Quantum teleportation exemplifies how the transmission of quantum information starkly differs from that of classical information and serves as a key protocol for quantum communication and quantum computing. While an ideal teleportation protocol requires noiseless quantum channels to share a pure maximally entangled state, the reality is that shared entanglement is often severely degraded due to various decoherence mechanisms. Although the quantum noise induced by the decoherence is indeed a major obstacle to realizing a near-term quantum network or processor with a limited number of qubits, the methodologies considered thus far to address this issue are resource-intensive. Here, we demonstrate a protocol that allows optimal quantum teleportation via noisy quantum channels without additional qubit resources. By analyzing teleportation in the framework of generalized quantum measurement, we optimize the teleportation protocol for noisy quantum channels. In particular, we experimentally demonstrate that our protocol enables to teleport an unknown qubit even via a single copy of an entangled state under strong decoherence that would otherwise preclude any quantum operation. Our work provides a useful methodology for practically coping with decoherence with a limited number of qubits and paves the way for realizing noisy intermediate-scale quantum computing and quantum communication.

**RESULTS**

**Protocol**

Consider the schematic of quantum teleportation via noisy quantum channels as shown in Fig. 1. Alice has an arbitrary
unknown quantum state $\rho$, which she wishes to transmit to Bob without physically transporting the qubit. An entangled state $|\psi\rangle_{AB}$ is distributed to Alice and Bob via noisy quantum channels, resulting in sharing a mixed entangled state $\mathcal{E}(\langle\psi\rangle_{AB}|\psi\rangle)$, where $\mathcal{E} = \{\hat{E}\}$ represents the decoherence channel with $\hat{E}$ denoting the Kraus operator for the noise operation. For teleportation, Alice performs joint measurement on the basis $\{|W_i\rangle\}_{i=0}^3$ on qubit $a$ with the state $\rho_a$ and qubit $B$, the mixed entangled state $\mathcal{E}(\langle\psi\rangle_{AB}|\psi\rangle)$ shared between Alice and Bob. In the framework of generalized quantum measurement, the noisy channel and the joint measurement together constitute an effective generalized quantum measurement. That is, after the joint measurement, the reduced state in mode $B$ can be written as

$$a_{x}(\hat{W}_{i}^{x}|\rho|^\mathcal{E}(\langle\psi\rangle_{AB}|\psi\rangle)|\hat{W}_{i}^{x}) = \sum_{x} \hat{M}^{x}_{a}\rho_{a}^{x}\hat{M}^{x}_{a},$$

for the outcome $r$. Here, we define an effective operator $\hat{M}^{x}_{a}$, satisfying the completeness relation, $\sum_{x} \hat{M}^{x}_{a} = 1$, to represent quantum measurement whose input ($a$) and output ($b$) modes are spatially separated. The measurement result is then sent to Bob via a classical channel and Bob performs an appropriate reversing operation $\hat{R}^{b}$ to obtain an output state $\rho_{b}$, i.e., $\hat{R}^{b}(\sum_{x} \hat{M}^{x}_{a}\rho_{a}^{x}\hat{M}^{x}_{a}) \hat{R}^{b} = \rho_{b}$. Here, the reversing operation is designed to reverse the effective quantum measurement by a non-unitary operation. As the effective quantum measurement encapsulates the joint measurement and the entangled state distributed via a noisy quantum channel, the reversing operation can be optimized relying on the prior information on the noise affecting the entangled state.

Our teleportation protocol can be thus generally represented by a quantum measurement $\mathcal{M}_{a\rightarrow b}$ and its reversal process $\mathcal{R}$, i.e., $\langle\mathcal{R}\cdot\mathcal{M}\rangle_{a\rightarrow b}(\rho_{a}) \propto \rho_{a}^{34,35}$. This framework encompasses all the previously proposed teleportation protocols, in which the reversing operation is limited to a conditional unitary operation $\hat{R} = \hat{U}$ (referred to as the conventional teleportation protocols in what follows). It recovers the original teleportation protocol if the joint measurement is performed on the Bell basis and Bob applies a conditional Pauli operation. Our teleportation protocol can be optimized for a given quantum channel $\mathcal{E}(\langle\psi\rangle_{AB}|\psi\rangle)$ by modifying the joint measurement performed by Alice and the reversing operation performed by Bob (i) to maximize the average teleportation fidelity $F$, indicating the closeness between the input $\rho_{a}$ and the teleported state $\rho_{b}$ and then (ii) to maximize the overall success probability $P$ as well as the given fidelity (see Supplementary Note 1 for details). For a noiseless channel, we can always find protocols to recover the input state faithfully $\hat{R} \cdot \mathcal{M} \cdot \rho_{a} \cdot \hat{R}^{\dagger} = \rho_{a}$, i.e., $F = 1$. The protocol can be then optimized such that the success probability $P$ reaches up to the fundamental limit in terms of the trade-off relation between $P$ and the amount of extracted information $G$ by $\mathcal{M}_{a\rightarrow b}$, i.e., $6G + P \leq 4^{35-39}$. It implies that the more information is extracted by $\mathcal{M}_{a\rightarrow b}$, the less possible the teleportation succeeds. In the presence of noise, we optimize the protocol to yield the maximum teleportation fidelity

$$F = \int d\psi \sum_{r} p(r, \psi)(\psi|\rho_{a}|\psi),$$

where $p(r, \psi) = \sum_{x} \langle\psi|\hat{M}^{x}_{a\rightarrow b}\hat{M}^{x}_{a\rightarrow b}|\psi\rangle$ is the probability obtaining the outcome $r$ and $\rho_{a}(\psi)$ is the output state when the teleportation succeeds (here we assume a pure input state $|\psi\rangle$ for simplicity, but the definitions are generally valid for any input state). The teleportation fidelity exceeding the classical limit $F > 2/3$ ensures genuine quantum teleportation of a qubit via a noisy channel.

In what follows, we shall first experimentally demonstrate that our protocol allows the teleportation fidelity $F = 1$ and saturates the trade-off relation, $6G + P = 4$ via noiseless quantum channels. This demonstration involves a pure non-maximally entangled state between Alice and Bob. Note that, for a pure non-maximally entangled channel, the original teleportation protocol does not yield $F = 1$. Moreover, probabilistic protocols proposed so far to achieve $F = 1$ either uses ancillary qubits, requires nontrivial joint measurement, or is unable to reach the maximum bound of $P$ in view of $6G + P = 4$. Then, we demonstrate that our protocol enables quantum teleportation with fidelity beyond the classical limit even via highly noisy quantum channels that would make it impossible to perform teleportation with conventional protocols.

**Experimental demonstration**

The experimental schematic for demonstrating optimal teleportation via noisy quantum channels is shown in Fig. 2a. Ultraviolet femtosecond laser pulses are used to pump spontaneous parametric down-conversion (SPDC) processes to prepare a pair of polarization-entangled photonic qubits in modes $A$ and $B$ as $|\psi\rangle_{AB} = (|10\rangle_{AB} + |11\rangle_{AB})/\sqrt{2}$ and to prepare a heralded single-photon polarization state in mode $a$ as
to Eq. (1), the effective quantum measurement is given as success probability $P = \cos^2(\theta/2)\cos^2(\phi/2)$. The reversing operation was found to be $\hat{R}_B = U^\dagger \begin{pmatrix} \cos(\theta/2) & \sin(\phi/2) \\ -\sin(\phi/2) & \cos(\theta/2) \end{pmatrix} U$ for $\theta \leq \phi$. Here, $U$ is the unitary operator determined by the measurement outcome $r$ and, for $r = 1$, $U$ is the identity operator. Therefore, the effective quantum measurement $M_1$ and the reversing operation $\hat{R}_B$ applied to the three qubits $a$, $A$, and $B$, respectively, destroys the qubit state of a photon $a$ and faithfully reconstructs it at photon $B$, i.e., $\hat{R}_B M_1 |\psi\rangle_a = \sin(\theta/2) \sin(\phi/2) |a(0)\rangle_a + \beta |1\rangle_B$. In the experiment, the joint measurement basis was chosen to be the Bell basis by setting $\phi = \pi/2$ to satisfy the condition $\theta \leq \phi$ for arbitrary values of $\theta$ ($0 \leq \theta \leq \pi/2$). The reversing operation was implemented with beam displacers (BD) and half-wave plates (HWP). We find the average fidelity as we chose six initial states in mutually unbiased bases on the Bloch sphere, i.e., $|0\rangle$, $|1\rangle$, $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$, $|-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$, $|+i\rangle = (|0\rangle + i|1\rangle)/\sqrt{2}$, and $|-i\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$.

In order to experimentally obtain $G$ by the effective quantum measurement and $P$ by the reversing operation, quantum teleportation is performed for all four joint measurements (not simultaneously, but two at a time), see “Methods” for details on evaluating $G$ and $P$. Figure 3a shows the experimentally obtained trade-off relation between $G$ and $P$ for five different pure non-maximally entangled states. It is clear that our teleportation protocol saturates the trade-off relation $6G + P = 4$, i.e., is optimal in the sense that the performance of the teleportation reaches the fundamental upper bound. The result demonstrates that “the more information on the input state is extracted by Alice, the less possible the teleportation becomes successful”. The teleportation fidelity, which can be estimated by performing quantum state tomography (QST) between the input qubit states in mode $a$ and of the teleported qubit states in mode $B$, in the cases of sharing a Bell state or other pure non-maximally entangled states have also been obtained, see, for example, Fig. 3b, c. The teleportation fidelity always far exceeds the classical limit of $2/3$: Fig. 3b, c exhibits the average fidelities of 0.938 and 0.915, respectively. Slightly reduced fidelity from the ideal value of 1 can be attributed to a number of experimental imperfections, e.g., the fidelity of 0.98 for shared entangled states, lowered two-photon visibility of 0.97 due to remaining partial distinguishability of the photons for the joint measurement, and the interferometric reversing operation with the visibility of 0.96. See Supplementary Note 2 for further details.
We now describe the demonstration of the optimal teleportation via an entangled state under strong decoherence. Here, we consider the amplitude damping in mode B. Note that this framework is generally applicable to the decoherence in mode A and also for the dephasing and depolarizing decoherence. For this demonstration, the decoherence channel is inserted in the path of photon B, at the same time removing PPBS1, see Fig. 2. The mixed entangled state shared between A and B is given as \( \langle 00 \rangle_{AB} + \sqrt{1 - D} \langle 11 \rangle_{AB} \), where \( D \) is the degree of decoherence. After the joint measurement in the basis \( |W_r\rangle_{A} \), with the measurement outcome \( r \), the reversing operation \( U(\sqrt{1 - D}|0\rangle\langle 0| + |1\rangle\langle 1|) \) is applied to optimally reconstruct the initial state of qubit a at mode B. See “Methods” for further details.

Figure 4 presents both the theoretically and experimentally obtained average teleportation fidelities \( F \) by varying degrees of decoherence \( D \). The colored region in Fig. 4 represents the available teleportation fidelities by our protocol beyond the reach of the conventional protocols based on the unitary reversing operation. The experimental results clearly demonstrate that our protocol enables quantum teleportation even under strong decoherence that would otherwise preclude any quantum operations. For instance, if \( D \geq 0.5 \), the mixed entangled state would not violate Bell’s inequality. \(^{54} \) However, even for very strong decoherence values of \( D = 0.74 \) and \( D = 0.92 \), our protocol allows to teleport unknown quantum states significantly beyond the classical limit \( F > 2/3 \). Note that, for amplitude damping decoherence, our teleportation protocol achieves even higher teleportation fidelities if Alice and Bob share a pure non-maximally entangled state. The teleportation fidelity can be enhanced arbitrarily close to unity by decreasing the success probability depending on how much the channel has decohered. The experimental results and detailed analysis for this specific case are presented in Supplementary Note 3.

**DISCUSSION**

We have proposed and experimentally demonstrated a protocol for optimal quantum teleportation via noisy quantum channels, which does not require any additional qubits. We have shown that quantum teleportation can be generally optimized in the framework of generalized quantum measurements and corresponding reversing operations. This approach allows to teleport an unknown qubit via a single copy of an entangled state under strong decoherence that would otherwise preclude any quantum operations. In particular, we have experimentally demonstrated that our protocol enables quantum teleportation even through highly noisy quantum channels, overcome the limit of the conventional teleportation protocols based on the unitary reversing operation.

In order to cope with the effects of noise in the quantum channel during quantum teleportation, two different approaches may be considered. One approach is to recover the entangled state from the effect of noise to carry out the conventional teleportation protocol. Schemes to recover two-qubit entanglement from the noise in the quantum channel include entanglement distillation/concentration, protecting entanglement by weak measurement and reversal, and controlling open quantum system. The other approach is to modify the teleportation protocol itself to adapt to the noisy quantum channel. In this work, by analyzing teleportation in the framework of generalized quantum measurement, we optimize the teleportation protocol itself for noisy quantum channels, offering clear advantages over the above-mentioned approaches. Unlike entanglement concentration/purification schemes, multiple copies of identically decohered two-qubit entangled states are not required and our teleportation protocol achieves optimal quantum teleportation (i.e., saturating the fundamentally achievable fidelity and maximizing the success probability for a given fidelity) of an unknown qubit via a single copy of an entangled state under
strong decoherence that would otherwise preclude any quantum operations. Similarly to other approaches for tackling decoherence in quantum information processing, our optimal quantum teleportation protocol requires prior information of the channel noise so as to determine proper quantum measurement and reversing operations: recent advances in quantum process tomography\cite{59} and noise characterization techniques\cite{60,61} offer systematic and efficient approaches for obtaining the information about the quantum noise in the channel.

While there has been immense progress in quantum information processing and long-distance quantum communication in recent years, degradation of entanglement due to noise remains to be an important issue to address in constructing scalable quantum systems. Our work provides insights into practically coping with decoherence with a limited number of qubits and paves the way for realizing noisy intermediate-scale quantum technologies. Potential directions of future research include entanglement-based quantum communication (e.g., long-distance quantum teleportation, deterministc secure quantum communication, etc.) and distributed quantum information processing in a noisy environment.

METHODS

Details on the experimental setup

The SPDC process was pumped by a 390-nm centered ultrafast pulse ($\sim 140$ fs) and the central wavelength of the SPDC photons is 780 nm. The polarization-entangled photonic qubit pair, $|Ψ_{ab}\rangle = (|00\rangle_α + |11\rangle_α)/\sqrt{2}$, was then prepared by using two 1-mm thick type-II BBO crystals in the frequency-degenerate beamlike SPDC configuration, with a HWP sandwiched between them and a set of compensating crystals to remove spatial and temporal distinguishability\cite{35,47}. The generated polarization-entangled qubit pair is shared between Alice and Bob.

The arbitrary initial state $|ψ_{a}\rangle$ to be teleported from Alice to Bob was prepared by using another 1-mm thick BBO crystal in the frequency-degenerate beamlike SPDC configuration. One photon of the SPDC photon pair is detected at $D_2$, heralding the presence of a single photon in mode $a$. The polarization qubit state for the single photon in mode $a$, $|ψ_{a}\rangle$, was then prepared by using the set of HWP and QWP. Joint measurements $|ψ_{a}\rangle$ and $|ψ_{b}\rangle$ were implemented by two-photon quantum interference and coincidence detection\cite{51,52}. To improve quantum interference, 2 mm full-width at half-maximum interference filters were used in front of all detectors to further reduce any remaining spectral/temporal distinguishability between the two single photons.

The joint measurement between photons $a$ and $b$, analogous to the Bell measurement in conventional teleportation protocols, is to be performed in the following basis set: $|Ψ_{ab}\rangle_ω = \cos{(ψ/2)|0\rangle}_ω + \sin{(ψ/2)|1\rangle}_ω$, $|Ψ_{ab}\rangle_ω = \cos{(ψ/2)|0\rangle}_ω - \sin{(ψ/2)|1\rangle}_ω$, $|Ψ_{ab}\rangle_ω = \cos{(ψ/2)|0\rangle}_ω + \sin{(ψ/2)|1\rangle}_ω$, and $|Ψ_{ab}\rangle_ω = \cos{(ψ/2)|0\rangle}_ω - \sin{(ψ/2)|1\rangle}_ω$. In the experiment, by setting the HWP1 angle in Fig. 2, at $ψ_1 = \pi/4$, joint measurement between detectors D1–D2 or D3–D4 implements $|Ψ_{ab}\rangle$ measurement and joint measurement between detectors D1–D3 or D2–D4 implements $|Ψ_{ab}\rangle$ measurement. For the remaining two joint measurements $|Ψ_{ab}\rangle$ and $|Ψ_{ab}\rangle$, they are similarly performed by setting $ψ_1 = 0$.

The amplitude damping decoherence channel is given by $ɛ_r(|Ψ_{ab}\rangle_ω) = Ė_{a} |Ψ_{ab}\rangle_ω Ė_{a}^† + Ė_{b} |Ψ_{ab}\rangle_ω Ė_{b}^†$, where the Kraus operators are $( Ė_{a} = |0\rangle_ω \langle 0| + \sqrt{1 - D}|1\rangle_ω \langle 1|$, $ Ė_{a} = |0\rangle_ω \langle 0| + \sqrt{1 - D}|1\rangle_ω \langle 1|)$. In experiment, $ Ė_{a}$ is implemented by a partially polarizing beam splitter BPBSB and $ Ė_{a}$ is implemented by reflection at BPBSB and HWP at $\pi/4$. Incoherent mixing of the two processes results in the amplitude damping decoherence channel.

Consider a pure arbitrary entangled state $|Ψ_{ab}\rangle_ω = \cos{(ψ/2)|0\rangle}_ω + \sin{(ψ/2)|1\rangle}_ω$, with $0 \leq ψ \leq 2\pi$ as the quantum channel, where mode $B$ experiences the amplitude damping decoherence, and assume that the joint measurement is performed on the Bell basis ($ψ = \pi/2$). According to Eq. (1), the effective quantum measurement is then described by a set of operators:

\[ M_1 = \cos ψ |0⟩_b ⟨0| + \sqrt{1 - \cos^2 ψ} |1⟩_b ⟨1|, \]
\[ M_2 = \sqrt{\frac{1}{2}} \sin(θ/2) |0⟩_b ⟨0|, \]
\[ M_3 = -\sqrt{\frac{1}{2}} \sin(θ/2) |1⟩_b ⟨1|, \]
\[ M_4 = \sqrt{\frac{1}{2}} |0⟩_b ⟨0| + \sqrt{\frac{1}{2}} |1⟩_b ⟨1|. \]

In the presence of noise, the input state $|ψ_{a}\rangle$ is changed to $\sum_\lambda |ψ_\lambda⟩_a |ψ_\lambda⟩_b$ after the joint measurement as given in Eq. (1). In this case, the optimal reversing operator for the outcome $r$ is given by $R = \Lambda_{ab} |ψ_r⟩_a |ψ_r⟩_b$, where $\Lambda_{ab}$ yields the maximum smallest singular value, i.e., $Λ_{ab} = \max|x_{ab}^-|$. For the effective quantum measurement in Eq. (3), the optimal reversing operator is given by the form $R = U \tan(θ/2) |ψ⟩ |ψ⟩$, where $U = \{I, \gamma_+, \gamma_-, \gamma_0\}$ for $r = \{1, 2, 3, 4\}$. In the experiment, as $|0⟩$ and $|1⟩$ are encoded in the polarization states $|H⟩$ and $|V⟩$, respectively, the reversing operation can be implemented with a Mach–Zehnder interferometer built with polarization-dependent beam displacers and half-wave plates as shown in Fig. 2a. The Mach–Zehnder interferometer implements $cos^2(2φ)|0⟩ |0⟩ + |1⟩ |1⟩$, where $φ_r$ is the angle of HWP2.

Evaluation of information gain and success probability

Assume a quantum measurement, described by a set of operators $\{M_i\}$, applied to an arbitrary input state $|ψ⟩$ (a pure input state is considered for simplicity, but the definition is valid for any mixed states). To quantify the information gain, we use the mean estimation fidelity\cite{36}. In every trial, we can make a guess that the input state is $|ψ⟩$ for the outcome $r$. The quality of the guess can be evaluated by $\langle|ψ⟩|ψ⟩^2$. By averaging this over all possible input states and outcomes, we can define the information gain as $G = \langle\sum_r \langle|ψ⟩|M_r |ψ⟩ \langle|ψ⟩|ψ⟩^2\rangle$. The effective measurement in Eq. (3) with $D = 0$, the information gain is evaluated as $G = \langle(1 + \cos(θ/2))/3\rangle$.

In experiment, $G$ is estimated from the fourfold coincidence counts involving the detector $D_2$, the heralding detector $D_3$, and the joint measurement detectors shown in Fig. 2a. The probability of state projection is evaluated from the ratio of fourfold coincidences as $\langle|ψ⟩|M_r |ψ⟩ \langle|ψ⟩|ψ⟩^2\rangle / (\sum_r \langle|ψ⟩|M_r |ψ⟩ \langle|ψ⟩|ψ⟩^2\rangle)$, where $r = \{1, 2, 3, 4\}$. The quality of guess $\langle|ψ⟩|ψ⟩^2$ is obtained by calculating with the optimal guessing state, i.e., the eigenstate of a measurement operator corresponding to the largest eigenvalue\cite{36}. The average fidelity can be obtained by averaging any six input states forming a regular octahedron on Bloch sphere\cite{37}. Here, six input states $|0⟩, |1⟩, |+⟩, |−⟩, |+⟩, |−⟩$, and $|−⟩$ are used for evaluating the average fidelity.

In a noiseless scenario, an appropriate reversing operation chosen for each measurement operator can recover the input state faithfully, st., $R |M_r⟩ = \eta_r |ψ⟩$ for $|ε_r⟩$ is the success probability for each $r$. The maximum overall success probability of reversing operation is then given by $P = \max_r |ε_r|^2$. It was shown that the information gain and the success probability of reversing operation for a quantum measurement are in a trade-off relation as $td = 1 + G (d - 1) \geq 2d$ in arbitrary $d$-dimensional Hilbert space\cite{36}. For qubits $d = 2$, it becomes $G \geq 2$. For the effective measurement in Eq. (3) with $D = 0$, the maximum success probability of reversing operation is obtained as $P = 2sin^2(θ/2)$.

In the experiment, $P$ is estimated from the fourfold coincidence counts involving the detector $D_2$, the heralding detector $D_3$, and the joint measurement detectors shown in Fig. 2a. Similarly as before, the
probability of successful teleportation is evaluated from the ratio of fourfold coincidences as $\langle \psi | M_1^R R^T \tilde{M}_2^R | \psi \rangle / \sum \langle \psi | M_1^R M_2^R | \psi \rangle$.

**Optimal teleportation via noisy quantum channels**

Here, we consider optimal teleportation via a maximally entangled state under amplitude damping decoherence (on mode B). If the joint measurement is performed on $|W\rangle_{\text{in}} = (|0\rangle_{\text{in}} + |1\rangle_{\text{in}})/\sqrt{2}$, the effective quantum measurement is given as $\tilde{M}_1^R = (|0\rangle_{\text{R}} \langle 0| + \sqrt{1-D} |1\rangle_{\text{R}} \langle 1|)/2$ and $\tilde{M}_2^R = (\sqrt{D}/2 |0\rangle_{\text{R}} \langle 0| + |1\rangle_{\text{R}} \langle 1|)/2$. Then, the final output state at mode B is given by $|\rho_B = (1-D) (\alpha |0\rangle \langle 0| + \beta |1\rangle \langle 1|) + D (\alpha |1\rangle \langle 0| + \beta |0\rangle \langle 1|) + 4 |D(1-D) |0\rangle \langle 0| \rangle/4$, the corresponding reversing operator is $R_B = U = (\sqrt{I-D} |0\rangle \langle 0| + |1\rangle \langle 1|)/2$ and $R_B = (\sqrt{D}/2 |0\rangle \langle 0| + |1\rangle \langle 1|)/2$ from Eq. (3). The corresponding reversing operator is $R_B = U = (\sqrt{I-D} |0\rangle \langle 0| + |1\rangle \langle 1|)/2$ and $R_B = (\sqrt{D}/2 |0\rangle \langle 0| + |1\rangle \langle 1|)/2$ from Eq. (3). The correspond-

**DATA AVAILABILITY**

Data are available from the corresponding authors upon reasonable request.

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**REFERENCES**

1. Bennett, C. H. et al. Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. Phys. Rev. Lett. 70, 1895 (1993).
2. Duan, L.-M., Lukin, M. D., Cirac, J. I. & Zoller, P. Long-distance quantum communication with atomic ensembles and linear optics. Nature 414, 413 (2001).
3. Gottesman, D. & Chuang, I. L. Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature 402, 390 (1999).
4. Knill, E., Laflamme, R. & Milburn, G. J. A scheme for efficient quantum computation with linear optics. Nature 409, 46 (2001).
5. Bouwmeester, D. et al. Experimental quantum teleportation. Nature 390, 575 (1997).
6. Boschi, D., Branca, S., De Martini, F., Hardy, L. & Popescu, S. Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein-Podolsky-Rosen channels. Phys. Rev. Lett. 80, 1121 (1998).
7. Furusawa, A. et al. Unconditional quantum teleportation. Science 282, 706 (1998).
8. Kim, Y.-H., Kulik, S. P. & Shih, Y. Quantum teleportation of a polarization state with a complete bell state measurement. Phys. Rev. Lett. 86, 1370 (2001).
9. Ma, X.-S. et al. Quantum teleportation over 143 kilometres using active feed-forward. Nature 489, 269 (2012).
10. Ren, J.-G. et al. Ground-to-satellite quantum teleportation. Nature 549, 70 (2017).
11. Wang, X.-L. et al. Quantum teleportation of multiple degrees of freedom of a single photon. Nature 518, 516 (2015).
12. Graham, T. M., Bernstein, H. J., Wei, T.-C., Junge, M. & Kwiat, P. G. Superdense teleportation using hyperentangled photons. Nat. Commun. 6, 7185 (2015).
13. Barrett, M. Deterministic quantum teleportation of atomic qubits. Nature 429, 737 (2004).
14. Olmschenk, S. et al. Quantum teleportation between distant matter qubits. Science 323, 486 (2009).
15. Steffen, L. et al. Deterministic quantum teleportation with feed-forward in a solid state system. Nature 500, 319 (2013).
16. Pfaff, W. et al. Unconditional quantum teleportation between distant solid-state quantum bits. Science 345, 532 (2014).
17. Jou, K. S. et al. Deterministic teleportation of a quantum gate between two logical qubits. Nature 561, 368 (2018).
18. Wain, Y. et al. Quantum gate teleportation between separated qubits in a trapped-ion processor. Science 364, 875 (2019).
19. Lee, S. M., Lee, S-W., Jeong, H. & Park, H. S. Quantum teleportation of shared quantum secret. Phys. Rev. Lett. 124, 060501 (2020).
20. Llewellyn, D. et al. Chip-to-chip quantum teleportation and multi-photon entanglement in silicon. Nat. Phys. 16, 148 (2020).
21. Kwiat, P. G. et al. New high-intensity source of polarization-entangled photon pairs. Phys. Rev. Lett. 75, 4337 (1995).
22. Kim, Y.-H., Kulik, S. P., Chekhova, M. V., Grice, W. P. & Shih, Y. Experimental entanglement concentration and universal bell-state synthesizer. Phys. Rev. A 67, 010301 (2003).
23. White, A. G., James, D. F. V., Munro, W. J. & Kwiat, P. G. Exploring Hilbert space: accurate characterization of quantum information. Phys. Rev. A 65, 012301 (2001).
58. Kim, Y. et al. Direct quantum process tomography via measuring sequential weak values of incompatible observables. Nat. Commun. 9, 1 (2018).
59. Kim, Y. et al. Universal compressive characterization of quantum dynamics. Phys. Rev. Lett. 124, 210401 (2020).
60. Emerson, J. et al. Symmetrized characterization of noisy quantum processes. Science 317, 1893 (2007).
61. Harper, R., Flammia, S. T. & Wallman, J. J. Efficient learning of quantum noise. Nat. Phys. 16, 1184 (2020).

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AUTHOR CONTRIBUTIONS
S.-W.L. and Y.-H.K. planned and supervised the research; D.-G.I. performed the experiment and analyzed the data; all authors contributed to analysis and discussion of the results; D.-G.I., S.-W.L., and Y.-H.K. wrote the manuscript with input from all authors.

COMPETING INTERESTS
The authors declare no competing interests.

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