

Full Characterization of Genuine 17-qubit Entanglement on the Superconducting Processor

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We present a least square state estimator regularized by state purity to accomplish the task of quantum state tomography and entanglement verification, and report an experimental validation on a superconducting processor. First, a scalable full-state tomography is achieved with state fidelity 0.8217(1) for the 9-qubit W state and 0.6817(1) for the 17-qubit Greenberger-Horne-Zeilinger state, with the latter reaching 0.7587(1) under a pure-state assumption. Then, the presence of genuine multiqubit entanglement in the majority of generated states is conclusively certified by violating the corresponding entanglement witness. Finally, it is demonstrated that our method can achieve superior tomography accuracy with limited measurement settings and that mitigating error is essential for leveraging noisy quantum systems in quantum processing tasks. Our results pave the way for more accurate full characterization of larger-scale many-body quantum systems.

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Introduction—Quantum information technology has made significant progress during recent years and thus generated widespread interest from both academia and industrial. Typical examples are the emerging quantum platforms, such as superconducting circuit [1–5], trapped ion [6,7], linear optics [8,9], and neutral atom [10], all allowing for dozens of qubits being programmed to verify the predicted quantum advantages and to explore potential applications. Thereof, it is of both fundamental and

practical importance to develop the capability of accurate identification of the underlying quantum system to benchmark its performance [11].

One useful tool capable of identifying quantum states is quantum state tomography (QST) [12], which has been widely applied across those hardware platforms [13–28]. Notably, numerous QST protocols exploit prior knowledge such as low rank [16,18,19,29,30], matrix product [31–33], permutationally invariant [34,35], low entanglement [36,37], and neural network [38–41]. Additionally, the randomized measurement toolbox [42] is adopted to efficiently learn key state properties, such as state fidelity via direct fidelity estimation (DFE) [43,44] and classical shadow (CS) [45–47]. Yet, it still remains challenging to achieve a full-state tomography of large-scale quantum system, due to the exponential scaling of measurement settings and computational resources with system size. Moreover, the state preparation and measurement errors further increase the difficulty of accurate state reconstruction. Therefore, it calls for methods to accomplish the tomography task with limited resources, under various noises.

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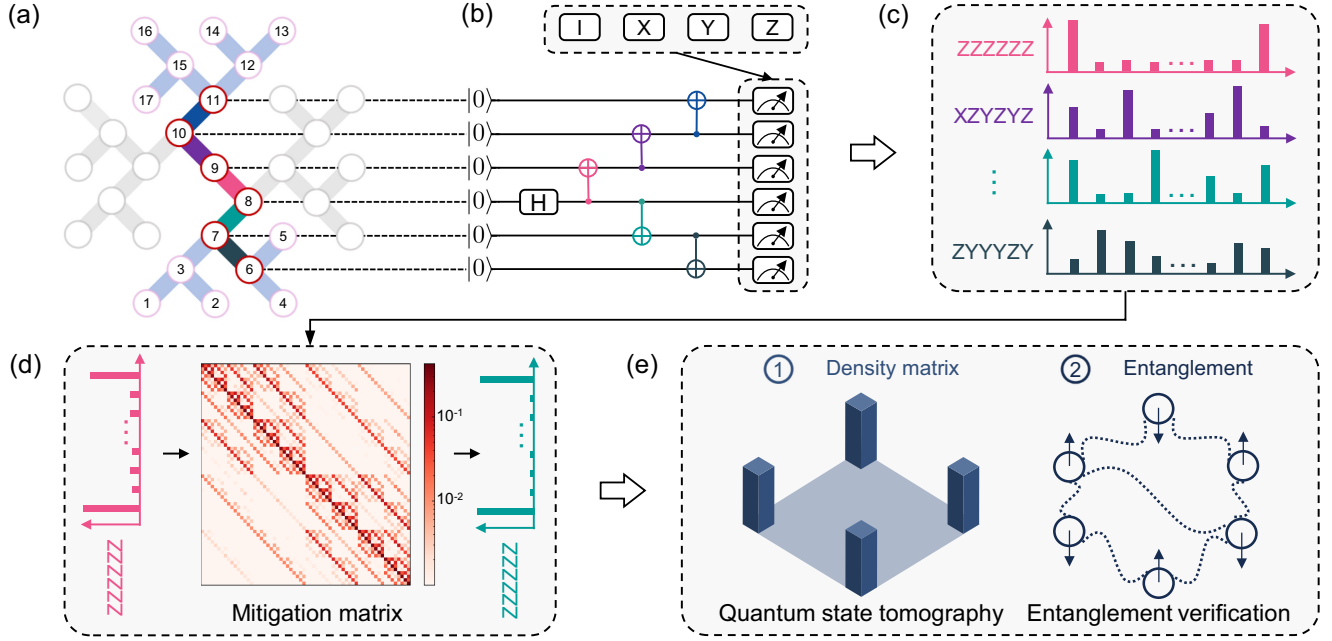


FIG. 1. The working pipelines of QST and entanglement verification. The demonstrative circuit of a (b) 6-qubit GHZ state is implemented on a (a) superconducting processor. The Pauli operators are measured on the system to yield the (c) statistical distributions, which are then calibrated via (d) error mitigation to reduce the readout error. (e) The purity-regularized state estimator in Eq. (1) is used to do the tasks of QST and entanglement verification.

In this Letter, we propose a least square (LS) state estimator regularized by state purity to enable accurate and scalable QST, and report an experimental validation on a 31-qubit superconducting processor. Leveraging maximum-likelihood (ML) readout mitigation technique [48–51] and a noniterative large-scale approximate solver, we accomplish full-state tomography of a 9-qubit W state with state fidelity 0.8217(1) and a 17-qubit Greenberger-Horne-Zeilinger (GHZ) state with fidelity 0.6817(1). This experimental report of full tomography for a 17-qubit GHZ state showcases the largest complete quantum state reconstruction performed to date. In contrast, the largest pure-state tomography reaches 20 qubits on an ion-trap simulator [33], underscoring the scalability of our method. Besides, under a pure-state constraint, the fidelity for the 17-qubit GHZ state reaches 0.7587(1).

We further verify the generation of genuine entanglement on the superconducting processor. Specifically, genuine multiqubit entanglement is conclusively certified for all experimentally prepared GHZ states via the violation of corresponding entanglement witness [52], supported by our regularized LS estimator and cross-validated via DFE and CS techniques. In contrast, for the W state, entanglement is detectable in small systems but quickly vanishes as the system size increases, reflecting their fragility under noise and decoherence.

We finally remark that our method enables superior reconstruction of generated states by consuming limited measurement settings, signaling its great utility in

characterizing quantum systems. It is also important to note that error mitigation [48–51,53–57] can play a crucial role in the noisy intermediate-scale quantum era, complementary to the numerical simulation and previous experimental validations [49,50,53,54].

Quantum state tomography—The state of a quantum system, including those generated on the superconducting processor in Fig. 1(a), is described by a positive semidefinite operator ρ with unit trace on Hilbert space $\mathcal{H}_d$ of dimensionality d . Extracting information about the state requires quantum measurement, which is modeled as positive operator-valued measure $\{M_i\}$ with $M_i \geq 0$ and $\sum_i M_i = \mathbb{1}$. Ideally, measuring identically prepared copies of state ρ yields a probabilistic distribution that each outcome i associated with a measurement element M_i occurs with probability $p_i = \text{Tr}[M_i \rho]$. The QST process is illustrated in Fig. 1, which aims to reconstruct the unknown state ρ from statistical data generated via measurements on the state ensemble.

For an N -qubit system, measurements are typically performed in the tensor-product form of single qubit Pauli operator $\sigma_j = \{\mathbb{1}_2, \sigma_x, \sigma_y, \sigma_z\}$ [labeled as I, X, Y, Z in Fig. 1(b)], i.e., $O_k = 1/\sqrt{d} \otimes_{n=1}^N \sigma_j$ for $k = 1, \dots, K = d^2 = 4^N$. Given a complete set of Pauli operator $\{O_k\}$, any state ρ can be reconstructed via $\rho = \sum_{k=1}^{K=d^2} o_k O_k$, from a collection of measurement expectations $o_k = \langle O_k \rangle_\rho = \text{Tr}[O_k \rho]$. In practice, various errors such as readout error and statistical noise arise in obtaining expectations $\hat{o}_k$ and reconstructing state ρ . Besides, only a subset

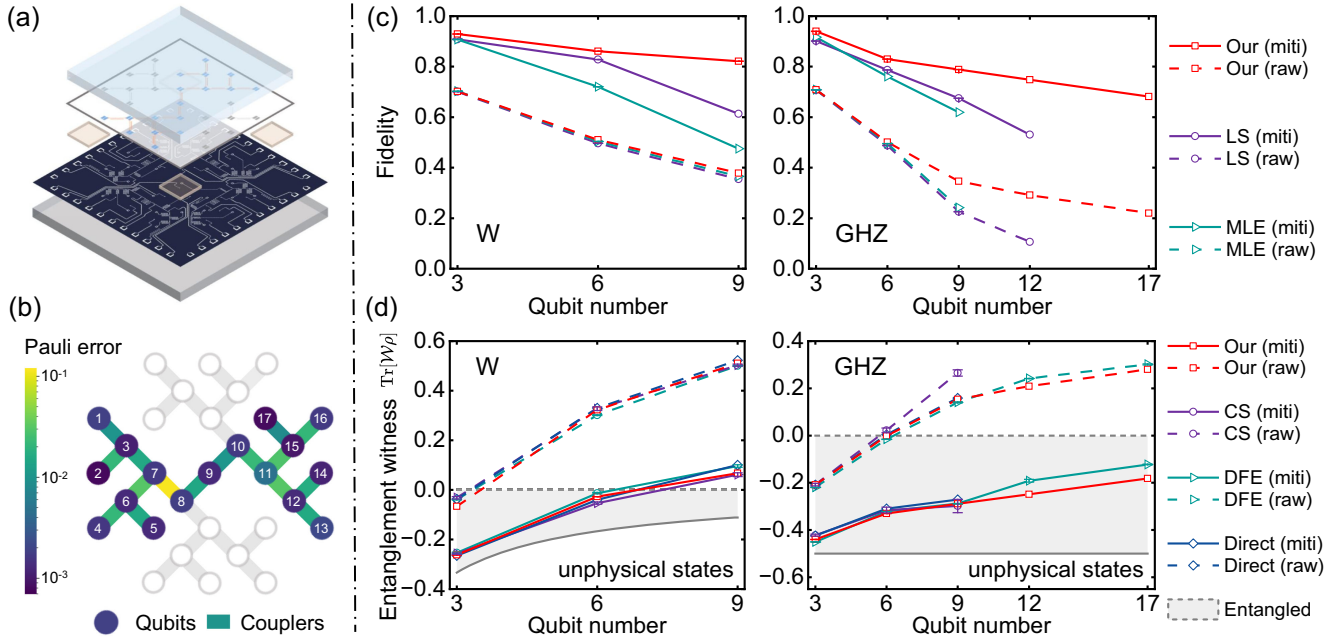


FIG. 2. (a) The architecture of the processor. (b) The configuration of 17 qubits is in a binary tree topology where the colored dots and lines represent qubits and couplers, respectively, with the heat map of single- and two-qubit Pauli errors. (c) The full-state tomography is achieved on N -qubit W and GHZ states, based on our estimator in Eq. (1), LS given by Eq. (1) with $\lambda = 0$, and MLE. (d) Genuine N -qubit entanglement is verified by using our method, CS, and DFE to evaluate the witness in Eq. (2) for GHZ states and the witness in Eq. (3) for W states. The blue line describes $\text{Tr}[\mathcal{W}\rho]$ directly estimated from the measured data, and the gray region admits $\text{Tr}[\mathcal{W}\rho] \in [\alpha - 1, 0]$, signaling the presence of entanglement. The experimental data are calibrated via the ML readout mitigation (labeled as “miti”) or no mitigation (labeled as “raw”). Error bars are computed from using each method 20 times with random initial conditions, and are not shown in (c) as it is the order of 10^{-4} .

$K \ll d^2$ of operators remains accessible as N increases, making full tomography on large-scale systems increasingly challenging.

Purity-regularized state estimator—To alleviate the above issues in QST, we propose the state estimator

$$\min_{\tilde{\rho}} \frac{1}{2} \sum_{k=1}^K (\text{Tr}[O_k \tilde{\rho}] - \hat{o}_k)^2 + \frac{\lambda}{2} (\epsilon(\rho) - \text{Tr}[\tilde{\rho}^2]) \quad (1)$$

to yield a unique estimate $\tilde{\rho}$ approximating the target state ρ , given operators $\{O_k\}$, and measured data $\{\hat{o}_k\}$. The purity term guides $\tilde{\rho}$ toward the target purity $\epsilon(\rho)$, mitigating nonuniqueness and improving accuracy over the standard LS method [17,58–60]. It can also be interpreted as minimizing the infidelity $1 - F(\tilde{\rho}, \rho) = 1 - (\text{Tr}[\sqrt{\tilde{\rho}\rho}])^2$ [61,62] when ρ is nearly pure and $\lambda = 1$ [63]. Relations to LS, ML estimator (MLE) [58,64,65], and compressed sensing estimator (CSE) [29,30] are detailed in Supplemental Material (SM) [66].

Analogous to Tikhonov regularization [67,68], the L -curve method can determine suitable λ and $\epsilon(\rho)$ in Eq. (1) [66], for the unknown state ρ . If the purity $\epsilon(\rho)$ is known or efficiently estimated from measured data (e.g., via randomized measurement [66,69]), λ can be obtained more efficiently using the method of Lagrange multipliers [66].

Moreover, imposing a pure-state constraint simplifies the estimator to a pure-state tomography protocol, which significantly reduces resource requirements [66].

The purity-regularized estimator incorporates purity guidance to reduce the inaccuracies of direct data fitting in LS and MLE, while enabling efficient and meaningful parameter selection that avoids overhead of CSE. For scalability (e.g., to 17 qubits), we leverage Pauli sparsity [70] and large-scale approximate optimization [71] to construct a noniterative solver offering accurate, scalable estimation. To further improve accuracy, we adopt the widely used ML readout mitigation to correct noisy measurement data and suppress error effects [66].

Witnessing genuine multipartite entanglement—For every entangled state ρ , there exists a Hermitian witness $\mathcal{W}$ such that $\text{Tr}[\mathcal{W}\rho] < 0$, and $\text{Tr}[\mathcal{W}\sigma] \geq 0$ for all separable states σ [52]. Here, we choose

$$\mathcal{W}_{\text{GHZ}} = \frac{1}{2} \mathbb{1} - |\text{GHZ}_N\rangle\langle\text{GHZ}_N| \quad (2)$$

for the N -qubit GHZ state $(|\underbrace{0\dots 0}_N\rangle + |\underbrace{1\dots 1}_N\rangle)/\sqrt{2}$, and

$$\mathcal{W}_W = \frac{N-1}{N} \mathbb{1} - |W_N\rangle\langle W_N| \quad (3)$$

for the N -qubit W state $(|1, \dots, 0\rangle + \dots + |0, \dots, 1\rangle)/\sqrt{N}$. The witness value satisfies $\text{Tr}[\mathcal{W}\rho] = \alpha - \langle\psi|\rho|\psi\rangle = \alpha - F(\rho, |\psi\rangle\langle\psi|)$, with $\alpha = 1/2$ for the GHZ and $(N-1)/N$ for the W state. Thus, entanglement certification reduces to fidelity estimation between the prepared state ρ and the known pure state $|\psi\rangle$, readily achieved by our estimator. Alternatively, tools like DFE and CS via randomized measurements can also estimate $\text{Tr}[\mathcal{W}\rho]$ to verify entanglement without full state reconstruction, serving as a cross-validation of the accuracy of our estimator.

Experimental setup—As depicted in Fig. 2(a), the superconducting processor, which integrates transmon qubits and couplers, is situated in a dilution refrigerator and maintained at a base temperature of approximately 10 mK. These qubits are configured in a binary tree topology and interconnected through frequency-tunable couplers. This configuration allows for selective idling of couplers to mitigate the undesired ZZ couplings and hence enabling high-quality adiabatic controlled-Z gates between adjacent qubits [72,73]. Additionally, the XY lines of qubits are integrated with the Z lines of couplers to enhance its design scalability [74], and the three-quarters lambda Purcell filter is further introduced to extend the Purcell T_1 limit and to further improve the readout fidelity. As shown in Fig. 2(b), 17 superconducting qubits are utilized, and the median fidelity is achieved with 0.9987 for the single-qubit gates, 0.9811 for the two-qubit gates, and 0.9740 and 0.9260 for the readout states $|0\rangle$ and $|1\rangle$. The specifications of the processor are detailed in SM [66].

On this processor, W states with up to 9 qubits and GHZ states with up to 17 qubits are generated. The circuits used for state preparation are implemented with logarithmic-depth complexity [75] and are explicitly laid out in SM [66]. For states of 3, 6, and 9 qubits, measurements are performed on all $S = 3^N$ Pauli operators $\{\sigma_x, \sigma_y, \sigma_z\}^{\otimes N}$, while almost $S = 10^3$ operators are unrepeatedly sampled for 12- and 17-qubit GHZ states, with 10^4 shots measured per operator. To demonstrate the generality of our method, we also provide extensive experimental results on random mixed states [66,76].

The state estimator in Eq. (1) is optimized via the projected gradient descent algorithm, due to its superior convergence properties [77]. An alternative method to ensure the physicality of estimate $\tilde{\rho}$ has also been proposed in [78]. In contrast, the DFE method selects 10^4 operators $\{O_k\}$ with probabilities $p_k = (\text{Tr}[O_k|\psi\rangle\langle\psi|])^2 > 0$ [43], where $|\psi\rangle$ represents a W or GHZ state, with 10^4 shots per operator. Since only $\mathcal{O}(d)$ operators O_k have nonzero probabilities, the DFE method is efficient for fidelity estimation of W and GHZ states. The CS method, on the other hand, randomly samples 10^5 operators with replacement from the measured set and samples a random basis measurement from 10^4 shots data for each operator [46].

Experimental results—Our first main result is the full-state tomography of multiqubit entangled states, with the

qubit number N up to 9 for the W state and 17 for the GHZ state, shown in Fig. 2(c). By calibrating the readout error with ML technique, we obtain tomography fidelity 0.8217 (1) for the 9-qubit W state and 0.7933(1) for the 12-qubit GHZ state. It is evident from Fig. 2(c) that the regularized LS in Eq. (1) outperforms the LS and MLE. Notably, we report the experimental full-state tomography of the 17-qubit GHZ state with fidelity 0.6817(1), further reaches fidelity 0.7587(1) under pure-state tomography. The main parts of all final reconstructed density matrices are illustrated in SM [66]. These results demonstrate the scalability of our approach for larger-scale quantum systems.

Our second main result is the certification of genuine multiqubit entanglement on the processor. As shown in Fig. 2(d), with error mitigation, entanglement witnesses are conclusively violated using our regularized LS in Eq. (1), achieving $\text{Tr}[\mathcal{W}\rho] < 0$ with values -0.0274 for the 6-qubit W state and -0.1817 for the 17-qubit GHZ state, hence confirming the presence of genuine multiqubit entanglement. Comparable violations observed via DFE and CS further confirm the reliability of our method. Fidelity above 0.8889 is needed to verify entanglement on the 9-qubit W state, which is achievable under the pure-state tomography protocol [66], while the mixed-state case requires improved hardware capabilities.

Our experimental results reported in Figs. 2(c) and 2(d) also highlight the critical role of error mitigation in QST and entanglement verification for noisy quantum systems, although these tasks can be accomplished without mitigation on 3-qubit systems. Particularly, readout error mitigation for up to 9-qubit W states and up to 17-qubit GHZ states lead to significant improvements of up to 0.46 in state fidelity [66]. Our results confirm the great utility of

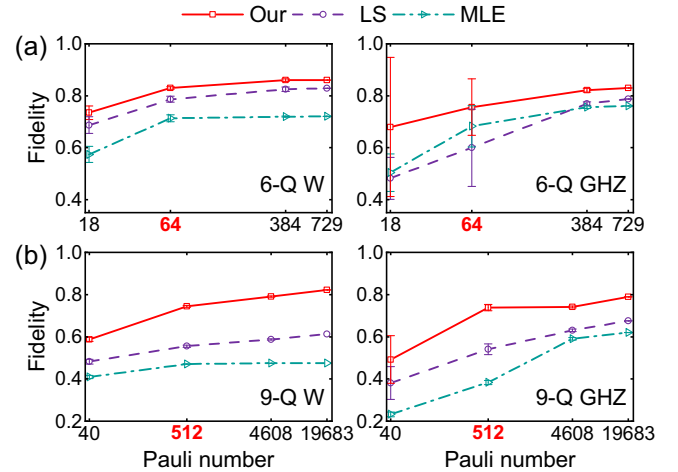


FIG. 3. The state fidelity obtained with randomly sampled S Pauli operators for the W and GHZ states of (a) 6 and (b) 9 qubits, using regularized LS in Eq. (1), LS, and MLE. S is chosen as $N^2/2, 2^N, N2^N, 3^N$ ($d = 2^N$ is marked in red color). The data are calibrated with the ML readout mitigation, and error bars are computed from 20 experiments with random initial conditions.

readout error mitigation in characterizing noisy quantum systems, complementary to numerical simulations and GHZ-state-based experimental validations [49,50,53,54].

Finally, the full-state tomography is tested with a randomly sampled incomplete set of Pauli operators. It is first natural to find in Fig. 3 that an increase in the number of measurement settings improves the tomography accuracy of these methods. It is then observed that, compared to other methods, our protocol exhibits superior tomography accuracy with limited measurement resources [such as $\mathcal{O}(d)$], which is further confirmed by the random-state experiments [66]. These results indicate that our method operates effectively under limited measurement and computational resources, making it well suited for scaling to larger quantum systems.

Conclusion—We have presented a QST approach via a purity-regularized LS estimator, experimentally validating it on a superconducting processor. In terms of scalability, our method successfully achieves full-state tomography of a 17-qubit GHZ state with fidelity above 0.68, reaching fidelity 0.75 under pure-state constraints. Moreover, genuine multiqubit entanglement is conclusively certified, and readout error mitigation is shown to be crucial for accurate characterization in noisy quantum processing tasks. Our findings highlight the critical role of incorporating prior knowledge, such as state purity, in boosting reconstruction accuracy. This provides an effective pathway toward more accurate full characterization of noisy intermediate-scale quantum systems, with promising applications in large-scale device calibration, quantum algorithm engineering, and fundamental tests of quantum theory.

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Data availability—The data that support the findings of this Letter are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project.

The data are available from the authors upon reasonable request.

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