee\rangle$ and $|S\rangle$ [48].

The Raman process discussed above involves applying detuned drive(s) to the readout resonator(s), which can be done on either one or both resonators. When only one resonator is driven, the other remains in its vacuum state, resulting in the system stabilizing to a more mixed state with a slower decay rate compared to when both resonators are driven, as shown in Fig. 2(d). This is expected because utilizing only one dissipative channel weakens the system's ability to remove entropy. Hence, the fidelity of the target state remains unstable even after $6 \mu\text{s}$, with its steady-state value being lower than when both dissipative channels are energized. This result highlights the flexibility of using individually controllable cavities over a common resonator for bath engineering [44].

Next, we extend our protocol to stabilize the three-qubit W state. In a three-qubit system, the coupling rates are set to $J_{12}/2\pi = J_{23}/2\pi = J/2\pi = 5 \text{ MHz}$. Notice the $|W\rangle = (|egg\rangle + |geg\rangle + |gge\rangle)/\sqrt{3}$ state is not an eigenstate if all qubits are in resonance. To overcome this issue, the frequency of qubit Q_2 [see Fig. 1(a)] is detuned from those of Q_1 and Q_3 by $\Delta_2^q/2\pi = J = 5 \text{ MHz}$ so that the $|W\rangle$ state, along with two other states $|A\rangle$ and $|B\rangle$, become the eigenstates in the single-excitation manifold of the system (see SM [48] for more details about states $|A\rangle$ and $|B\rangle$).

Similar to the Bell state stabilization, dissipative channels are engineered so that the $|W\rangle$ state becomes the steady state of the driven-dissipative system with the assistance of the Raman process and rapid dissipation in the readout resonators. However, due to the more complex energy landscape of the system, two separate paths are now used to steer $|A\rangle$ and $|B\rangle$ to the $|W\rangle$ state, as illustrated in Fig. 3(a). Again, to counterbalance the relaxation from the target state to the ground state $|ggg\rangle$, Q_2 is driven at frequency $\omega^p = \omega_{|B\rangle}$ with a Rabi frequency of $\Omega^p/2\pi = 0.51 \text{ MHz}$, which pumps $|ggg\rangle$ back to the single-excitation manifold. Due to the dynamical symmetry of the pumping drive, the resonant transitions to the higher excitation manifolds are forbidden [48]. For an initial state of $|ggg\rangle$, the driven-dissipative system stabilizes after around $4 \mu\text{s}$, with fidelity obtained via QST measurements consistently over 85%. The lower fidelity of the stabilized

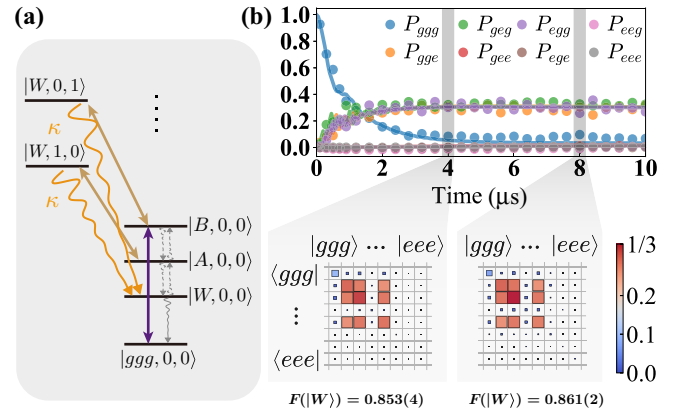


FIG. 3. Stabilization of the W state of three qubits. (a) Energy level diagram of the system depicting the relevant processes for stabilization. Two Raman processes utilizing different resonators engineer the paths $|B\rangle \rightarrow |W\rangle$ and $|A\rangle \rightarrow |W\rangle$. The resonant transition $|ggg\rangle \rightarrow |B\rangle$ is induced by driving Q_2 at a Rabi frequency Ω . (b) Dynamics of the population of the eight basis states of the three qubits over time, with the system initially in $|ggg\rangle$. Two QST measurements are performed at 4 and 8 μs .

$|W\rangle$ state compared to the Bell state is expected, as there are more dephasing paths, and only one dissipative channel is engineered to counteract the effect of each path. Additionally, the probability of leakage to higher excitation states via the pumping drive is larger due to a smaller energy gap between $|W\rangle$ and $|A\rangle$ at the same coupling strength.

In conclusion, we have demonstrated a hardware-efficient scheme for generating entangled states via engineered dissipative channels. The scheme leverages the individual controllability of each qubit and its associated local readout resonator to realize precise quantum bath engineering, making it compatible with mainstream scalable architectures for superconducting quantum computation. The two-qubit Bell state and the three-qubit W state have been prepared and preserved indefinitely, with state fidelities (by averaging the QST data from 4 to 10 μs with intervals of 2 μs) of 90.7% and 86.2%, respectively. Further improvement of this scheme is possible through additional parity measurements [37], optimizing parameters with larger κ —a necessary ingredient in QEC [52]—and enhancing the coherence performance of qubits (see SM [48]). Moreover, since the present work only uses simple time-independent drives, introducing time-dependent control techniques such as Floquet engineering [42] or digital circuits [9] could provide more flexible and effective solutions for sophisticated entanglement generation requirements.

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