Generating quantum entanglement in large systems on timescales much shorter than the coherence time is key to powerful quantum simulation and computation. Trapped ions are among the most accurately controlled and best isolated quantum systems with low-error entanglement gates operated within tens of microseconds using the vibrational motion of few-ion crystals. To exceed the level of complexity tractable by classical computers the main challenge is to realize fast entanglement operations in crystals made up of many ions (large ion crystals). The strong dipole–dipole interactions in polar molecule and Rydberg atom systems allow much faster entangling gates, yet stable state-independent confinement comparable with trapped ions needs to be demonstrated in these systems. Here we combine the benefits of these approaches: we report a two-ion entangling gate with 700-nanosecond gate time that uses the strong dipolar interaction between trapped Rydberg ions, which we use to produce a Bell state with 78 per cent fidelity. The sources of gate error are identified and a total error of less than 0.2 per cent is predicted for experimentally achievable parameters. Furthermore, we predict that residual coupling to motional modes contributes an approximate gate error of $10^{-4}$ in a large ion crystal of 100 ions. This provides a way to speed up and scale up trapped-ion quantum computers and simulators substantially.

Trapped atomic ions are one of the most promising architectures for realizing a universal quantum computer. The fundamental single- and two-qubit quantum gates have been demonstrated with errors less than 0.1%, sufficiently low for fault-tolerant quantum error-correction schemes. A single-qubit coherence time of 10 min (ref. 3) as well as the proof-of-principle demonstration of error correction have been realized. Nevertheless, a scalable quantum computer requires a large number of qubits and a large number of gate operations to be conducted within the coherence time. Most established gate schemes using a common motional mode are slow (typical gate times are between 40 μs and 100 μs) and difficult to scale up since the motional spectrum becomes more dense with increasing ion number. Many schemes have been proposed and implemented, with the fastest experimentally achieved gate in a two-ion crystal being 1.6 μs (99.8% fidelity) and 480 ns (60% fidelity), realized by driving multiple motional modes simultaneously. Although the gate speed is not limited by the trap frequencies, the gate protocol requires the phase-space trajectories of all modes to close simultaneously at the end of the pulse sequence. In long ion strings with a large number of vibrational modes, it becomes increasingly challenging to find and implement laser pulse parameters that execute this gate with a low error. Thus, a slow-down of gate speed appears inevitable.

Two-qubit entangling gates in Rydberg atom systems are substantially faster, owing to strong dipole–dipole interactions. The gate fidelities in recent experiments using neutral atoms are fairly high. However, the atom traps need to be turned off during Rydberg excitation. This can cause unwanted coupling between qubits and atom motion as well as atom loss. By employing blue-detuned optical tweezers at a magic wavelength, one may achieve the trapping of Rydberg states, although the predicted residual change in trapping frequency of about 50% (ref. 16) will still result in entanglement between qubits and motional states and thus a reduction in gate fidelity. In addition, switching between different trapping potentials or switching the trap off and on will exponentially heat up the atoms and reduce the gate fidelity (the unwanted motional effects are stronger at higher temperatures). Because cooling without destroying the qubit information is challenging (direct cooling by lasers will destroy the qubit, whereas sympathetic cooling will cause entanglement between qubit and coolant atoms unless their interaction is state-independent), this may limit the number of gate operations despite the long coherence times of these systems.

In solid-state platforms, such as superconducting circuits and silicon-based qubits, the interactions are also strong, enabling fast two-qubit gates, and tremendous progress has been made recently. However, the number of entanglement operations that can be executed in the coherence time using these systems is typically about 10^3 (with superconducting circuits gate times of approximately 50 ns and coherence times of approximately 100 μs), which is orders of magnitude
less than about $10^8$ in atomic systems (with trapped-ion gate times of around 100 μs and coherence times of around 100 s, Rydberg gates may improve this to about $10^9$).

Combining the benefits of trapped-ion qubits and Rydberg interactions is a promising approach for scalable quantum computation [22]. Rydberg interactions may enable fast, motion-independent gates between trapped ions. Additionally, because ions are trapped via their electric charges and interact via the state-independent Coulomb interaction, Rydberg ions do not suffer from most of the limitations of neutral Rydberg atom systems. It has been shown that ions in Rydberg states can be confined [23] and coherence between Rydberg states and low-lying states can be maintained [24] in radio-frequency traps. However, strong interactions between Rydberg ions and their use in fast-entangling gates had not been previously demonstrated.

In our experiment $^{88}$Sr$^+$ ions are confined in a linear Paul trap. Two low-lying electronic states ($|0\rangle$ and $|1\rangle$) are used to store a qubit, and $|0\rangle$ is coupled to Rydberg state $|r\rangle$ via a two-photon laser field. The relevant level scheme is shown in Fig. 1a, and more details can be found in ref. [24].

Two ions excited to Rydberg states interact through the dipole–dipole interaction:

\[
\hat{V}_{dd} = \frac{1}{4\pi\varepsilon_0} \left( \hat{\mu}_1 \cdot \hat{n} - 3 (\hat{\mu}_1 \cdot \hat{r}_1)(\hat{\mu}_2 \cdot \hat{r}_2) \right) \frac{1}{|\hat{r}_1\hat{r}_2|} \tag{1}
\]

where $\hat{\mu}_i$ is the electric dipole moment of ion $i$ ($i = 1, 2$), $\hat{r}_i = \hat{r}_2 - \hat{r}_1$ is the relative ion position, and $\hat{n} = \hat{r}_1 \hat{r}_2$. Trapped ions in atomic eigenstates have zero dipole moments and $\hat{V}_{dd}$ has no first-order effect. The second-order effect (van der Waals interaction) can be sufficiently strong to cause Rydberg blockade in neutral atom systems with principal quantum number $n = 50$ within a few micrometres [25]. However, this interaction is much weaker in Rydberg-ion systems; it scales with net core charge as $Z^+Z^+$ (for Sr$^+$ with one valence electron $Z = 2$). Instead, we achieve a strong first-order interaction by inducing rotating electric dipole moments via a microwave field.

When two Rydberg states $|s\rangle$ and $|p\rangle$ are coupled by a microwave field with Rabi frequency $\Omega_{mw}$ and detuning $\Delta_{mw}$ (Fig. 1b), the eigenstates become:

\[
|\pm\rangle = \mathcal{C} \left( \frac{\Delta_{mw} \pm \sqrt{\Delta_{mw}^2 + \Omega_{mw}^2}}{\Omega_{mw}} |s\rangle + |p\rangle \right)
\]

where $\mathcal{C}$ is the normalization constant [25]. In our system the electric dipole moments of the dressed states $|\pm\rangle$ rotate with the microwave field in the plane perpendicular to the magnetic field, as shown in Fig. 1c, d. For two ions, each in state $|r\rangle = |+\rangle$, the dipole–dipole interaction given by Eq. (1) yields an energy shift:

\[
V(\Delta_{mw}, \Omega_{mw}) = \langle \hat{V}_{dd} \rangle = \frac{1}{4\pi\varepsilon_0} \frac{\langle \hat{\mu}_1 | \hat{\mu}_2 \rangle^2}{r^2} \left( \frac{\Omega_{mw}^2}{\Delta_{mw}^2 + \Omega_{mw}^2} \right) \frac{n^3}{Z^2} \tag{2}
\]

with maximum interaction strength $V_{\text{max}} = \frac{1}{4\pi\varepsilon_0} \frac{\langle \hat{\mu}_1 | \hat{\mu}_2 \rangle^2}{r^2}$. For the measurements described here, we use Rydberg states with principal quantum number $n = 46$ and ion separation 4.2 μm, resulting in $V_{\text{max}} = 2\pi \times 1.9$ MHz. By tuning the ratio between $\Omega_{mw}$ and $\Delta_{mw}$ the interaction strength can be varied between approximately zero and $V_{\text{max}}$. Higher-order terms in $\hat{V}_{dd}$ can be neglected because the energy between dressed states $\Delta_{mw} \gg V_{\text{max}}$.

We probe the interaction between Rydberg ions as shown in the Rabi oscillations between $|0\rangle$ and $|r\rangle$ in Fig. 2. Either one or two ions are trapped and initialized in $|0\rangle$. A two-photon laser field then couples $|0\rangle \leftrightarrow |r\rangle$, and the pulse length is varied and the population that is excited out of resonance from $|0\rangle$ is monitored. Two-ion oscillations (pink data points) are suppressed as the interaction shifts the pair state $|rr\rangle$ out of resonance from

![Diagram](image-url)

**Fig. 1** | Level scheme of $^{88}$Sr$^+$ and the rotating dipole moment of a microwave-dressed Rydberg state. a. The ground state $|S\rangle$ is coupled to the Rydberg state $|r\rangle$. The qubit transition is driven by a 243-nm laser field. Projective measurements in any basis are carried out by qubit rotations and fluorescence detection. b. Two-photon laser field couples $|0\rangle \leftrightarrow |e\rangle$. The pulse length is varied and the population that is excited out of resonance from $|0\rangle$. c. The Rydberg electron density for the microwave-dressed state $|\pm\rangle$ yields a permanent dipole that rotates in antiphase with the microwave electric field about the magnetic field direction. d. The two microwave-dressed Rydberg ions interact via the dipole–dipole interaction. They are confined on the trap axis.
the laser excitation. When $|rr\rangle$ is far from resonance the population oscillates between two states $|00\rangle$ and the Bell state $(1/\sqrt{2})(|0r\rangle + |r0\rangle)$. This is the blockade regime, which is corroborated by the enhancement of the two-ion Rabi oscillation frequency (light blue data points) over the single-ion oscillation frequency (green data points) in Fig. 2d.

We then use the maximum interaction strength ($V = V_{\text{max}}$) to implement a 700-ns controlled phase gate between two ions. The experimental sequence is described in Fig. 3. First the two ions are initialized in state $\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$, and then the gate operation is applied— the population is transferred from $|00\rangle \rightarrow |rr\rangle \rightarrow |00\rangle$, and the Rydberg interaction causes component $|00\rangle$ to occupy phase $\phi$. Finally, qubit rotations and projective measurements are used to determine the final two-ion state.

The gate operation consists of a double stimulated Raman adiabatic passage (STIRAP) pulse sequence. The three level states $|0\rangle$, $|e\rangle$ and $|r\rangle$ are coupled by two laser fields with coupling strengths $D_1$ and $D_2$, $|0\rangle$ and $|r\rangle$ are resonantly coupled while $|e\rangle$ is detuned by $\Delta$ (see Fig. 1). $D_1$ and $D_2$ are gradually changed such that an ion initially in $|0\rangle$ adiabatically follows an eigenstate to $|r\rangle$ and back to $|0\rangle$. An ion initially in $|r\rangle$ is unaffected. For the initial pair states $|11\rangle$, $|10\rangle$ and $|01\rangle$ the eigenenergies remain zero and no phase is accumulated. From the initial state $|00\rangle$, the population can be excited to $|rr\rangle$ (provided $\Delta \geq V_{\text{max}}$), more details can be found in the Supplementary Information or ref. [24]. The energy of which is shifted due to the Rydberg interaction. Thus $|00\rangle$ acquires the phase $\phi = V_{\text{max}} \int_0^\tau (|rr\rangle \rho(t) |rr\rangle) dt$, with the two-ion density operator $\rho(t)$ and pulse length $\tau$. We achieve $\phi = \pi$ using sinusoidal profiles for $D_1(t)$, $D_2(t)$ and $T = 8\pi/3V_{\text{max}} = 700$ ns. In the ideal case the final target state $\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$ is maximally entangled.

The correlation of the final state is measured as follows: the projection of ion 1 on $|0\rangle$, $|1\rangle$, and the phase between $|0\rangle$, $|1\rangle$ of ion 2 are measured simultaneously; results are shown in Fig. 4a. The phase between $|0\rangle$ and $|1\rangle$ of ion 2 is 0 (π) when ion 1 is projected onto $|1\rangle$, $|0\rangle$—this indicates $\phi = \pi$. Entanglement is characterized by parity-oscillation measurements after rotating the target state $\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$.

The contributions of different gate error sources are estimated by numerical simulation (Table I). They can account for the observed gate infidelity. The largest error contributions are technical and can be diminished by improving the microwave power stability, increasing the laser intensities and decreasing the laser linewidths. Further, several error contributions depend on the gate time, which can be reduced by using higher Rydberg states which interact more strongly, together with higher laser intensities. In our gate implementation we use sideband cooling to mitigate the mechanical effects of Rydberg ion polarizability, which will become unnecessary when we use microwave-dressed Rydberg states with zero polarizability. In turn, this may allow implementation of the gate in higher-dimensional ion
coupling strengths ($\propto 22$, followed by the gate
Simulation and is consistent with the target entangled (see Supplementary Figs. 1, 2). The gate error induced by black-body radiation through spontaneous decay and double-ionization may be further reduced in a cryogenic environment (see Supplementary Fig. 3 for more details).

In summary, we have demonstrated a strong Rydberg dipole–dipole interaction ($2\pi \times 1.9$ MHz) and a 700-ns controlled phase gate in a trapped ion experiment. This provides a promising way to increase both the number of entangling operations within the coherence time and the number of qubits in a trapped-ion quantum computer or simulator. Although gates based on Rydberg interactions have already been demonstrated for neutral atoms, their availability in trapped ion systems offers many opportunities and advantages.

Ions are trapped by their electric charges, which enables deep, tight and state-independent confinement. The spread of the motional wavefunction is typically about 10 nm, much smaller than the effective excitation laser wavelengths, and as a result the system is in the Lamb–Dicke regime and motion is largely decoupled from electronic transitions.

The state-independent Coulomb interaction enables many important techniques in trapped-ion systems, such as sympathetic cooling$^{32}$ and multi-element logic gates$^{33}$, which are compatible with the Rydberg gate. The ion crystal can be cooled via the common motional modes without affecting the qubits or the Rydberg gate operation (since the gate does not rely on the motional modes), so the crystal is protected from heating by the trap or other noise sources. The advantages of different ion species can be combined; for example, qubit information can be transferred to ions with long coherence times for storage and to ions with strong interactions for gate operations.

The insensitivity of the Rydberg gate to ion temperature and motional modes enables its application in scalable architectures, such as large or even higher-dimensional ion crystals and ion shuttling systems$^{34}$. A Rydberg gate may be applied using a fixed pulse sequence to achieve a robust gate fidelity in large crystals or shuttling systems despite the difficulty in reaching low ion temperatures, and even though the number of ions and the motional modes vary. Here we have explored a short-range Rydberg interaction, but inside a microwave cavity the interaction can be made all-to-all without decreasing the interaction with distance.

Furthermore, the combination of the Rydberg dipole–dipole interaction and the Coulomb interaction may enable coupling between electronic and vibrational degrees of freedom, and thus interesting

**Fig. 3** | Experimental sequence of the Rydberg interaction gate. a. Pulse sequence: two ions are prepared in $\frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$, followed by the gate operation involving Rydberg excitation using a double-STIRAP sequence, the qubit rotation is applied for parity-oscillation measurements, and finally the two-ion state is measured using qubit rotation and fluorescence detection. b. Gate operation: the $|0\rangle \leftrightarrow |r\rangle$ and $|r\rangle \leftrightarrow |1\rangle$ coupling strengths ($\Omega$ and $\Omega_r/\sqrt{2}$) are varied sinusoidally over 700 ns. c. Simulation of one- and two-ion population dynamics during gate operation; the controlled phase accumulated by $|00\rangle$ is proportional to area enclosed by the $|rr\rangle$ population curve. Other states ($|01\rangle, |10\rangle$ and $|11\rangle$) do not accumulate phases because their eigenenergies remain zero.

Crystals. Importantly, we observe no heating effects of the ion motion after the gate operation in the two-ion crystal. Numerical simulation indicates that the gate error induced by mechanical forces between interacting Rydberg ions, which can excite ion motion, is about $10^{-4}$ in a 100-ion crystal using a zero-polarizability microwave-dressed

**Fig. 4** | Analysis of the two-ion state after the entangling gate operation. a. A Ramsey-type experiment measures the relative phase between $|02\rangle$ and $|12\rangle$ (a $\pi/2$ pulse of varied phase applied on ion 2 followed by projection measurement on $|02\rangle, |12\rangle$) conditional on the state of ion 1; the $\pi$-phase difference between the cases $|01\rangle, |10\rangle$ is consistent with the target entangled state $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. The mismatch between simulation and data is mainly because of imperfect single-ion addressing of the qubit laser state. This simulation and more details about gate errors caused by mechanical effects in large ion crystals can be found in the Supplementary Information (see Supplementary Figs. 1, 2). The gate error induced by black-body radiation through spontaneous decay and double-ionization may be further reduced in a cryogenic environment (see Supplementary Fig. 3 for more details).

In summary, we have demonstrated a strong Rydberg dipole–dipole interaction ($2\pi \times 1.9$ MHz) and a 700-ns controlled phase gate in a trapped ion experiment. This provides a promising way to increase both the number of entangling operations within the coherence time and the number of qubits in a trapped-ion quantum computer or simulator. Although gates based on Rydberg interactions have already been demonstrated for neutral atoms, their availability in trapped ion systems offers many opportunities and advantages.

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Furthermore, the combination of the Rydberg dipole–dipole interaction and the Coulomb interaction may enable coupling between electronic and vibrational degrees of freedom, and thus interesting
quantum simulations, such as tunable multi-body interactions\textsuperscript{35} or excitation transport through motion in biomolecules\textsuperscript{36}.

**Online content**

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1. Wineland, D. J. et al. Experimental issues in coherent quantum-state manipulation of trapped atomic ions. J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998).
2. Ballance, C. J. et al. High-fidelity quantum logic gates using trapped-ion hyperfine qubits. Phys. Rev. Lett. 117, 060504 (2016).
3. Gaebler, J. P. et al. High-fidelity universal gate set for $^{139}$Ba ion qubits. Phys. Rev. Lett. 117, 060505 (2016).
4. Hempel, C. et al. Quantum chemistry calculations on a trapped-ion quantum simulator. Phys. Rev. X 8, 031022 (2018).
5. Andergog, L. et al. Laser cooling of optically trapped molecules. Nat. Phys. 14, 890–893 (2018).
6. Wilk, T. et al. Entanglement of two individual neutral atoms using Rydberg blockade. Phys. Rev. Lett. 104, 010502 (2010).
7. Isenhower, L. et al. Demonstration of a neutral atom-controlled NOT quantum gate. Phys. Rev. Lett. 104, 010503 (2010).
8. Saffman, M. Quantum computing with atomic qubits and Rydberg interactions: progress and challenges. J. Phys. B 49, 020501 (2016).
9. Wang, Y. et al. Single-qubit quantum memory exceeding ten-minute coherence time. Nat. Photon. 11, 646–650 (2017).
10. Chiaverini, J. et al. Realization of quantum error correction. Nature 422, 602–605 (2003).
11. Schindler, P. et al. Experimental repetitive quantum error correction. Science 332, 1059–1061 (2011).
12. Wong-Campos, J. D. et al. Demonstration of two-atom entanglement with ultrafast optical pulses. Phys. Rev. Lett. 119, 230501 (2017).
13. Schaffer, V. M. et al. Fast quantum logic gates with trapped-ion qubits. Nature 555, 75–78 (2018).
14. Levine, H. et al. Parallel implementation of high-fidelity multiqubit gates with neutral atoms. Phys. Rev. Lett. 123, 170503 (2019).
15. Graham, T. M. et al. Rydberg mediated entanglement in a two-dimensional neutral atom qubit array. Phys. Rev. Lett. 123, 230501 (2019).
16. Zhang, S., Robicheaux, F. & Saffman, M. Magic-wavelength optical traps for Rydberg atoms. Phys. Rev. A 84, 043408 (2011).
17. Savard, T. A., O’Hara, K. M. & Thomas, J. E. Laser-noise-induced heating in far-off resonance optical traps. Phys. Rev. A 46, R1095 (1997).
18. Belyansky, R. et al. Nondestructive control of an atomic quantum register via state-insensitive Rydberg interactions. Phys. Rev. Lett. 123, 213603 (2019).
19. Devoret, M. H. & Schoelkopf, R. J. Superconducting circuits for quantum information: an outlook. Science 339, 1169–1174 (2013).
20. Veldhorst, M. et al. A two-qubit logic gate in silicon. Nature 526, 410–414 (2015).
21. Müller, M. et al. Trapped Rydberg ions: from spin chains to fast quantum gates. New J. Phys. 10, 095009 (2008).
22. Feldker, T. et al. Rydberg excitation of a single trapped ion. Phys. Rev. Lett. 115, 173001 (2015).
23. Higgins, G. et al. Single strontium Rydberg ion confined in a Paul trap. Phys. Rev. X 7, 021038 (2017).
24. Higgins, G. et al. Coherent control of a single trapped Rydberg ion. Phys. Rev. Lett. 119, 220501 (2017).
25. Saffman, M., Walker, T. G. & Melker, K. Quantum information with Rydberg atoms. Rev. Mod. Phys. 82, 2313 (2010).
26. Li, W. & Lesanovsky, I. Entangling quantum gate in trapped ions via Rydberg blockade. Appl. Phys. B 111, 37–44 (2014).
27. Urban, E. et al. Observation of Rydberg blockade between two atoms. Nat. Phys. 5, 110–114 (2009).
28. Gaetan, A. et al. Observation of collective excitation of two individual atoms in the Rydberg blockade regime. Nat. Phys. 5, 115–118 (2009).
29. Rao, D. D. B. & Mølmer, K. Robust Rydberg-atom interactions with adiabatic passage. Phys. Rev. A 89, 030301 (2014).
30. Leibfried, D. et al. Creation of a six-atom ‘Schrödinger cat’ state. Nature 438, 639–642 (2005).
31. Higgins, G., Pokorny, F., Zhang, C. & Hennrich, M. Highly polarizable Rydberg ion in a Paul trap. Phys. Rev. Lett. 123, 153602 (2019).
32. Barrett, M. D. et al. Thermometric coupling of “Ba” and “Mg” for quantum logic. Phys. Rev. A 68, 043402 (2003).
33. Tan, T. R. et al. Multi-element logic gates for trapped-ion qubits. Nature 528, 380–383 (2015).
34. Kippen, D., Monroe, C. & Wineland, D. J. Architecture for a large-scale ion-trap quantum computer. Nature 417, 709 (2002).
35. Gambetta, F. M., Li, W., Schmidt-Kaler, F. & Lesanovsky, I. Engineering non-binary Rydberg interactions via electron-phonon coupling. Phys. Rev. Lett. 124, 034402 (2020).
36. Wüster, S. & Rost, J.-M. Rydberg aggregates.
Data availability
The datasets generated during and analysed during the current study are available from the corresponding authors on reasonable request.

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Author contributions
G.H., F.P. and M.H. built the experimental system. C.Z. and F.P. set up the microwave dressing and improved the ultraviolet laser system. A.P. set up ablation loading of ions and the camera software. C.Z. had the idea of combining microwave dressing and STIRAP excitation. C.Z. and G.H. carried out the measurements. C.Z. analysed the data. C.Z. and W.L. simulated the results. M.H. designed and administered the experiment, W.L. and I.L. calculated properties of atomic Rydberg states. W.L., I.L. and C.Z. analysed the scaling of the gate error. All authors contributed to discussions and the writing of the manuscript.

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The authors declare no competing interests.

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