An elementary quantum network of entangled optical atomic clocks

B. C. Nichol1,2, R. Srinivas1,2, D. P. Nadlinger1, P. Drmota1, D. Main1, G. Araneda1, C. J. Ballance1 & D. M. Lucas1

Optical atomic clocks are our most precise tools to measure time and frequency1–3. Precision frequency comparisons between clocks in separate locations enable one to probe the space–time variation of fundamental constants4,5 and the properties of dark matter6,7, to perform geodesy8–10 and to evaluate systematic clock shifts. Measurements on independent systems are limited by the standard quantum limit; measurements on entangled systems can surpass the standard quantum limit to reach the ultimate precision allowed by quantum theory—the Heisenberg limit. Although local entangling operations have demonstrated this enhancement at microscopic distances11–16, comparisons between remote atomic clocks require the rapid generation of high-fidelity entanglement between systems that have no intrinsic interactions. Here we report the use of a photonic link17,18 to entangle two 88Sr+ ions separated by a macroscopic distance19 (approximately 2 m) to demonstrate an elementary quantum network of entangled optical clocks. For frequency comparisons between the ions, we find that entanglement reduces the measurement uncertainty by nearly $\sqrt{2}$, the value predicted for the Heisenberg limit. Today’s optical clocks are typically limited by dephasing of the probe laser20; in this regime, we find that entanglement yields a factor of 2 reduction in the measurement uncertainty compared with conventional correlation spectroscopy techniques20–22. We demonstrate this enhancement for the measurement of a frequency shift applied to one of the clocks. This two-node network could be extended to additional nodes23, to other species of trapped particles or—through local operations—to larger entangled systems.

Non-classical states enable measurement precision beyond the standard quantum limit (SQL)24–27. For example, quantum-enhanced measurements have been used for gravitational wave sensing28, searches for dark matter29, force sensing30, measurements of quadrupole moments31, local Lorentz invariance32 and atomic isotope shifts33. Although quantum networks33 have been used for quantum cryptography34, quantum computation35 and verifications of quantum theory36, they could potentially be used for enhanced metrology by distributing entanglement between remote systems. This enhancement is particularly important for optical atomic clock comparisons, for which the number of measurements required to reach the noise floor is presently limited by the single-shot measurement uncertainty set by the SQL. Harnessing entanglement to move beyond the SQL and reach precision floors faster will enable the detection of phenomena on shorter timescales, and reveal previously undetectable signals by reducing the demands on the stability of the system.

The standard method for optical atomic clock comparisons requires the measurement of each atomic frequency relative to a laser. This laser is used to drive a narrow optical atomic transition and its relative frequency is determined by observing changes in the atomic state. This measurement is typically performed using a Ramsey experiment37,38, in which a superposition of two states, $|\uparrow\rangle$ and $|\downarrow\rangle$, evolves for a duration $T_R$ in between two $\pi/2$ pulses. A difference in frequency between the atom and the laser results in a relative phase between the two atomic states, which can be measured by repeated observations of the final state of the atom. For a single atom $i$, the expectation value of this measurement is

$$\langle \hat{\Pi} \rangle = C_i \cos(\Delta_i T_R + \phi_i),$$

where $\Delta_i = \omega_L - \omega_i$ is the detuning between the laser frequency, $\omega_L$, and the atomic resonance frequency, $\omega_i$. Here $\phi_i$ is the phase of the second $\pi/2$ pulse with respect to the first pulse, $C_i$ is the signal contrast, which is ideally 1 in the absence of decoherence, and $\hat{\Pi} = \hat{S}_z = |\uparrow\rangle \langle \uparrow | - |\downarrow\rangle \langle \downarrow |$ is the spin measurement operator. The corresponding uncertainty in the frequency $\Delta_i$ for a single quantum measurement is

$$\delta \Delta_i = \frac{\delta \langle \hat{\Pi} \rangle}{C_i T_R},$$

where $\delta \langle \hat{\Pi} \rangle$ is the deviation from the mean.

1Department of Physics, Clarendon Laboratory, University of Oxford, Oxford, UK. 2These authors contributed equally: B. C. Nichol, R. Srinivas. 3e-mail: bethan.nichol@physics.ox.ac.uk; raghavendra.srinivas@physics.ox.ac.uk
The network comprises two trapped-ion systems, Alice and Bob, separated by 2 m, each containing a single \( ^{88}\text{Sr}^+ \) ion (not to scale). We use a photonic link to generate remote entanglement; spontaneously emitted 422 nm photons are transmitted through optical fibres to a Bell state analyser, in which a measurement projects the ions into an entangled state within the \( S_{1/2} \) manifold. We map this entanglement to the \( S_{3/2} \) manifold, using simultaneous 422 nm excitation pulses, is repeatedly attempted until a coincident two-photon detection at the Bell state analyser heralds entanglement. A 674 nm π pulse maps the entanglement to the optical clock transition. We then simultaneously perform a Ramsey experiment on each ion with a total probe duration of \( T_R \); spin-echo pulses during \( T_R \) are not shown. The phase of the first π/2 pulse on Alice is \( \phi_i = \phi + \pi \), where \( \phi \) is the phase of the initial entangled state. Following ion readout, cooling and state preparation, this process is repeated for the unentangled state.

![Diagram of the network of entangled optical clocks](image)

**Fig. 1** | Network of entangled optical clocks. **a**, Experimental apparatus. The network comprises two trapped-ion systems, Alice and Bob, separated by 2 m, each containing a single \( ^{88}\text{Sr}^+ \) ion (not to scale). We use a photonic link to generate remote entanglement; spontaneously emitted 422 nm photons are transmitted through optical fibres to a Bell state analyser, in which a measurement projects the ions into an entangled state within the \( S_{1/2} \) manifold. We map this entanglement to the \( S_{3/2} \) manifold, using simultaneous 422 nm excitation pulses, is repeatedly attempted until a coincident two-photon detection at the Bell state analyser heralds entanglement. A 674 nm π pulse maps the entanglement to the optical clock transition. We then simultaneously perform a Ramsey experiment on each ion with a total probe duration of \( T_R \); spin-echo pulses during \( T_R \) are not shown. The phase of the first π/2 pulse on Alice is \( \phi_i = \phi + \pi \), where \( \phi \) is the phase of the initial entangled state. Following ion readout, cooling and state preparation, this process is repeated for the unentangled state.

**b**, Experimental pulse sequence. In a single experimental sequence, we measure the ion states after Ramsey experiments on both the entangled and unentangled states. Entanglement generation, using simultaneous 422 nm excitation pulses, is repeatedly attempted until a coincident two-photon detection at the Bell state analyser heralds entanglement. A 674 nm π pulse maps the entanglement to the optical clock transition. We then simultaneously perform a Ramsey experiment on each ion with a total probe duration of \( T_R \); spin-echo pulses during \( T_R \) are not shown. The phase of the first π/2 pulse on Alice is \( \phi_i = \phi + \pi \), where \( \phi \) is the phase of the initial entangled state. Following ion readout, cooling and state preparation, this process is repeated for the unentangled state.
We perform Ramsey experiments on Alice’s (blue) and Bob’s (pink) atoms, using a probe laser with frequency $\omega_a$. These experiments can measure the atoms’ detunings $\Delta_1$ and $\Delta_2$ between $\omega_a$ and and the $|+\rangle \leftrightarrow |\downarrow\rangle$ transitions. Thus, two independent measurements are required to obtain the difference frequency $\Delta = \Delta_1 - \Delta_2$. With entanglement, only a single measurement is required for $\Delta$, using the two-atom states $|+\downarrow\rangle$ and $|\downarrow+\rangle$. A single measurement can also be performed using unentangled states, at the cost of having population in the additional states $|\downarrow\downarrow\rangle$ and $|\downarrow+\rangle$ that does not contribute to the signal. c–f. We scan the analysis phase $\phi = -\phi_i$ from 0 to $\pi$ radians. We plot the single-ion (c) and two-ion (d) parity signals at a Ramsey duration of 0.1 ms. Imperfect entangled state generation and an increased effect from the imperfect spin-echo pulses reduce the contrast of the entangled state (green diamonds), compared to the single-ion scans (blue squares and pink triangles). The two-ion signal from the unentangled state $|\downarrow\downarrow\rangle$ has almost no visibility and increased uncertainty in the fits owing to sensitivity to common-mode laser phase noise. Experimental data are shown as points, with error bars calculated from projection noise. Fits to the data (lines), and their corresponding contrasts $C$, are shown with 68% confidence intervals (shaded region), following equations (1) and (3) for the single-ion and two-ion signals, respectively.

The Ramsey frequency is $\Delta = -1.00$, with an uncertainty of $0.25$. The Ramsey offset is $\Delta_y = -1.00$, with an uncertainty of $0.25$. The Ramsey contrast is $C = 0.95(1)$, indicating a high fidelity of the entangled state.

We use active magnetic field stabilization and a modified spin-echo sequence as shown in Fig. 1b. We use the data from the unentangled state $|\downarrow\downarrow\rangle$ to measure the oscillation only from the term in equation (3) containing $\Delta$. We set $\phi = -\phi_i$ and scan $\Phi_i$. At $\Delta_y = 0.1 ms$, we observe a slight reduction in contrast for the unentangled ions, mainly due to imperfect spin-echo pulses; imperfect entanglement fidelity further reduces the contrast for the entangled state. At longer durations, qubit decoherence due to magnetic field noise reduces the contrast of all the parity signals (Supplementary Fig. S2). The sensitivity of the single-ion signal to laser phase noise is evident from the additional reduction in the contrast. When the laser phase noise at the fibre output was intentionally increased by turning off the fibre-noise cancellation, we observed a high contrast for the two-ion signals at probe durations for which the single-ion signals had decohered completely (Supplementary Fig. S6). This demonstrates a decoherence-free subspace encoded in two qubits separated by a macroscopic distance. In principle, our network could also be used to enhance measurements of $\Delta_y$, which is required to stabilize the laser frequency to the mean atomic frequency. However, the entangled state needed for this measurement has an increased sensitivity to laser dephasing (Supplementary Fig. S3), and hence accessing this enhancement will require improvements in laser technology.
To illustrate the enhancement from the entangled state for frequency comparisons, we plot the single-shot uncertainty for single-ion ($\delta_{\Delta_{-u}}$), correlated unentangled ($\delta_{\Delta_{-e}}$), and entangled ($\delta_{\Delta_{-e}}$) measurements, versus Ramsey duration ($T_R$), excluding other contributions to the experimental duty cycle. The blue dashed line indicates the minimum uncertainty achievable by single-ion measurements limited only by quantum projection noise (QPN), that is, single-ion measurements with perfect contrast. The data at $T_R = 0.1$ ms are omitted for clarity. At all durations, the entangled state achieves the lowest single-shot uncertainty. At longer durations, the single-ion measurements have the highest uncertainty because of their sensitivity to laser dephasing.

**Fig. 3** Characterization of entanglement enhancement. a. Single-shot frequency uncertainties for single-ion ($\delta_{\Delta_{-s}}$), correlated unentangled ($\delta_{\Delta_{-u}}$), and entangled ($\delta_{\Delta_{-e}}$) measurements, versus Ramsey duration ($T_R$), excluding other contributions to the experimental duty cycle. The blue dashed line indicates the minimum uncertainty achievable by single-ion measurements limited only by quantum projection noise (QPN), that is, single-ion measurements with perfect contrast. The data at $T_R = 0.1$ ms are omitted for clarity. At all durations, the entangled state achieves the lowest single-shot uncertainty. At longer durations, the single-ion measurements have the highest uncertainty because of their sensitivity to laser dephasing. b. Entanglement enhancement versus Ramsey duration ($T_R$) relative to single-ion measurements (olive squares) and relative to measurements with two unentangled ions (turquoise circles), where $N_{1p}/N_s = (\delta_{\Delta_{-s}}/\delta_{\Delta_{-e}})^2$. The theoretical enhancements are a factor of two relative to the single-ion (olive dashed line) and a factor of four relative to the unentangled state (turquoise dash-dotted line). All error bars indicate 68% confidence intervals.

**Fig. 4** Measurement of clock–clock frequency difference with and without entanglement. a. We plot the two-ion parity signal with (green diamonds) and without (orange circles) entanglement at a Ramsey duration of 15 ms, choosing the analysis phase $\phi_a$ to sit at the steepest slope of the parity signal (Supplementary Fig. 58). The average parity signals with and without the shift are shown for the entangled (green dashed line) and unentangled states (orange dash-dotted line). The first five points are without any frequency shift and the next five points (shaded area) are with a shift applied to Alice’s ion. The change in parity signal for the entangled state is about twice as large as for the unentangled states. Error bars indicate 68% confidence intervals, given by quantum projection noise. b. Measured frequency difference with and without entanglement. From the change in the parity signal measured in a, we determine frequency differences of $-8.6 \pm 0.6$ Hz and $-8.8 \pm 2.5$ Hz with and without entanglement, respectively. Error bars indicate 68% confidence intervals.

simultaneously at longer Ramsey durations, for which the uncertainty for the single-ion measurements increases because of laser dephasing. At all durations, the entangled state yields the lowest experimental uncertainty, with a minimum at $T_R = 10$ ms.

We define the entanglement enhancement as the ratio of the number of measurements required to reach a given precision $\sigma$ without entanglement ($N_{1p}$), to the number of measurements required using the entangled state ($N_s$), where $\sigma$ is given by

$$\sigma = \frac{\delta_{\Delta_{-s}}}{\sqrt{N_{1p}}}.$$  (4)

Thus, the entanglement enhancement is equivalent to $N_{1p}/N_s = (\delta_{\Delta_{-s}}/\delta_{\Delta_{-e}})^2$, where s, u and e correspond to measurements with single ions, unentangled ions or entangled ions, respectively. In Fig. 3b we plot this entanglement enhancement versus the Ramsey duration. Relative to the single-ion measurements, we observe an enhancement that is initially close to the expected factor of two, but increases at longer durations. In this regime, correlated measurements using two unentangled ions have a reduced uncertainty compared with the single-ion measurements. Entanglement yields an even greater enhancement: we observe an enhancement close to a factor of four relative to the unentangled state at all durations.
Finally, as a proof of principle, we use entanglement to enhance the measurement precision of an applied frequency difference between the two ions. This frequency difference arises from a c.c. Stark effect due to a far-detuned 674 nm beam that illuminates Alice’s ion throughout the Ramsey duration (here 15 ms). As shown in Fig. 4a, when the a.c. Stark field is applied we see a factor two increase in the signal for the entangled state as compared to the unentangled state. From the parity response, we measure a frequency difference $\Delta \nu = -8.8 \pm 2.5\text{Hz}$ with the unentangled state and $-8.6 \pm 0.6\text{Hz}$ with the entangled state (Fig. 4b), which gives a fractional frequency uncertainty of about 10^{-2}. The measurement uncertainty without entanglement is higher than the expected factor of two compared with the measurement with entanglement. This is probably due to an increased uncertainty in the parity signal for the unentangled state due to the term corresponding to $P$ in equation (3), which contributes excess noise to the measurement at this Ramsey duration even though the mean offset has averaged to zero (Supplementary Information section J).

This results in an above-statistical scatter in the unentangled measurements, as can be seen in Fig. 4a. Probing the atoms at a duration much longer than the timescale for laser dephasing would remove this noise.

In conclusion, we have demonstrated enhanced frequency comparisons using an elementary quantum network of two entangled-trapped-atom atomic clocks. The high fidelity and speed of entanglement generation in our network, which give a large signal and an efficient duty cycle, show that entangled clocks can potentially offer a practical enhancement for metrology. Compared to probe durations of around 500 ms used in state-of-the-art optical clocks, our mean entanglement generation duration of 9 ms would have a negligible effect on the measurement duty cycle. We were restricted to the use of short probe durations (compared to the limit set by the 88Sr+ $^{4}D_{3/2}$ lifetime of approximately 400 ms) by qubit decoherence due to magnetic field fluctuations. The magnetic field fluctuations could be reduced significantly through the use of superconducting solenoids, mu-metal shielding or more advanced dynamical decoupling schemes. Although our demonstration used single 88Sr+ ions, whose simple level structure enables fast entanglement generation, the remote entanglement could in principle be mapped to any ion species through quantum logic operations, with negligible loss of fidelity or speed. For example, we could choose an ion with a transition that has a reduced magnetic field sensitivity, a narrower linewidth or an increased sensitivity to fundamental constants. The stability of the entangled state phase would be an important consideration for attaining state-of-the-art measurement precisions. Increasing the distance between nodes is important for remote sensing and geodesy. Longer fibres with phase noise cancellation could be used at the cost of a reduced entanglement duration owing to fibre losses at 422 nm; downconversion to telecom wavelengths could reduce losses. Using local operations to increase the number of entangled ions in each node could further reduce the measurement uncertainty for frequency comparisons. In principle, an entangled clock network with additional nodes connected by photonic links could also improve measurements of a common frequency reference, however, such an implementation would not have the common-mode phase suppression achieved here for atom–atom frequency comparisons. Our demonstration provides the first building block towards such a network that could operate beyond the SQL, at the fundamental Heisenberg limit.

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**Data availability**
Source data for all plots are available. All other data or analysis code that support the plots are available from the corresponding authors upon reasonable request.

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**Correspondence and requests for materials** should be addressed to B. C. Nichol or R. Srinivas.

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