

Multipartite Mixed-Species Entanglement over a Quantum Network

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We generate multipartite entangled states of two, three, and four matter qubits, where the entanglement is distributed over macroscopic distances via a photonic network link. Trapped-ion $^{88}\text{Sr}^+$ qubits are entangled directly via an optical fibre link, and the entanglement is subsequently extended to $^{43}\text{Ca}^+$ memory qubits cotrapped in each network node, using local mixed-species logic gates. We create remotely entangled Sr^+-Ca^+ and Ca^+-Ca^+ states, as well as mixed-species Greenberger-Horne-Zeilinger (GHZ) states of up to four qubits. We demonstrate storage of the remotely entangled memory qubits for ~ 10 s, more than $100\times$ the state creation time.

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Introduction—Quantum networks enable the distribution of entanglement between physically separated systems. This capability is critical for a variety of quantum technologies such as entanglement-based cryptography [1], distributed quantum computing [2–4], quantum sensing [5], and metrology [6]. Many of these applications are based on the ability to repeatedly generate multipartite entangled states between separated modules during the execution of a protocol. Realizing these applications requires network modules that can not only establish remote entanglement but also process and store quantum information locally between subsequent rounds of entanglement generation. Therefore, integrating robust quantum memories with photonic interfaces into quantum networking modules is essential [7–11].

The generation of multipartite entanglement across network nodes is a key milestone toward scalable architectures. Multipartite entangled states underpin many advanced quantum networking protocols, such as networked quantum error correction, quantum secret sharing, and distributed sensing with entanglement-enhanced sensitivity [6,12,13]. Demonstrating such states in real networks is, therefore, essential to benchmark performance beyond bipartite entanglement.

At the same time, supporting multiple types of qubits within a quantum network is critical to building heterogeneous modular systems that combine the strengths of different types of qubits, such as optimal photonic coupling, high-fidelity logic, or long-lived memory [14–18]. Cross-qubit entanglement opens the door to hybrid quantum networks that can integrate diverse platforms or future-proof evolving hardware.

Trapped ions are among the leading candidates for quantum information processing due to their long coherence times [19], high-fidelity quantum gates [18,20–26], and robust state preparation and measurement protocols [27–29]. Furthermore, trapped ions naturally interface with optical photons, and photonic interconnects between ion-based modules have demonstrated state-of-the-art networking capabilities, enabling the generation of remote entanglement between qubits separated by macroscopic distances [30–33].

In trapped-ion quantum networks, it is often advantageous to separate the roles of photon generation and long-lived quantum storage across distinct qubit types. This separation can be realized either using different internal states of a single atomic species (dual-type encoding) [34,35] or by employing two different atomic species [16,36]. In this Letter, we present an elementary quantum network consisting of two mixed-species trapped-ion modules—each containing one $^{88}\text{Sr}^+$ ion and one $^{43}\text{Ca}^+$ ion—where the $^{88}\text{Sr}^+$ ion serves as the network interface and the $^{43}\text{Ca}^+$ ion provides a robust quantum memory [36]. We demonstrate the integration of local mixed-species operations with quantum networking by generating bipartite entangled states and multipartite Greenberger-Horne-Zeilinger (GHZ) states of up to four qubits. We also show enhanced storage of remote entanglement using the $^{43}\text{Ca}^+$ memory qubits, preserving entanglement between the modules for more than 10 s, which greatly exceeds the entanglement generation timescale (~ 100 ms).

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Quantum networking modules—The quantum networking apparatus comprises two trapped-ion modules connected by a quantum optical link, as depicted in Fig. 1(a). Each module comprises an ultrahigh vacuum chamber containing a microfabricated surface-electrode Paul trap, which is used to cotrap one $^{88}\text{Sr}^+$ and one $^{43}\text{Ca}^+$ ion (see Supplemental Material, Section S1 [37]). A ~ 0.5 mT magnetic field sets the quantisation axis and lifts the Zeeman state degeneracies, enabling the selection of pairs of energy states to form qubits, as outlined in Figs. 1(b) and 1(c). Specifically, $^{88}\text{Sr}^+$ provides an optical network qubit, $\mathcal{Q}_N = \{|0_N\rangle \equiv |S_{1/2}, m_J = -\frac{1}{2}\rangle, |1_N\rangle \equiv |D_{5/2}, m_J = -\frac{3}{2}\rangle\}$. The ground hyperfine manifold of $^{43}\text{Ca}^+$ provides a long-lived memory qubit, $\mathcal{Q}_M = \{|0_M\rangle \equiv |F = 4, m_F = 0\rangle, |1_M\rangle \equiv |F = 3, m_F = 0\rangle\}$, which has a first-order magnetic field

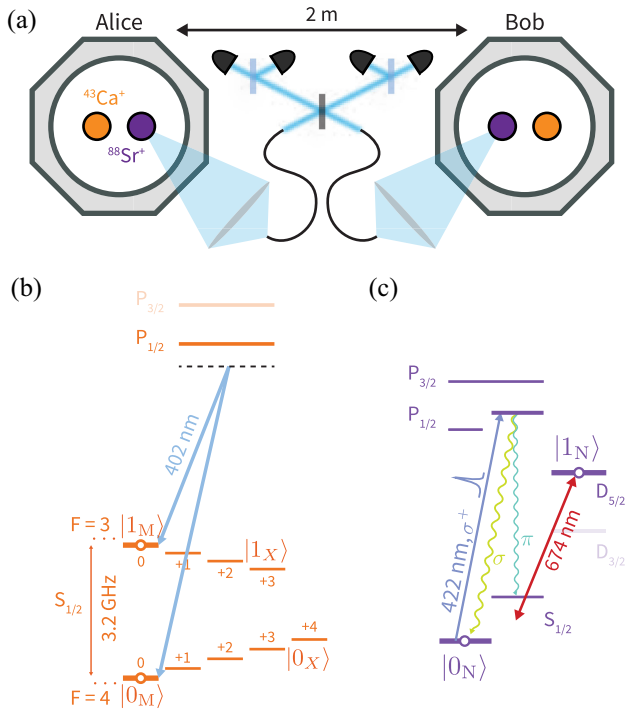


FIG. 1. Overview of mixed-species trapped-ion quantum networking. (a) Two modules, Alice and Bob, each cotrap one $^{88}\text{Sr}^+$ and one $^{43}\text{Ca}^+$ ion. High-numerical-aperture lenses collect single photons from the $^{88}\text{Sr}^+$ ions and couple them into optical fibers. The photons interfere at a central heralding station, where particular detection patterns herald the generation of entanglement between the Sr^+ ions in each module. (b) The ground hyperfine manifold of $^{43}\text{Ca}^+$ provides a robust memory qubit, $\{|0_M\rangle, |1_M\rangle\}$, and an auxiliary qubit $\{|0_X\rangle, |1_X\rangle\}$. Transitions between the states within this manifold are driven using a pair of 402 nm Raman beams. (c) The $^{88}\text{Sr}^+$ ion provides a network qubit, $\{|0_N\rangle, |1_N\rangle\}$, which is connected by the optical 674 nm quadrupole transition. Ion-photon entanglement is generated via the rapid excitation of the Sr^+ ion and subsequent decay via the 422 nm transition, generating entanglement between the polarization state of the spontaneously emitted photon and the ground Zeeman states of the $^{88}\text{Sr}^+$ ion.

sensitivity of 122 kHz mT^{-1} at 0.5 mT, roughly 2 orders of magnitude lower than that of the network qubit. In addition, an *auxiliary* qubit is defined in the ground hyperfine manifold of $^{43}\text{Ca}^+$, $\mathcal{Q}_X = \{|0_X\rangle \equiv |F = 4, m_F = +4\rangle, |1_X\rangle \equiv |F = 3, m_F = +3\rangle\}$. The auxiliary qubit is used in the state preparation and measurement of the memory qubit, as well as for mediating mixed-species quantum logic.

Within each module, laser beams are used for cooling, state preparation, coherent manipulation, and fluorescence detection of each species of ion. Single-qubit rotations of the $\mathcal{Q}_M$ and $\mathcal{Q}_X$ qubits are implemented using a pair of copropagating 402 nm Raman beams; single-qubit rotations of the optical network qubit, $\mathcal{Q}_N$, are implemented using a 674 nm laser to drive the quadrupole transition connecting the qubit states, as shown in Fig. 1. To perform mixed-species entangling gates between the two ions, we follow Ref. [18], in which the interference pattern generated by a pair of non-co-propagating Raman beams gives rise to a $\sigma_z \otimes \sigma_z$ -type spin-dependent force (see Supplemental Material, Section S2 [37]). This spin-dependent force is used to implement geometric phase gates between the $\mathcal{Q}_N$ and $\mathcal{Q}_X$ qubits. As this gate mechanism does not couple to the $\mathcal{Q}_M$ qubit, we require the ability to coherently interconvert between the $\mathcal{Q}_M$ and $\mathcal{Q}_X$ qubits. This conversion is performed using the copropagating Raman beams to coherently address the transitions within the ground hyperfine manifold of Ca^+ (see Supplemental Material, Section S2 [37]).

Complementing the ability to perform local quantum operations with the two ions in each module, another critical tool is the ability to establish remote entanglement between the two network qubits in separate modules. This is achieved using a two-photon try-until-success protocol [78–81], outlined in Ref. [31]. Each entanglement generation attempt begins with the preparation of the Sr^+ ion in each module in the $|0_M\rangle = |S_{1/2}, m_J = -\frac{1}{2}\rangle$ state in the ground Zeeman manifold using approximately 320 ns of optical pumping. A ~ 10 ps pulse of σ^+ polarized 422 nm light excites the Sr^+ ion to the $|P_{1/2}, m_J = +\frac{1}{2}\rangle$ state, which has a lifetime of 7 ns. The excited state decays to the ground Zeeman states, resulting in the spontaneous emission of a 422 nm photon [82]. The spontaneously emitted photons are collected from each module using high-numerical-aperture imaging systems, which couple the photons into single-mode optical fibers. These fibers bring the spontaneously emitted photons from each module to a central heralding station, where a projective Bell state measurement is performed on the photons. Particular measurement outcomes herald the successful generation of entanglement between the Zeeman states of the Sr^+ ions in the two modules. Finally, a 674 nm pulse maps one of the Zeeman states into the $D_{5/2}$ manifold, thereby establishing the remote entanglement of network qubits.

Characterization of entangled states—In this Letter, we combine the ability to generate remote entanglement between

trapped-ion modules with local mixed-species quantum logic to create higher-dimensional entangled states. In particular, we consider N -particle states of the following form:

$$|\psi\rangle = \frac{|0\rangle^{\otimes N} + e^{i\varphi}|1\rangle^{\otimes N}}{\sqrt{2}}, \quad (1)$$

where for $N = 2$, this is the $|\Phi^+\rangle$ Bell state, and for $N > 2$, this is the N -particle GHZ state, up to a phase φ .

We characterize the generated multipartite states using both partial [83] and full state tomography (see Supplemental Material, Section S3 [37]). Full state tomography enables the complete reconstruction of the density matrix representing the quantum state of the ions from a tomographically complete set of single-qubit measurements. Partial state tomography assumes that the ideal target states have the form given by Eq. (1); thus, to characterize the fidelity of the produced state to a particular target state, it is sufficient to perform population measurements, i.e., measurements of all qubits in the computational basis to determine $P = \mathbb{P}(|0\rangle^{\otimes N}) + \mathbb{P}(|1\rangle^{\otimes N})$, and parity measurements, i.e., measurements of all qubits in the $\hat{\sigma}_\phi = \cos(\phi)\hat{\sigma}_x + \sin(\phi)\hat{\sigma}_y$ basis. Given quantum states of the form of Eq. (1), we anticipate that the expectation values for the parity measurements will be of the following form:

$$\left\langle \bigotimes_{n=1}^N \hat{\sigma}_{\phi,n} \right\rangle = C \cos(N\phi - \varphi), \quad (2)$$

where C and φ are the parity contrast and phase, respectively. By performing these population and parity measurements, we can estimate the fidelity to the target state, up to the parity phase offset, as

$$\mathcal{F} = \frac{P + C}{2}. \quad (3)$$

A summary of all the entanglement fidelities and average generation rates for the remotely entangled states generated in this Letter is given in Table I.

Bipartite mixed-species entanglement—We first characterize remotely entangled bipartite states, i.e., states with

$N = 2$, starting with the remote entanglement of two network qubits, shown in Fig. 2(a). Full state tomography with 200,000 tomographic measurements of the Sr^+ - Sr^+ ions yielded a density matrix representing a state with an entanglement fidelity of 96.94(9)%. This is consistent with the results of partial state tomography, shown in Fig. 2(a), which yielded a fidelity of 96.0(7)%. The average entanglement generation success probability was measured to be $1.236(3) \times 10^{-4}$. We suppress excess heating during entanglement generation by interleaving 500 μs of entanglement generation attempts with approximately 320 μs of Doppler cooling on both Ca and Sr and 500 μs of electromagnetically induced transparency (EIT) cooling on the axial modes of the crystal via Sr^+ . Including this cooling, we observe a net entanglement generation rate of $39.31(9) \text{ s}^{-1}$. A comparison with earlier results in the same setup and a discussion of the impact of cooling on the remote entanglement fidelity are provided in Supplemental Material, Section S5 [37].

We combine this remote entanglement generation between each module's network qubits with local operations to create mixed-species entangled states. In particular, we use local mixed-species iSWAP gates to transfer the quantum states of the remotely entangled network qubits to the Ca^+ auxiliary qubits, thereby enabling the generation of remotely entangled Sr^+ - Ca^+ and Ca^+ - Ca^+ states, as shown in Figs. 2(b) and 2(c), respectively. To enhance the fidelity of this quantum state transfer process, we perform mid-circuit measurements of the Sr^+ ions after the iSWAP gates to detect errors in the mixed-species gates (see Supplemental Material, Section S2 [37]). The modules exchange the outcomes of these measurements in real time via a classical communication link connecting the two control systems, allowing them to abort and restart the experiment if either module detects an error.

As with the Sr^+ - Sr^+ entangled state, we characterize the Sr^+ - Ca^+ and Ca^+ - Ca^+ remotely entangled states using both full and partial state tomography. In these experiments, the Sr^+ qubit and the auxiliary qubit Q_X of $^{43}\text{Ca}^+$ are used, while the $^{43}\text{Ca}^+$ memory qubit is not employed. Full state tomography with 10,000 tomographic

TABLE I. Summary of mixed-species remotely entangled states characterized in this Letter. This table includes the observed entanglement fidelities extracted from both partial state tomography (PST) and full state tomography (FST). The density matrices extracted from FST can be found in Supplemental Material, Section S3 [37].

Ions			Fidelity		Total success probability	Average rate
Alice	Bob	State	PST (%)	FST (%)	$\times 10^{-4}$	s^{-1}
Sr^+	Sr^+	$ 0_N 0_N\rangle + 1_N 1_N\rangle$	96.0(7)	96.94(9)	1.236(3)	39.31(9)
Sr^+	Ca^+	$ 0_N 0_X\rangle + 1_N 1_X\rangle$	95.1(8)	94.1(6)	1.03(1)	7.14(7)
Ca^+	Ca^+	$ 0_X 0_X\rangle + 1_X 1_X\rangle$	92(1)	93.1(7)	1.24(1)	8.6(1)
Sr^+	Sr^+, Ca^+	$ 0_N 0_N 0_X\rangle + 1_N 1_N 1_X\rangle$	94(1)	93.1(7)	1.20(1)	8.26(8)
Sr^+, Ca^+	Sr^+, Ca^+	$ 0_N 0_N 0_X 0_X\rangle + 1_N 1_N 1_X 1_X\rangle$	91(1)	91.9(8)	1.44(2)	9.9(1)

measurements yielded density matrices representing states with entanglement fidelities of 94.1(6)% and 93.1(7)% for the Sr^+-Ca^+ and Ca^+-Ca^+ states, respectively. The parity and/or population measurements for the Sr^+-Ca^+ and Ca^+-Ca^+ states are shown in Figs. 2(b) and 2(c), respectively. From these measurements, we extract entanglement fidelities of 95.1(8)% and 92(1)% for the Sr^+-Ca^+ and Ca^+-Ca^+ states, respectively. The error detection following the iSWAP gate reduces the infidelity of the Sr^+-Ca^+ and Ca^+-Ca^+ entangled states by 4.2(2)% and 8.4(2)%, respectively. For these experiments, we interleave 200 μs of entanglement generation attempts with 500 μs of Doppler cooling and 500 μs of EIT cooling of the out-of-phase mode using the Sr^+ ions since the local mixed-species operations require the motional mode used to be cooled close to its ground state, resulting in an overall reduction of entanglement generation rate. This cooling sequence allows us to achieve average phonon numbers of the two-qubit gate motional mode of $\bar{n} \sim 0.15$ and $\bar{n} \sim 0.1$ before entering the excitation loop in Alice and Bob, respectively, with an additional average heating of ~ 0.2 phonons accumulated during the excitation loop [36].

Multipartite mixed-species entanglement—We go on to generate multipartite entangled states using the mixed-species trapped-ion modules. As shown in Figs. 2(d) and 2(e), these states are generated by first creating a $|\Phi^+\rangle$ Bell state between the network qubits in each module, followed by local mixed-species CNOT gates to entangle the Ca^+ auxiliary qubits with the network qubits, creating the states in Eq. (1) with $N = 3$ and $N = 4$, respectively.

Full state tomography with 10,000 tomographic measurements yielded density matrices representing states with entanglement fidelities of 93.1(7)% and 91.9(8)% for the 3-qubit and 4-qubit GHZ states, respectively. The parity and/or population measurements for the 3-qubit and 4-qubit GHZ states are shown in Figs. 2(d) and 2(e), respectively. From these measurements, we extract entanglement fidelities of 94(1)% and 91(1)% for the 3-qubit and 4-qubit GHZ states, respectively.

Storage of remote entanglement—The ability to faithfully preserve quantum information in the modules on timescales longer than the time taken to generate remote entanglement is critical for many quantum networking applications. In the mixed-species experiments presented so far, the additional cooling required to implement the mixed-species operations means that this timescale is on the order of 100 ms. We have observed coherence times of the network qubit of approximately 8 ms; while this can be somewhat extended using dynamical decoupling, it is not sufficient for practical applications. We, therefore, utilize the long-lived memory qubit in $^{43}\text{Ca}^+$ to gain access to a longer-lived memory qubit. In previous work, we demonstrated the integration of this memory qubit into one of our network modules [36]; we stored the ionic half of an ion-photon Bell pair for up to 10 s and demonstrated that the storage was robust to network activity, i.e., the simultaneous generation of photons using the cotrapped Sr^+ ion. Here, we extend this to both modules, thereby enabling the long-lived storage of entanglement between remote matter qubits.

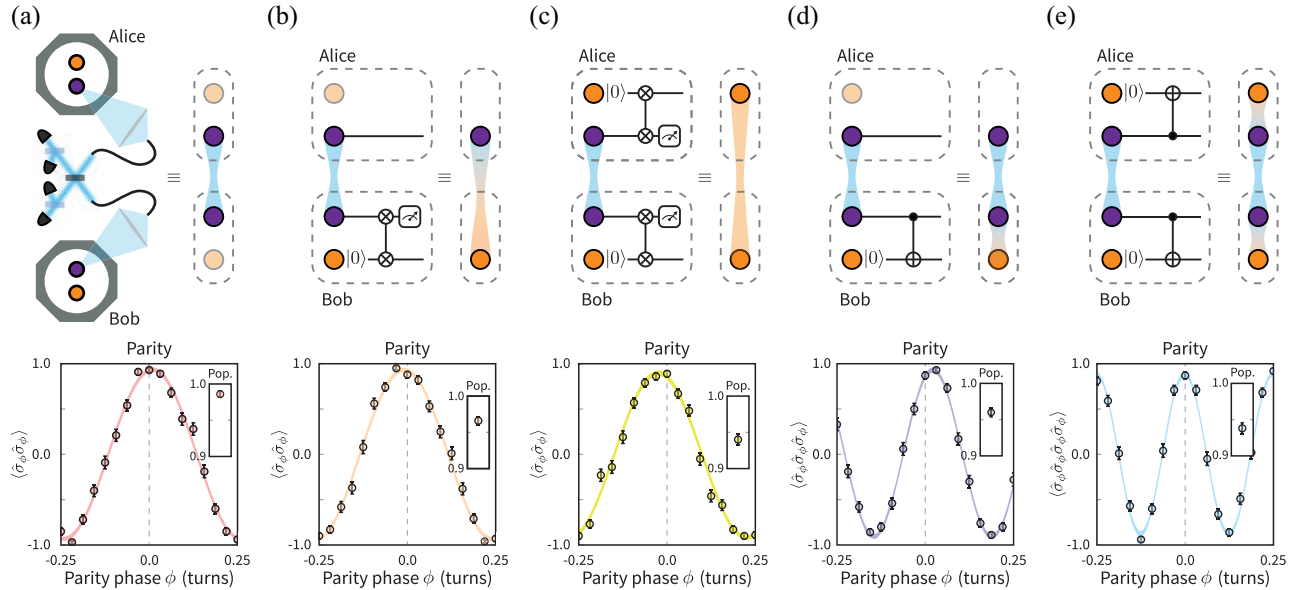


FIG. 2. Partial state tomography of the mixed-species remotely entangled states. (a) “Raw” Sr^+-Sr^+ entanglement. (b) Sr^+-Ca^+ entanglement, created using an error-detected iSWAP. (c) Ca^+-Ca^+ entanglement, created using error-detected iSWAPs. (d) 3-qubit GHZ state, created using a CNOT gate. (e) 4-qubit GHZ state, created using CNOT gates. Parity measurements are shown below each circuit, with insets displaying the population measurements. The shaded regions represent the 95% confidence interval of the fit given by Eq. (2). The error bars on the measurements indicate one standard deviation. The inferred remote entanglement fidelities are given in Table I.

In order to demonstrate the storage enhancement provided by our memory qubits, we compare the abilities of the network and memory qubits to store remote entanglement, measuring the fidelity as a function of storage duration. The experimental circuits used to characterize the storage capabilities of the qubits are shown in Figs. 3(a) and 3(b). The first step is to generate entanglement between the desired pair of qubits. For the network qubits, this is achieved as described above. To generate the remote entanglement between the memory qubits, we first use error-detected *i*SWAP gates to map the entanglement from the network to the auxiliary qubits (see Supplemental Material, Section S2 [37]), before using a pair of Raman beams to coherently map the quantum information from the auxiliary qubits to the memory qubits (see Supplemental Material, Section S2 [37]).

With the entanglement created, we store the states for a variable storage duration Δt . We deploy universally robust (UR) dynamical decoupling [84] to suppress sources of dephasing. The lengths of the UR sequence were adjusted for each storage duration, ranging from 4 pulses (UR4) to

48 pulses (UR48). Additionally, over this duration, the ion species not used to store the entanglement is used as a sympathetic coolant to prevent ion loss and mitigate single-qubit rotation errors due to heating. Finally, we perform parity and population measurements to estimate the fidelity of the entanglement after storage.

The fidelities of the stored entanglement as a function of storage duration for the two types of qubit are shown in Fig. 3(c). For the network qubit, we observe a significant degradation in the stored entanglement for storage durations exceeding 10 ms. We attribute this to the relatively high sensitivity of the network qubits to magnetic field fluctuations (-11 MHz mT^{-1}). Additionally, we observe that the fidelity of the network qubit entanglement decays below 50% at storage durations exceeding 100 ms, indicating the presence of amplitude damping processes such as the decay of the $|1_N\rangle$ state due to the finite lifetime of the $^{88}\text{Sr}^+$ metastable $D_{5/2}$ manifold (approximately 390 ms [85]). We fit an exponential decay to the fidelities, extracting a decay time constant of 44(3) ms for the network qubits.

For the memory qubits, we observe a marked enhancement of the storage capability, observing a remote entanglement fidelity of 69(4)% after 10 s. Using the same exponential decay model as above, we extract a decay time constant of 14(4) s. This significantly exceeds the average time taken to generate entanglement in the mixed-species experiments (~ 100 ms).

Discussion—In this Letter, we have demonstrated the integration of remote entanglement generation between trapped-ion modules with local mixed-species quantum logic. Specifically, we have realized bipartite entangled states between Sr^+-Sr^+ , Sr^+-Ca^+ , and Ca^+-Ca^+ ion pairs, as well as 3-qubit and 4-qubit multispecies GHZ states. All entangled states were generated with fidelities in the range of 91% to 97%.

We have also shown that remote entanglement can be reliably stored for more than 10 s in the long-lived memory qubits of $^{43}\text{Ca}^+$, a duration approximately 2 orders of magnitude longer than the average entanglement generation time. This capability is critical for protocols requiring multiple instances of entanglement generation, such as entanglement distillation [86], and for long-distance entanglement where storage buffers are essential. A discussion on how this memory time will impact other quantum networking scenarios is presented in Supplemental Material, Section S6 [37].

Previous demonstrations of multipartite entanglement across two or three remote nodes have been realized and characterized in solid-state platforms [10,87], but with more modest fidelities and shorter coherence times. In contrast, the present Letter achieves high-fidelity multipartite entanglement between independent trapped-ion modules together with long-lived quantum memory. This combination of fidelity, modularity, and storage time

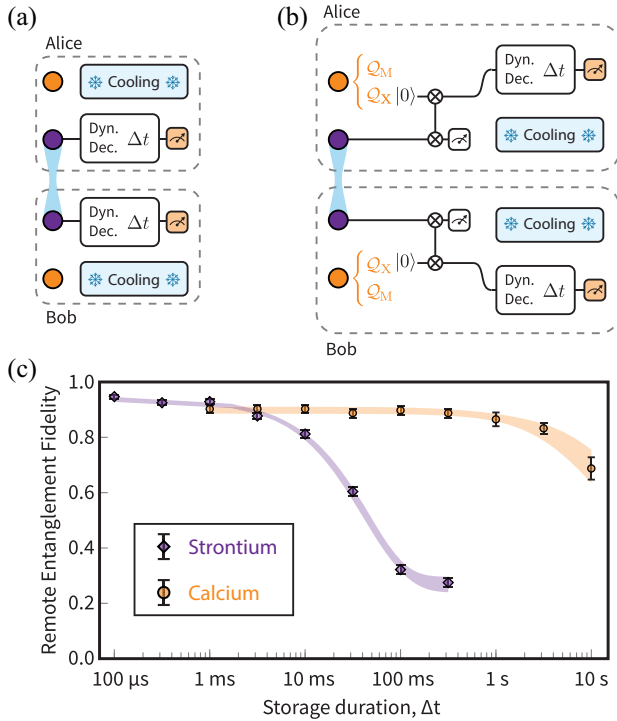


FIG. 3. Demonstration of the long-lived storage of remote entanglement. Circuits for probing the remote entanglement fidelity as a function of storage duration for (a) two network qubits and (b) two memory qubits. Sympathetic cooling via the unused ion species and dynamical decoupling is performed to extend the storage capabilities of each qubit. (c) Remote entanglement fidelity as a function of storage duration for each qubit. Exponential decay fits (shaded bands) yield decay time constants of 44(3) ms and 14(4) s for the network and memory qubits, respectively. All error bars indicate one standard deviation.

represents an important advance toward scalable matter-based quantum networks. The techniques demonstrated here are complementary to those being developed to operate a quantum network within the *omg* architecture [34,35,88]. A discussion of the respective advantages and trade-offs of these architectures for quantum network implementations is presented in Supplemental Material, Section S6 [37].

Heterogeneous entanglement—such as that between different atomic species—can be utilized for advanced applications, including enhanced frequency comparisons in atomic clock networks. In such networks, entangled states engineered across species with complementary sensitivities can yield improved stability and reduced systematic uncertainties [89] or enable remote quantum logic spectroscopy [14].

Moreover, the generation of multipartite entangled states across remote modules opens pathways to enhanced remote sensing protocols [6,90,91] and could serve as a distributed entanglement resource for quantum error correction in networked quantum computing architectures [12,92].

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The remaining authors declare no competing interests.

Data availability—There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] A. K. Ekert, Quantum cryptography based on Bell’s theorem, *Phys. Rev. Lett.* **67**, 661 (1991).
 - [2] J. I. Cirac, A. K. Ekert, S. F. Huelga, and C. Macchiavello, Distributed quantum computation over noisy channels, *Phys. Rev. A* **59**, 4249 (1999).

- [3] L. Jiang, J. M. Taylor, A. S. Sørensen, and M. D. Lukin, Distributed quantum computation based on small quantum registers, *Phys. Rev. A* **76**, 062323 (2007).
- [4] D. Main, P. Drmota, D. P. Nadlinger, E. M. Ainley, A. Agrawal, B. C. Nichol, R. Srinivas, G. Araneda, and D. M. Lucas, Distributed quantum computing across an optical network link, *Nature (London)* **638**, 383 (2025).
- [5] X. Guo, C. R. Breum, J. Borregaard, S. Izumi, M. V. Larsen, T. Gehring, M. Christandl, J. S. Neergaard-Nielsen, and U. L. Andersen, Distributed quantum sensing in a continuous-variable entangled network, *Nat. Phys.* **16**, 281 (2020).
- [6] P. Komar, E. M. Kessler, M. Bishof, L. Jiang, A. S. Sørensen, J. Ye, and M. D. Lukin, A quantum network of clocks, *Nat. Phys.* **10**, 582 (2014).
- [7] H. J. Kimble, The quantum internet, *Nature (London)* **453**, 1023 (2008).
- [8] A. Reiserer and G. Rempe, Cavity-based quantum networks with single atoms and optical photons, *Rev. Mod. Phys.* **87**, 1379 (2015).
- [9] S. Wehner, D. Elkouss, and R. Hanson, Quantum internet: A vision for the road ahead, *Science* **362** (2018).
- [10] M. Pompili *et al.*, Realization of a multinode quantum network of remote solid-state qubits, *Science* **372**, 259 (2021).
- [11] D. Hucul, I. V. Inlek, G. Vittorini, C. Crocker, S. Debnath, S. M. Clark, and C. Monroe, Modular entanglement of atomic qubits using photons and phonons, *Nat. Phys.* **11**, 37 (2015).
- [12] D. Gottesman and I. L. Chuang, Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations, *Nature (London)* **402**, 390 (1999).
- [13] M. Hillery, V. Bužek, and A. Berthiaume, Quantum secret sharing, *Phys. Rev. A* **59**, 1829 (1999).
- [14] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, Spectroscopy using quantum logic, *Science* **309**, 749 (2005).
- [15] T. R. Tan, J. P. Gaebler, Y. Lin, Y. Wan, R. Bowler, D. Leibfried, and D. J. Wineland, Multi-element logic gates for trapped-ion qubits, *Nature (London)* **528**, 380 (2015).
- [16] I. V. Inlek, C. Crocker, M. Lichtman, K. Sosnova, and C. Monroe, Multispecies trapped-ion node for quantum networking, *Phys. Rev. Lett.* **118**, 250502 (2017).
- [17] C. Bruzewicz, R. McConnell, J. Stuart, J. Sage, and J. Chiaverini, Dual-species, multi-qubit logic primitives for Ca^+/Sr^+ trapped-ion crystals, *npj Quantum Inf.* **5**, 102 (2019).
- [18] A. C. Hughes, V. M. Schafer, K. Thirumalai, D. P. Nadlinger, S. R. Woodrow, D. M. Lucas, and C. J. Ballance, Benchmarking a high-fidelity mixed-species entangling gate, *Phys. Rev. Lett.* **125**, 080504 (2020).
- [19] P. Wang, C.-Y. Luan, M. Qiao, M. Um, J. Zhang, Y. Wang, X. Yuan, M. Gu, J. Zhang, and K. Kim, Single ion qubit with estimated coherence time exceeding one hour, *Nat. Commun.* **12**, 233 (2021).
- [20] C. J. Ballance, T. P. Harty, N. M. Linke, M. A. Sepiol, and D. M. Lucas, High-fidelity quantum logic gates using trapped-ion hyperfine qubits, *Phys. Rev. Lett.* **117**, 060504 (2016).

- [21] J. P. Gaebler *et al.*, High-fidelity universal gate set for $^9\text{Be}^+$ ion qubits, *Phys. Rev. Lett.* **117**, 060505 (2016).
- [22] R. Srinivas *et al.*, High-fidelity laser-free universal control of trapped ion qubits, *Nature (London)* **597**, 209 (2021).
- [23] C. R. Clark *et al.*, High-fidelity Bell-state preparation with $^{40}\text{Ca}^+$ optical qubits, *Phys. Rev. Lett.* **127**, 130505 (2021).
- [24] M. Weber, M. F. Gely, R. K. Hanley, T. P. Harty, A. D. Leu, C. M. Loschnauer, D. P. Nadlinger, and D. M. Lucas, Robust and fast microwave-driven quantum logic for trapped-ion qubits, *Phys. Rev. A* **110**, L010601 (2024).
- [25] C. Löschnauer *et al.*, Scalable, high-fidelity all-electronic control of trapped-ion qubits, *PRX Quantum* **6**, 040313 (2025).
- [26] M. C. Smith, A. D. Leu, K. Miyanishi, M. F. Gely, and D. M. Lucas, Single-qubit gates with errors at the 10^{-7} level, *Phys. Rev. Lett.* **134**, 230601 (2025).
- [27] T. P. Harty, D. T. C. Allcock, C. J. Ballance, L. Guidoni, H. A. Janacek, N. M. Linke, D. N. Stacey, and D. M. Lucas, High-fidelity preparation, gates, memory, and readout of a trapped-ion quantum bit, *Phys. Rev. Lett.* **113**, 220501 (2014).
- [28] F. A. An, A. Ransford, A. Schaffer, L. R. Sletten, J. Gaebler, J. Hostetter, and G. Vittorini, High fidelity state preparation and measurement of ion hyperfine qubits with $I > \frac{1}{2}$, *Phys. Rev. Lett.* **129**, 130501 (2022).
- [29] A. Sotirova *et al.*, High-fidelity heralded quantum state preparation and measurement, [arXiv:2409.05805](https://arxiv.org/abs/2409.05805).
- [30] D. L. Moehring, P. Maunz, S. Olmschenk, K. C. Younge, D. N. Matsukevich, L.-M. Duan, and C. Monroe, Entanglement of single-atom quantum bits at a distance, *Nature (London)* **449**, 68 (2007).
- [31] L. J. Stephenson, D. P. Nadlinger, B. C. Nichol, S. An, P. Drmota, T. G. Ballance, K. Thirumalai, J. F. Goodwin, D. M. Lucas, and C. J. Ballance, High-rate, high-fidelity entanglement of qubits across an elementary quantum network, *Phys. Rev. Lett.* **124**, 110501 (2020).
- [32] V. Krutyanskiy *et al.*, Entanglement of trapped-ion qubits separated by 230 meters, *Phys. Rev. Lett.* **130**, 050803 (2023).
- [33] S. Saha, M. Shalaev, J. O'Reilly, I. Goetting, G. Toh, A. Kalakuntla, Y. Yu, and C. Monroe, High-fidelity remote entanglement of trapped atoms mediated by time-bin photons, *Nat. Commun.* **16**, 2533 (2025).
- [34] H.-X. Yang, J.-Y. Ma, Y.-K. Wu, Y. Wang, M.-M. Cao, W.-X. Guo, Y.-Y. Huang, L. Feng, Z.-C. Zhou, and L.-M. Duan, Realizing coherently convertible dual-type qubits with the same ion species, *Nat. Phys.* **18**, 1058 (2022).
- [35] D. T. C. Allcock, W. C. Campbell, J. Chiaverini, I. L. Chuang, E. R. Hudson, I. D. Moore, A. Ransford, C. Roman, J. M. Sage, and D. J. Wineland, OMG blueprint for trapped ion quantum computing with metastable states, *Appl. Phys. Lett.* **119**, 214002 (2021).
- [36] P. Drmota *et al.*, Robust quantum memory in a trapped-ion quantum network node, *Phys. Rev. Lett.* **130**, 090803 (2023).
- [37] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/qpsf-nlp9> for additional details on the experimental methods, state characterization, error detection, quantum-memory performance, and comparison with alternative quantum-network architectures, which includes Refs. [38–77].
- [38] P. L. W. Maunz, High optical access trap 2.0, Technical Report, Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States), 2016.
- [39] M. C. Revelle, Phoenix and peregrine ion traps, [arXiv:2009.02398](https://arxiv.org/abs/2009.02398).
- [40] S. Bourdeauducq *et al.*, m-labs/artiq: 6.0 (Version 6.0), [10.5281/zenodo.1492176](https://zenodo.org/record/1492176) (2021).
- [41] A. C. Hughes *et al.*, Benchmarking a high-fidelity mixed-species entangling gate, *Phys. Rev. Lett.* **125**, 080504 (2020).
- [42] D. Hayes, K. Khodjasteh, L. Viola, and M. J. Biercuk, Reducing sequencing complexity in dynamical quantum error suppression by Walsh modulation, *Phys. Rev. A* **84**, 062323 (2011).
- [43] D. Hayes *et al.*, Coherent error suppression in multiqubit entangling gates, *Phys. Rev. Lett.* **109**, 020503 (2012).
- [44] C. J. Wood, J. D. Biamonte, and D. G. Cory, Tensor networks and graphical calculus for open quantum systems, *Quantum Inf. Comput.* **15**, 0759 (2001).
- [45] D. Main *et al.*, Distributed quantum computing across an optical network link, *Nature (London)* **638**, 383 (2025).
- [46] J. Řeháček, Z. Hradil, E. Knill, and A. I. Lvovsky, Diluted maximum-likelihood algorithm for quantum tomography, *Phys. Rev. A* **75**, 042108 (2007).
- [47] L. J. Stephenson *et al.*, High-rate, high-fidelity entanglement of qubits across an elementary quantum network, *Phys. Rev. Lett.* **124**, 110501 (2020).
- [48] D. P. Nadlinger *et al.*, Experimental quantum key distribution certified by Bell's theorem, *Nature (London)* **607**, 682 (2022).
- [49] B. C. Nichol *et al.*, An elementary quantum network of entangled optical atomic clocks, *Nature (London)* **609**, 689 (2022).
- [50] J. Apolín and D. P. Nadlinger, Recoil-induced errors and their correction in photon-mediated entanglement between atomic qubits, *PRX Quantum* **7**, 010326 (2026).
- [51] P. Drmota *et al.*, Robust quantum memory in a trapped-ion quantum network node, *Phys. Rev. Lett.* **130**, 090803 (2023).
- [52] C. Bruzewicz, R. McConnell, J. Stuart, J. Sage, and J. Chiaverini, Dual-species, multi-qubit logic primitives for Ca^+/Sr^+ trapped-ion crystals, *npj Quantum Inf.* **5**, 102 (2019).
- [53] I. V. Inlek, C. Crocker, M. Lichtman, K. Sosnova, and C. Monroe, Multispecies trapped-ion node for quantum networking, *Phys. Rev. Lett.* **118**, 250502 (2017).
- [54] N. Akerman and R. Ozeri, Atomic combination clocks, *New J. Phys.* **20**, 123026 (2018).
- [55] S. M. Brewer *et al.*, $^{27}\text{Al}^+$ quantum-logic clock with a systematic uncertainty below 10^{-18} , *Phys. Rev. Lett.* **123**, 033201 (2019).
- [56] H.-X. Yang *et al.*, Realizing coherently convertible dual-type qubits with the same ion species, *Nat. Phys.* **18**, 1058 (2022).
- [57] D. T. C. Allcock *et al.*, omg blueprint for trapped ion quantum computing with metastable states, *Appl. Phys. Lett.* **119**, 214002 (2021).

- [58] P.-C. Lai *et al.*, Realization of a crosstalk-free two-ion node for long-distance quantum networking, *Phys. Rev. Lett.* **134**, 070801 (2025).
- [59] Z.-B. Cui *et al.*, Metropolitan-scale ion-photon entanglement via a quantum network node with hybrid multiplexing enhancements, *Nat. Commun.* **17**, 697 (2025).
- [60] A. Ruskuc *et al.*, Multiplexed entanglement of multi-emitter quantum network nodes, *Nature (London)* **639**, 54 (2025).
- [61] Y.-Y. Huang *et al.*, Realization of a functioning dual-type trapped-ion quantum network node, *Sci. Adv.* **11**, eaeb4076 (2025).
- [62] A. Sotirova *et al.*, High-fidelity heralded quantum state preparation and measurement, *arXiv:2409.05805*.
- [63] D. Hucul, J. E. Christensen, E. R. Hudson, and W. C. Campbell, Spectroscopy of a synthetic trapped ion qubit, *Phys. Rev. Lett.* **119**, 100501 (2017).
- [64] K. Dietze *et al.*, Entanglement-enhanced optical ion clock, *Phys. Rev. Lett.* **136**, 073601 (2026).
- [65] S. Olmschenk, Doubly ionized lanthanum as a qubit candidate for quantum networks, *Phys. Rev. A* **105**, 042617 (2022).
- [66] S. Yu *et al.*, Efficient quantum frequency conversion of ultra-violet single photons from a trapped ytterbium ion, *Appl. Phys. Lett.* **126**, 084001 (2025).
- [67] W.-Z. Liu *et al.*, Long-lived remote ion-ion entanglement for scalable quantum repeaters, *Nature (London)* **652**, 51 (2026).
- [68] J. Hannegan *et al.*, C-band single photons from a trapped ion via two-stage frequency conversion, *Appl. Phys. Lett.* **119**, 084001 (2021).
- [69] T. A. Wright *et al.*, Two-way photonic interface for linking the Sr^+ transition at 422 nm to the telecommunication C band, *Phys. Rev. Appl.* **10**, 044012 (2018).
- [70] S. Kasture *et al.*, Frequency conversion between uv and telecom wavelengths in a lithium niobate waveguide for quantum communication with Yb^+ trapped ions, *J. Opt.* **18**, 104007 (2016).
- [71] V. Krutyanskiy, M. Meraner, J. Schupp, and B. Lanyon, Polarisation-preserving photon frequency conversion from a trapped-ion-compatible wavelength to the telecom c-band, *Appl. Phys. B* **123**, 228 (2017).
- [72] V. Krutyanskiy *et al.*, Light-matter entanglement over 50 km of optical fibre, *npj Quantum Inf.* **5**, 72 (2019).
- [73] M. Bock *et al.*, High-fidelity entanglement between a trapped ion and a telecom photon via quantum frequency conversion, *Nat. Commun.* **9**, 1998 (2018).
- [74] M. Petrovich *et al.*, Broadband optical fibre with an attenuation lower than 0.1 decibel per kilometre, *Nat. Photonics* **19**, 1203 (2025).
- [75] M. A. Zalewski, D. Wu, A. L. Ferrari, Y. Xie, and N. M. Linke, Kilometer-scale ion-photon entanglement with a metastable $^{88}\text{Sr}^+$ qubit, *Phys. Rev. A* **113**, 012615 (2026).
- [76] P. Wang *et al.*, Single ion qubit with estimated coherence time exceeding one hour, *Nat. Commun.* **12**, 233 (2021).
- [77] Z.-B. Cui *et al.*, Temporally multimode ion-ion entanglement over 1.2 kilometer fibers, *Phys. Rev. Lett.* **137**, 020803 (2026).
- [78] X.-L. Feng, Z.-M. Zhang, X.-D. Li, S.-Q. Gong, and Z.-Z. Xu, Entangling distant atoms by interference of polarized photons, *Phys. Rev. Lett.* **90**, 217902 (2003).
- [79] L.-M. Duan and H. Kimble, Efficient engineering of multiatom entanglement through single-photon detections, *Phys. Rev. Lett.* **90**, 253601 (2003).
- [80] C. Simon and William T. M. Irvine, Robust long-distance entanglement and a loophole-free bell test with ions and photons, *Phys. Rev. Lett.* **91**, 110405 (2003).
- [81] L.-M. Duan, B. Blinov, D. Moehring, and C. Monroe, Scalable trapped ion quantum computation with a probabilistic ion-photon mapping, *Quantum Inf. Comput.* **4**, 165 (2003).
- [82] There is also a 5% branching ratio for decays to the $D_{3/2}$ manifold; however, these result in an unsuccessful entanglement attempt and so can be neglected.
- [83] C. A. Sackett *et al.*, Experimental entanglement of four particles, *Nature (London)* **404**, 256 (2000).
- [84] G. T. Genov, D. Schraft, N. V. Vitanov, and T. Halfmann, Arbitrarily accurate pulse sequences for robust dynamical decoupling, *Phys. Rev. Lett.* **118**, 133202 (2017).
- [85] V. Letchumanan, M. A. Wilson, P. Gill, and A. G. Sinclair, Lifetime measurement of the metastable $4d^2D_{5/2}$ state in $^{88}\text{Sr}^+$ using a single trapped ion, *Phys. Rev. A* **72**, 012509 (2005).
- [86] R. Nigmatullin, C. J. Ballance, N. De Beaudrap, and S. C. Benjamin, Minimally complex ion traps as modules for quantum communication and computing, *New J. Phys.* **18**, 103028 (2016).
- [87] A. Ruskuc, C.-J. Wu, E. Green, S. L. N. Hermans, W. Pajak, J. Choi, and A. Faraon, Multiplexed entanglement of multi-emitter quantum network nodes, *Nature (London)* **639**, 54 (2025).
- [88] P.-C. Lai *et al.*, Realization of a crosstalk-free two-ion node for long-distance quantum networking, *Phys. Rev. Lett.* **134**, 070801 (2025).
- [89] N. Akerman and R. Ozeri, Atomic combination clocks, *New J. Phys.* **20**, 123026 (2018).
- [90] E. A. Van Milligen, C. N. Gagatsos, E. Kaur, D. Towsley, and S. Guha, Utilizing probabilistic entanglement between sensors in quantum networks, *Phys. Rev. Appl.* **22**, 064085 (2024).
- [91] R. Finkelstein, R. B.-S. Tsai, X. Sun, P. Scholl, S. Direkci, T. Gefen, J. Choi, A. L. Shaw, and M. Endres, Universal quantum operations and ancilla-based read-out for tweezer clocks, *Nature (London)* **634**, 321 (2024).
- [92] N. H. Nguyen, M. Li, A. M. Green, C. Huertaalderete, Y. Zhu, D. Zhu, K. R. Brown, and N. M. Linke, Demonstration of Shor encoding on a trapped-ion quantum computer, *Phys. Rev. Appl.* **16**, 024057 (2021).
- [93] S. Bourdauducq *et al.*, m-labs/artiq: 6.0 (version 6.0), [10.5281/zenodo.1492176](https://doi.org/10.5281/zenodo.1492176) (2021).