Probing quantum many-body scars on a superconducting processor

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Thermalization in complex and strongly interacting quantum many-body systems represents an obstacle to applications. It was recently suggested theoretically that quantum many-body scarring (QMBS) states embedded in the thermalized energy spectrum can overcome this difficulty. Here, by programming a superconducting circuit of two-dimensional multiqubit array with tunable couplings, we experimentally investigate the slow quantum thermalization dynamics associated with QMBS states in the paradigmatic settings of chain and comb tensor topologies, which are effectively described by the unconstrained spin model. Robust QMBS states have been successfully observed in a superconducting circuit of up to 30 qubits with an extraordinarily large Hilbert space for exact diagonalization simulations of classical computers. The QMBS states can be readily distinguished from the conventional thermalized states through the population dynamics, the entanglement entropy, and the fidelity, paving the way to exploiting these states for mitigating quantum thermalization for significant applications in quantum information science and technology.

INTRODUCTION

Quantum dynamics in complex and strongly interacting many-body systems are fundamental with applications in condensed matter physics [1], quantum simulation and computing [2–4], and quantum engineering [5] in general. A universal behavior is quantum thermalization caused by the inevitable interactions with the environment, where the initial information tends to uniformly spread into the Hilbert space quickly, analogous to ergodic dynamics in classical chaotic systems. Quantum thermalization in isolated systems generally obeys the eigenstate thermalization hypothesis (ETH) [6–9], leading to quantum information scrambling [10–13] that presents a significant challenge in applications. To develop methods to defy the ETH so as to achieve long-lived-dynamic states preserving quantum information is of great importance.

A promising solution is to exploit quantum many-body scarring (QMBS) states that were first discovered in a 51 Rydberg-atom chain [14] and explained based on the effective PXP model [15, 16]. While breaking the thermalization rendered ergodicity, the QMBS states are distinct from the quantum states in classically integrable systems and from quantum many-body localized states as well [17–20]. Theoretically, QMBS states have been studied in diverse systems ranging from the Heisenberg spin [21–23], Affleck-Kennedy-Lieb-Tasaki [23, 24], extended Hubbard [25–27], and Ising [28] models to frustrated [29, 30] and topological [31, 32] lattices, quantum Hall systems [33, 34], Floquet-driven systems [35, 36], systems with a flat band [37, 38], and two-dimensional systems [39]. General theoretical frameworks were developed, in which QMBS states are constructed based on the embedding method [40, 41] and quasi-symmetry groups [42]. It has also been proposed that QMBS states can be used to generate GHZ entanglement state [43] and robust quantum sensing [44]. Because of their unusual ability to defy thermalization, QMBS states can be effective for manipulating and storing quantum information [45, 46].

Quite recently, quantum simulators with their demonstrated supremacy over classical computers open a new avenue to probing into complex quantum many-body dynamics. For example, superconducting circuits of two-dimensional qubit array [47, 48] with the advantages of high density integration and flexible controllability [49, 50] can emulate many models with a broad tunable range of local couplings in a single device. In this regard, the experimentally observed QMBS states in the atomic platform are specific with respect to the constrained model [14, 46, 51]. The superconducting platform enables the QMBS states in disparate many-body systems (e.g., the Heisenberg spin system [52], among others) to be studied in a more in-depth and comprehensive way. Further, the readout of the superconducting...
platform enables direct measurements of the observable quantities beyond the population-related dynamics, such as the entanglement entropy \[11\], out-of-time-ordered correlation \[4,12\], and energy spectrum information \[53\]. Those observable quantities associated with energy spectrum information and the feature of programmable technique make it possible to experimentally unearth the origin and robustness of the quantum scarring phenomena in large and extremely complex many-body systems.

In this article, we report experimental observation and characterization of the QMBS states predicted by a non-integrable hard-core Bose-Hubbard model (also known as the spin-1/2 XY model) in a superconducting circuit processor with qubits and couplers arranged in a square-lattice geometry. The couplers generate tunable interactions between any two nearest-neighbor qubits \[51\], enabling emulation of the many-body system with one- and quasi one-dimensional topology. We investigate circuits of up to 30 qubits and 29 couplers, with an exact Hilbert dimension of an effective Hilbert dimension C(30, 15) = 155,117,520. Measurements of the population dynamics and quantum state tomography for entanglement entropy and fidelity provide unequivocal evidence of the emergence of robust QMBS states characterized by a slow thermalization process and energy spectrum information in the underlying complex many-body system. The QMBS states are experimentally contrasted to the conventional thermalized states and are robust in systems of different sizes. To our knowledge, this is the first experimental confirmation of QMBS states in solid-state systems, and the successful observation and characterization of these slowly thermalized states in a superconducting circuit open the possibility of direct applications in quantum information science and technology.

**DEVICE AND EFFECTIVE MODEL**

We use a superconducting quantum processor in a flip-chip package, which hosts a square of 6 × 6 transmon qubits \(Q_0\) with 60 couplers \(Q_c\), each inserted in between two neighboring qubits, as shown in Fig. 1(a). Each qubit (coupler) is a quantum two-level system with two levels \(|0\rangle\) and \(|1\rangle\), whose energy separation can be dynamically tuned in the frequency range 4.3 – 4.8 GHz (4.9 – 6.0 GHz). Each qubit has individual microwave (XY) and flux (Z) controls and it is capacitively coupled to a readout resonator for state discrimination. Each coupler has an individual flux (Z) control and remains in the ground state during the experiment. We use high-precision synchronized analog signals to control the qubits and couplers, with microwave pulses for qubit XY rotations and state readout, and square flux pulses for tuning the qubit and coupler frequencies. A complete experimental sequence in Fig. 1(b) consists of three stages: (1) state preparation where single-qubit \(\pi\) pulses are applied to half of the qubits, (2) multiqubit interaction stage where the nearest neighboring qubit couplings are programmed by adjusting the couplers’ frequencies, and (3) the measurement stage where all qubits are jointly read out. The values of the relevant qubit parameters such as the qubit energy, the lifetimes (with mean about 50 μs) and \(\pi\)-gate randomized benchmarking fidelity (with mean about 0.993) can be found in Table S1 of Supplementary Materials (SM).

The Hamiltonian of the superconducting circuit-QED system is given by \[53\]

\[
\mathcal{H} / h = \sum_{i < j} g_{ij} (S^+_i S^-_j + S^+_j S^-_i) + \sum_{i,c} g_{ic} (S^+_i S^-_c + S^+_c S^-_i) + \sum_{i,c} \omega_{ic} S^x_i S^x_c, \quad \text{where } S^x_i = (S^+_i + S^-_i) / 2, \quad S^z_i = g_i, \quad \text{are the spin-1/2 Pauli matrices, and } \omega_{ij} \text{ is the dispersive shift in state } |1\rangle_i \text{ for the } i\text{th qubit. The subscripts } "i", "j", \text{ and } "c" \text{ are the indices of the qubits and couplers, respectively.}
\]

The coupler tunes the coupling of its two adjacent qubits \(g_{ij}\) with the detuning \(|\Delta_{i,j}| = |\omega_i - \omega_{i,j}| \gg g_{ij}\). The effective Hamiltonian of this complex quantum system can be written as

\[
\mathcal{H}_{\text{eff}} / h \approx \sum_{i < j} J_{ij} (S^+_i S^-_j + S^+_j S^-_i) + \sum_i \Omega_i S^z_i, \quad (1)
\]

where \(J_{ij} \approx g_{ij} + g_{ic} g_{jc} / \Delta_{ij}\) for nearest neighbor couplings, with \(g_{ij}\) denoting \(Q_i Q_j\) cross couplings and \(\Omega_i \approx \omega_i + g_{ic} / \Delta_i\) with \(1 / \Delta_i = 1 / 2 \Delta_1 + 1 / 2 \Delta_2\). In our device, the effective nearest neighboring coupling strength can be dynamically tuned over a wide range: from \(J_{ij} / 2 \pi = -15\) to 1 MHz, which is characterized by the one-photon swapping dynamics between two neighboring qubits (see details in SM).

**QMBS STATES AND EXPERIMENTAL INVESTIGATION**

The Gluttonous-snake-like layout in Fig. 1(a) is suited for exploiting the topological structure of the Su-Schrieffer-Heeger chain, where the intra-dimer coupling \(J_{i,i+1} / 2 \pi = J_a / 2 \pi \approx -9\) MHz with \(i \in \text{ odd}\) is slightly stronger than the inter-dimer coupling \(J_{i,i+1} / 2 \pi = J_c / 2 \pi \approx -6\) MHz with \(i \in \text{ even}\). Each dimer has four states: \(|d_0\rangle = |00\rangle, |d_1\rangle = |11\rangle, |d_+\rangle = |10\rangle, \text{ and } |d_-\rangle = |01\rangle\). The dominant cross couplings \(J_{s} / 2 \pi \in [0.5, 1.1]\) MHz, the couplings between two next nearest neighbor qubits with a physical separation distance \(a_{ij} = \sqrt{2} a_0\), break the reflection symmetries and drive the system toward quantum thermalization, where \(a_0 \approx 0.8\) mm is the separation distance of two nearest neighbor qubits. The level spacing statistic follows the Wigner-Dyson distribution with the level-statistic parameter \(\langle r \rangle \approx 0.53\) for each symmetrical sector and the bipartition entanglement entropy obeys the volume law.

In a half-filling \((N = L/2)\) chain, a pair of dimerized states with collectively dynamics [Fig. 1(c)], can be expressed as: \(|\Pi\rangle = |d_+ d_- d_- d_+ \cdots \rangle\) and \(|\Pi'\rangle = |d_- d_+ d_+ d_- \cdots \rangle\), which are associated with a pair of opposite corners in an \(N\)-dimensional hypercube in the Hilbert space without direct coupling, as shown in
Fig. 1(c) with photon number \( N = L/2 = 4 \), where \( L \) is the number of effective qubits (or the system size). Phenomenologically, the QMBS states are effectively a many-body version of single-particle scarred states in a quantum billiard with classical chaos. In the Hilbert space, the QMBS states are scarred eigenstates that can be visualized through the squared state overlap \( |\langle \alpha|E_n \rangle|^2 \), where the product states \( |\alpha \rangle = \cdot \cdot z_{i-1}z_i z_{i+1} \cdot \cdot \cdot \) constitute the basis, and \( z_i = 0, 1 \) represents the ground state \( |0\rangle \) and the excited state \( |1\rangle \) at \( Q_i \). The scarred eigenstates exhibit remarkable overlaps over the cross product states, whereas the ergodic eigenstates give a homogeneous pattern in the Hilbert space, as illustrated in Fig. 1(d).

Note that the other product states in the hypercube in Fig. 1(c) play a role of a buffer area to prevent the information of states |II⟩ and |II′⟩ from rapidly leaking to other thermalized areas. The robustness of |II⟩ and |II′⟩ is due to the collective many-body effect and enhanced by the structure-induced potential (\( J_a > J_e \)). The hypercubic structure is robust and naturally it does not contain any cross coupling, while the other parts of the Hilbert space are frustrated by the irregular cross couplings. The sum of the hypercubic thermal couplings gives the decay rate \( \Gamma \) of the hypercube to the thermalized parts. The summation of intra hypercubic couplings \( \Theta \) is given by the number of hypercubic edges, i.e., \( \Theta = N^2N^{-1} \) with \( N = L/2 \). The ratio between the sums of the inter and intra hypercubic couplings \( \Theta/\Gamma \) converges to a finite value for different values of \( J_a/J_e \), as shown in Fig. 1(c).

The dynamical evolution of a quantum state can be written as \( |\Psi(t)\rangle = \sum_n \langle \Psi(0)|E_n \rangle e^{-iE_nt} |E_n\rangle \), where \( E_n \) and \( |E_n\rangle = \sum_\alpha c_{n,\alpha}|\alpha\rangle \) are the eigenenergy and eigenvector of the \( n \)th eigenstate, respectively. Consider an
FIG. 2. Experimentally observed qubit dynamics. (a,b) Contour diagrams of the experimental qubit population as a function of the interaction time from a QMBS and rapid thermalized states, respectively. (c,d) The corresponding imbalance versus the interaction time. Insets: imbalance dynamics from experiments (hexagons or circles) and numerical simulations (solid curves) in a 20-qubit chain. (e,f) The respective Fourier transformation amplitude of the imbalance in (c,d) characterizing the squared overlap between the initial states and the eigenstates. The time window for the fast Fourier transform is extended to 4 µs with zero padding. (g) Fourier peak as a function of the coupling ratio \(J_s/J_i\) in a chain of \(L = 20\) from experimental measurements (green hexagons) and numerical simulations (red dashed curve). (h) The squared Fourier amplitude \(g_\alpha^2(\omega = \omega_i)\) of the product state \(|\alpha\rangle\) for 120 randomly chosen initial product states including two QMBS states (green hexagons) that are unequivocally distinct from the other thermalized product states. The simulation parameter values are \(J_s/2\pi = -9.3\) MHz, \(J_i/2\pi = -6.1\) MHz and \(J_s/2\pi \in [0.5, 1.1]\) MHz.

initial state with thermalized dynamics. Its squared overlap with the eigenstates \(|\langle \Psi | E_n \rangle|^2\) is homogeneously distributed in the physical space and the time evolution of the fidelity, defined as \(F(t) = |\langle \Psi(0) | \Psi(t) \rangle|^2 = \sum_n |\langle \Psi | E_n \rangle|^2 e^{-iE_n t}\), will rapidly decay to zero. This means that the initial information will uniformly diffuse out to all the eigenstates, which cannot be revived with a non-global operator. On the contrary, for the slowly thermalized QMBS state, the squared overlap \(|\langle \Psi | E_n \rangle|^2\) is appreciable for some special scarred eigenstates, for which the time evolution of the fidelity can be approximately written as the summation over a few distinct eigenstates as \(F(t) \sim \sum_{n_k} e^{-iE_n t}\), where \(E_n\) denotes the eigenenergy of the \(k\)th scarred eigenstate. This feature of the dynamics can also be characterized by measuring the generalized imbalance defined as \(I(t) = (2/L) \sum_n |\langle \Psi | E_n \rangle|^2 |\langle S^z(t) \rangle|^2\). The dynamics of the imbalance are determined by the sum of the overlaps between the product states and the eigenstates [Sec. I in SM]. The dynamical evolution of the imbalance for a conventional and a slowly thermalized state is characterized by the fidelity, where revivals occur in the latter case, as shown in Fig. 1(e).

Experimentally, we prepare a set of product states as initial states and measure the final states of all qubits as a function of the interaction time [see pulse sequence illustrated in Fig. 1(b)]. Particularly, we start a typical experimental session by preparing the initial product state of all qubits: each qubit \(Q_i\) is biased from its sweet point to the corresponding idle frequency, where we apply single-qubit \(XY\) rotations. To prepare a high-fidelity state, during this period, the couplers are tuned such that the net couplings between the neighboring qubits are turned off. To switch on the interactions among the qubits, we bias all qubits to the interaction frequency and tune the coupler frequencies to turn on the couplings between the neighboring qubits. After the interaction process, we bias all qubits to their readout frequencies for measurements. All directly measured qubit occupation probabilities are corrected to eliminate the measurement errors.

We observe the population evolution with time in each qubit for a 30-qubit chain. Figures 2(a) and 2(b) show the evolution of a QMBS state and a typical thermalized state, where the former exhibits remarkable oscillations which are absent in the latter. Figures 2(c) and 2(d) show the imbalances with the initial states, which are characteristically different between the two types of states. In general, for the thermalized state, after about 30 ns, the population is only half photon in each qubit. The distinct features of the QMBS states can be further highlighted through the overlap between the product states and the eigenstates \(|\langle \alpha | E_n \rangle|^2\), which can be represented
Quantum state tomography for the four-qubit fidelity and entanglement entropy in a 30-qubit chain. (a) Fidelity of subsystem A as a function of the interaction time. The upper left inset illustrates the division of the many-body system into subsystems A and B, where the former contains 4 qubits for measuring the entanglement entropy. The right inset shows the Fourier transformation amplitude of the four-qubit fidelity and $\omega_1/2\pi \approx 21$ MHz. (b) Entanglement entropy $S_A$ versus the interaction time for initial states of thermalization (red and orange) and QMBS states (green). Dashed gray line represent the page value $4\ln 2$.

by the Fourier spectrum of the imbalance, as shown in Figs. 2(e) and 2(f) for the QMBS and conventional states, respectively. The peak value of the squared Fourier spectrum $g_a(\omega)$ with the first-order domain eigenstates is $\omega_1/2\pi \approx 21$ MHz. We test 120 random initial product states and find that the squared Fourier amplitudes $g_a^2(\omega = \omega_1)$ of the QMBS states are unequivocally distinct from those of the conventional thermalized states, as shown in Fig. 2(h). The variations in the Fourier amplitude for rapidly thermalized dynamics are smaller in larger systems (see, for example, the case of $L = 20$ in SM). Note that, for the cases in Figs. 2(a-f), to carry out the exact simulations is computationally impractical. To validate the experimental data numerically, it is necessary to use a smaller system size, say $L = 20$, whose results are shown in the insets in Figs. 2(c-f), where the agreement between numerical and experimental results is good.

A virtue of our experimental system, namely the tunable effective couplings between two nearest-neighbor qubits, allows us to investigate the emergence of the QMBS states as the ratio of intra- and inter-couplings $J_a/J_c$ increases. As shown in Fig. 2(g), both the numerical and experimental results indicate that QMBS states emerge consistently in the regime of $J_a/J_c > 1$. Also, the finite value of $g_{11}(\omega_1) \approx 0.008$ for $J_a/J_c = 1$ implies that the origin of the QMBS state is from the many-body effect. In the regime of large coupling ($J_{a,c}/2\pi > 12$ MHz), the effective Hamiltonian in Eq. (1) is no longer accurate to describe the system due to the population leakage to couplers. The exact model with couplers has an enormous Hilbert dimension of $C(20 + 19, 10) = 635, 745, 396$ for a 20-qubit system, which is computationally infeasible.

With the high-precision control and readouts of our superconducting processor, it is feasible to conduct tomography measurements to obtain the non-diagonal elements of the reduced density matrix, which determine the time evolution of the fidelity of the subsystem $F_A(t)$ and the entanglement entropy $S_A(t)$. To be experimentally feasible, we consider four qubits as the subsystem A, as schematically illustrated by the upper-left inset in Fig. 3(a). The data points in Fig. 3(a) give, for a 30-qubit chain, the time evolution of the first four-qubit fidelity for a collective dimerized state and that of a typical thermalized state. The fidelity of the QMBS state exhibits remarkable revivals with the period of about 50 ns and the peak value of the first revival can be as high as 0.5, while no such revivals occur for the thermalized state. The fidelity dynamics give richer information about the energy spectrum than the imbalance is able to, as shown in the inset of Fig. 3(a) by the Fourier spectrum of the fidelity, where the two peaks indicate the overlap $|\langle \Pi | E_n \rangle |$. The only two possible peaks for the four-qubit subsystem agree with the numerical simulation.

We next examine the time evolution of the entangle-
direct correspondence between the local peaks of comparative examination of Figs. 2(a) and 2(b) reveals a rapidly to the maximum value of 4ln(2). Remarkably, a entropy, while for the thermalized state, the entropy rises the QMBS states lead to a slowly ascending entanglement amplitude in the cross couplings and the couplers. The Fourier amplitudes among the imbalance and the entanglement entropy, and the four-qubit fidelity exhibit highly variation entropy for both QMBS and conventional thermalized states. The von Neumann entropy is given by \( S_A = -\text{Tr}[\rho_A \log \rho_A] \), where \( \rho_A \) is the reduced density matrix of the subsystem \( A \). For the thermalized states, the entanglement entropy satisfies the volume law, i.e., entanglement is non-negligible between two arbitrary qubits. However, for the QMBS states in Fig. 2(b), since entanglement exists between the adjacent dimers only, the entanglement entropy does not obey the volume law and its value should be smaller than that of a thermalized state. Figure 2(b) shows the time evolution of the entanglement entropy for the state |II \rangle as well as a thermalized state. The slow thermalized dynamics underlying the QMBS states lead to a slowly ascending entanglement entropy, while for the thermalized state, the entropy rises rapidly to the maximum value of 4ln(2). Remarkably, a comparative examination of Figs. 2(a) and 2(b) reveals a direct correspondence between the local peaks of \( F_A(t) \) and \( S_A(t) \).

The results demonstrated so far are for a superconducting circuit system with \( L = 30 \) qubits. To verify the generality and persistence of the QMBS states for different system sizes, we perform experimental measurements of chains of sizes \( L = 12, 14, 16, 20, 24, 28, \) and 30. The time evolution of the imbalance, the entanglement entropy, and the four-qubit fidelity exhibit highly consistent behaviors for different system sizes, thereby establishing the robustness of the QMBS states due to the collective dimerized states. The relatively small variations among the imbalance and the entanglement entropy for different system sizes are due to the difference in the cross couplings and the couplers. The Fourier amplitude \( g_{\Pi}(\omega_1) \) and the four-qubit fidelity \( F_A(t_1) \) at the first revival plateaus for \( L > 16 \), as shown in Fig. 4(a), whereas the inverse of the Hilbert space dimension characterizing the scaling of a random state shows an expected rapid exponential decrease with the system size. The plateaued behavior in the scaling suggests that the QMBS states should persist in the regime of large system size approaching to the thermodynamic limit.

The programmable feature of our superconducting circuit allows us to emulate a topology beyond one dimension. For example, we have experimentally studied QMBS states in a system with a more complex qubit topology, as illustrated in Fig. 5(a) - a comb tensor whose topological dimension is larger than that of the 1D chain. As a concrete realization, the numbers of qubits and photons are \( L = 20 \) and \( N = 10 \) with the respective coupling \( J_q/2\pi \approx -6 \) MHz and \( J_a/2\pi \approx -9 \) MHz. Different from the chain system, the scarring states in the comb tensor are \( |Z_2 \rangle = |d_+,d_+\cdots\rangle \) and \( |Z'_2 \rangle = |d_-,d_-\cdots\rangle \). As for the chain geometry, QMBS states arise and are characteristically distinct from the conventional thermalized states, as revealed by the squared Fourier amplitude in Fig. 5(b). The striking contrast between a QMBS state and a thermalized state can be seen at a more detailed level from Figs. 5(c-f), which show the time evolution of the photon population of each qubit and imbalance \( I(t) \) for the collective dimer state and a typical thermalized state.

**DISCUSSION AND OUTLOOK**

In summary, we have experimentally observed QMBS states in a superconducting circuit that emulates quan-
tum many-body systems effectively described by the spin-1/2 XY model with both one- and quasi-one-dimensional geometries. Characterization of the population dynamics distinguishes the scarring states from the conventional thermalized states. Measurement of the entanglement entropy verifies that the QMBS states exhibit the property of weak ergodic breaking. The slowly thermalized dynamics associated with the QMBS states are demonstrated to be robust against variations in the system size. The tunable-coupling superconducting system can be exploited to simulate one- and quasi-one-dimensional quantum many-body systems. Measuring the entanglement entropy and fidelity together with the explicit energy spectrum in a single programmable superconducting processor enables us to directly investigate the many-body physics in a more in-depth way. Our work represents the first experimental observation and characterization of QMBS states in solid-state devices, suggesting the generality of the QMBS phenomenon in multidimensional experimental platforms beyond atomic systems \cite{14, 58, 59} and dipolar gas \cite{60}.

According to conventional wisdom, a large many-body system with a Hilbert dimension of fifteen millions should obey the ETH and exhibit quantum ergodicity. Our study indicates that QMBS states can arise in the superconducting processor even when the system size is this large, defying the conventional wisdom. Our experimental work represents a step forward in quantum simulation, opening the door to investigating QMBS states and other many-body phenomena with an enormous Hilbert space in a feasible way, e.g., as in classical programmable computers. Our observation and characterization of long-lived quantum states in complex and strongly interacting solid-state systems with inevitable defects such as cross-talkings, random disorders, and environment-induced decoherence and dephasing have significant applied values. For example, the robustness of the QMBS states in solid-state systems can substantially lengthen the coherent time of specific quantum information operations such as the generation of GHZ states. Our work points at the need to further investigate non-thermal states in experimental platforms to generate QMBS states against quantum thermalization for quantum information applications.

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