Realizing coherently convertible dual-type qubits with the same ion species

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Trapped ions constitute one of the most promising systems for implementing quantum computing and networking14,15. For large-scale ion-trap-based quantum computers and networks, it is critical to have two types of qubit: one for computation and storage, and another for auxiliary operations such as qubit detection1, sympathetic cooling4–7 and entanglement generation through photon links8,9. Although the two qubit types can be implemented using different ion species10–13, this approach introduces substantial complexity into creating and controlling each qubit type14–16. Here we resolve these challenges by implementing two coherently convertible qubit types using one ion species. We encode the qubits into two pairs of clock states of the 171Yb+ ions, and achieve microsecond-level conversion rates between the two types with one-way fidelities of 99.5%. We further demonstrate that operations on one qubit type, including sympathetic laser cooling, single-qubit gates and qubit detection, have crosstalk errors less than 0.06% on the other type, which is below the best-known error threshold of ~1% for fault-tolerant quantum computing using the surface code16. Our work establishes the feasibility and advantages of using coherently convertible dual-type qubits with the same ion species for large-scale quantum computing and networking.

Quantum computers have attracted widespread interest owing to the potential exponential speedup over any classical computer on certain tasks like factorizing large integers and quantum simulation of material properties1. However, quantum states are also fragile and require quantum error correction to protect against environmental noise and control errors1,16. It is thus crucial to have two types of qubits in fault-tolerant quantum computing1,16, one for the storage and the computation of the logical states and the other for the runtime diagnosis of the error syndromes so that they can be corrected promptly. For trapped ions, one of the leading platforms for quantum computing, these two types of qubit need to be spectrally separated to avoid crosstalk on one type as a result of the scattered photons during measurement of the other1,16–18. Besides, such ancilla ions are also required for sympathetic cooling for the computational ions and help stabilize large ion crystals as the qubit number increases19–21. Furthermore, ancilla ions also play a pivotal role in the photonic quantum network scheme for scaling up ion-trap quantum computers by continually generating ion–photon entanglement18,19,21.

Previously, it was assumed that such frequency-separated dual-type ion qubits have to be implemented in hybrid systems of two ion species, and this has attracted large experimental efforts, with remarkable progress1,10–11. For hybrid systems, apart from the experimental complexity of trapping and cooling two ion species and the lower mixed-species gate fidelity than the same-species case, it is also challenging to control the fraction and the positioning of each qubit type in many-ion crystals. Moreover, the mass mismatch between the ion species makes it very difficult to realize sympathetic cooling and high-fidelity gates with the transverse phonon modes4, a choice that is necessary for more scalable quantum gates in larger ion crystals10–12.

In this Letter we experimentally realize dual-type qubits that are coherently convertible to each other with the same species of 171Yb+ ions. Coherent conversion between different qubit types allows us to dynamically tune the fraction and positioning of each qubit type on demand in many-ion crystals during computation, which is highly desirable for efficient sympathetic cooling4 and quantum error correction16,18 in large-scale systems. In addition, the capability of fast and high-fidelity qubit type conversion indicates that entangling gates between different qubit types can be performed in exactly the same way as for gates with the same qubit types, hence eliminating the challenging requirement for mixed-species high-fidelity gates. Both types of qubit in our experiment are realized with clock states of 171Yb+ ions, in the S and F manifolds, respectively, which have a long coherence time and almost no relaxation. Coherent conversion is achieved with bichromatic narrowband laser beams at wavelengths of 411 nm and 3,432 nm (ref. 22), respectively, with a fidelity of ~99.5%, even in this preliminary experiment. We then demonstrate that, during operations on one qubit type such as cooling, gates and detection, the coherence of the other qubit type is well preserved, with a crosstalk error rate below 0.06% per operation. Note that the transition to the metastable D or F levels has been used before in ion-trap experiments for qubit detection through electron shelving23–25 and for temporary protection of the optical qubits under detection25,26. The contribution here is that we achieve fast coherent conversion between dual types of qubit, both carried by robust clock states with long coherence time and almost no relaxation (coherent conversion for optical qubits27,28 or magnetically sensitive hyperfine qubits29 has previously been demonstrated with a shorter lifetime). This allows us to realize the required whole set of protected operations through dual types of qubit with below-threshold crosstalk error rates, including a demonstration of sympathetic cooling using the same ion species with negligible crosstalk errors.

To demonstrate the protection accomplished by the use of dual types of qubit, it suffices to consider two ions. Our experimental set-up consists of two 171Yb+ ions, as shown schematically in Fig. 1. Each ion can be in one of the two qubit types, encoded either in the clock states |0⟩≡ |F = 0, m_F = 0⟩ and |1⟩≡ |F = 1, m_F = 0⟩ of the S_{1/2} levels (S-qubit) or |0′⟩≡ |F = 3, m_F = 0⟩ and
|′⟩ ≡ |F = 4, m_F = 0⟩ of the metastable F_{7/2} levels (F-qubit). The S-qubit can be manipulated by routine laser and microwave operations 23–26 such as optical pumping, qubit state detection, Doppler cooling, and single-qubit rotations with a 12.6-GHz microwave, which suffices for our experiment. If higher detection fidelity is needed, we can apply the electron shelving technique23–26; we have obtained a detection fidelity above 99.9% in our experiment. More details are provided in the Methods.

To prepare an F-qubit, we first initialize the ion in |0⟩ through optical pumping and then transfer it to |′⟩ via the intermediate state of D_{5/2} using a 411-nm π pulse (from a home-made narrowband laser; Methods). The 411-nm laser is focused to a beam waist radius of ~4 μm and supports selective control of one ion with small crosstalk on the other ion at a distance of ~14 μm. Because of the finite laser linewidth, the population transfer fidelity does not reach unity. We thus add a verification step to check whether the ion remains in the S_{1/2} or D_{5/2} levels, and discard these unsuccessful events. The F-qubit can then be operated by the 3.6-GHz microwave with a single-qubit gate fidelity of 99.99% (Methods). For its detection, we perform electron shelving by incoherently pumping the population in |0⟩ back to the S_{1/2} levels using continuous 3,432-nm and 976-nm lasers with 20-μs duration. In this way, |′⟩ is mapped to a bright state under the 370-nm detection laser while |1⟩ remains a dark state, which gives us a detection fidelity of 99.86% at a detection time of 250 μs. A higher detection fidelity of 99.97% is also demonstrated in our experiment using a longer detection time (Methods).

The two qubit types can be converted into each other coherently in less than 1 μs. As shown in Fig. 1c, an S-qubit can first be transferred to the D_{5/2} levels through a 411-nm π pulse with suitable microwave side bands for |0⟩ and |1⟩ simultaneously. Another 3,432-nm π pulse, again with suitable microwave side bands, then finishes the conversion to the F-qubit. By reversing the order of the two π pulses we can similarly achieve conversion from an F-qubit back to the S-type. During this process, the phase noise in the laser beams appears as a global phase for the qubit and thus does not lead to decoherence. In Fig. 2 we use the fidelity between the qubit states before and after the coherent conversion to quantify its performance. Specifically, we initialize an S-qubit state |ψ⟩ through a microwave pulse, perform N rounds of S–F–S conversions, and measure the fidelity of the final state |ψ⟩ with the initial state |ψ⟩ by mapping |ψ⟩ back to |1⟩ using another microwave pulse followed by detection in the |0⟩/|1⟩ basis. By averaging the initial state |ψ⟩ over a complete set of mutually unbiased bases (MUBs) 31,|0⟩, |1⟩, |+⟩ ≡ (|0⟩ + |1⟩)/√2, |−⟩ ≡ (|0⟩ − |1⟩)/√2, |L⟩ ≡ ((|0⟩ + i|1⟩)/√2 and |R⟩ ≡ ((|0⟩ − i|1⟩)/√2, we get the average fidelity F over the Bloch sphere 31, which is fitted as $F = F_0 - \epsilon_i N + cN^2$ (Methods). We thus extract 2.3 ± 0.2% state preparation and measurement (SPAM) error from $F_0$, and 0.97 ± 0.05% coherent transfer error for each round of S–F–S conversion (or ~0.5% error for one-way S-to-F or F-to-S conversions), with error bars representing one standard deviation (s.d.).

In Fig. 3 we analyse the crosstalk error of the S-qubit operations on a nearby F-qubit. We begin with two S-qubit ions in |0⟩ after Doppler cooling and optical pumping, and then initialize one ion into an F-qubit in the state |ψ⟩. As shown in Fig. 3b, we apply
co-propagating 355-nm Raman laser beams to drive the resonant transition between |0⟩ and |1⟩ of the S-qubit (the Rabi oscillation is presented in the inset). The average fidelity $\bar{F}$ of the F-qubit over the MUBs decays slowly with duration $t$ of the Raman laser, or measured in terms of the number of $\pi/2$ pulses $N_{\pi/2} \equiv t/t_{\pi/2}$, where $t_{\pi/2}$ is the Raman laser duration required to achieve a $\pi/2$ pulse. We fit the data with $\bar{F} = F_0 - \epsilon cN_{\pi/2} + cN_{\pi/2}^2$ and extract a crosstalk error of $\epsilon_c \approx 0.0007 \pm 0.0006\%$ on the F-qubit for a $\pi/2$ Raman pulse on the S-qubit. In Fig. 3c, after initializing the F-qubit, we turn on the Doppler cooling, optical pumping and state detection cycle for the S-qubit, and repeat this sequence $N$ times, after which we measure the F-qubit fidelity. As shown in the inset, we find an $\approx 1\%$ SPAM error when preparing an S-qubit in |0⟩ and detecting in |1⟩, which mainly arises from the imperfect S-qubit detection. The error bars in the inset reduce for larger $N$ because we are averaging over more experimental trials, but the mean value should stay constant. The weak decreasing tendency in the plot may be due to the slow parameter drifts in the experiment. In this case we fit the average F-qubit fidelity $\bar{F} = F_0 - \epsilon cN + cN^2$ with $\epsilon_c \approx 0.006\% \pm 0.003\%$ as the cross-talk error on the F-qubit when initializing and detecting a |0⟩-state S-qubit. Similarly, in Fig. 3d we add a microwave pulse into the experimental sequence to initialize the S-qubit in |1⟩ and we fit a cross-talk error of $\epsilon_c \approx 0.0005 \pm 0.004\%$. The detailed time sequence for the S-qubit and F-qubit is provided in Extended Data Fig. 1. The Doppler cooling stage in the above sequence turns out to be important for our experiment because, otherwise, the spatial motion of the ions will be heated during the evolution time of tens of milliseconds, which will hinder the accuracy of the subsequent laser manipulations. In Fig. 4 we explicitly study this sympathetic cooling dynamics. Before initializing the F-qubit when both ions are in the S-type, we first heat them with a blue-detuned 370-nm laser. We then prepare an F-qubit in |0⟩ and turn on the Doppler cooling beam for the S-qubit for various durations. Finally, we repump the F-qubit back to the S-type |0⟩ to measure the temperature of the two-ion crystal via the carrier Rabi oscillation of the side-band-resolved 411-nm transition (Methods). We also apply the heating–cooling sequence without preparing the F-qubit such that both ions can be cooled by the Doppler cooling beam. As can be seen, the cooling dynamics for the sympathetic cooling and global Doppler cooling cases are similar, which proves the efficiency of the sympathetic cooling. In the inset of Fig. 4, we further measure the average F-qubit fidelity $\bar{F}$ (similarly over the MUBs) versus the sympathetic cooling time $t$ and fit $\bar{F} = F_0 - \epsilon_f t + ct^2$. We obtain $0.055 \pm 0.036\%$ crosstalk error for a sympathetic cooling operation with a typical duration of 1 ms. Note that the 411-nm laser in our experiment is perpendicular to the two-ion chain, so it probes the temperature of transverse photon modes. It has been shown that sympathetic cooling of these transverse modes is inefficient in hybrid systems using two ion species due to localization of the modes caused by the mass mismatch, but our dual-type qubits within the same ion species allow efficient cooling for these modes, which can be used for more robust entangling gates in larger ion crystals, with advantages for scalable quantum computing.

In summary, we have experimentally demonstrated dual-type qubits within the same ion species. The two qubit types can be coherently converted into each other using microsecond narrow-band laser pulses, with $\approx 99.5\%$ transfer fidelity each way. The fidelity is currently limited by the imperfect population transfer due to the technical noise of the laser power and frequency fluctuation...
Fig. 4 | Sympathetic cooling and crosstalk error. We prepare an S-type qubit and an F-type qubit, and apply Doppler cooling on the S-qubit using a 370-nm laser with 10-MHz red detuning. Starting from a high temperature of ~12mK, we observe a decay in the measured average temperature versus the cooling time (red squares). In comparison, blue circles are the measured average temperature under global Doppler cooling when both ions are S-type. The cooling dynamics are fitted by exponential decays to guide the eye. The cooling rates and the final temperatures are comparable in the two cases. The inset shows the average fidelity of the F-qubit over the MUBs when the Doppler cooling laser is on. By fitting with a quadratic function $F = F_0 - c_1 t + c_2 t^2$, we obtain $0.055 \pm 0.036\%$ crosstalk error for a sympathetic cooling operation with a typical duration of 1 ms. Each data point is repeated 450 times. Error bars represent 1 s.d.

and can be improved by better frequency locking of the laser or using more robust composite pulses1. Crosstalk errors from sympathetic cooling, optical pumping, detection and single-qubit gates on the S-qubit are all measured to be below 0.06% for the F-qubit. The demonstrated below-threshold crosstalk errors between the dual types of qubits, together with their fast high-fidelity coherent conversion, opens up prospects of wide applications in large-scale quantum computing and quantum networking.

Online content
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Methods

Experimental set-up. In the experiment we use a single 370-nm laser beam to drive transitions between $S_{1/2}$ and $P_{1/2}$ of the $^{171}$Yb$^+$ ions, for Doppler cooling, optical pumping and detection of the S-qubit. To switch the role of the laser beam, we use an acousto-optical modulator controlled by a home-made digital synthesizer to quickly change the carrier frequency, and we turn on different electro-optical modulators (EOMs) to generate the desired microwave sidebands. For Doppler cooling, the laser is set to $-10$ MHz red-detuned from the $(f_{S1/2}, F = 1) \leftrightarrow \left( |P_{1/2}, F = 0 \rangle \right)$ transition, with a 14.7-GHz sideband for the $(S_{1/2}, F = 0) \leftrightarrow \left( |P_{1/2}, F = 1 \rangle \right)$ transition. For optical pumping into $|0 \rangle$, the laser is set to be resonant with the $(S_{1/2}, F = 1) \leftrightarrow \left( |P_{1/2}, F = 0 \rangle \right)$ transition, with a 2.1-GHz sideband for the $(S_{1/2}, F = 1) \leftrightarrow \left( |P_{1/2}, F = 1 \rangle \right)$ transition. The detection beam is resonant to the $(S_{1/2}, F = 1) \leftrightarrow \left( |P_{1/2}, F = 0 \rangle \right)$ transition, with no microwave sideband. The optical power for this laser beam is $-10$ mW, with a beam diameter (where the intensity drops to 1/e$^2$ of $60$ μm. The small population leaked to the $D_{5/2}$ levels is pumped back to $S_{1/2}$ by a 935-nm laser, with an optical power of $-1$ mW and a beam diameter of $100$ μm.

We use a 355-nm mode-locked pulsed laser (Coherent, Paladin Advanced 355-8000) with a repetition rate of $80.95$ MHz and a full bandwidth of $200$ GHz to pump the residual population in $D_{5/2}$ back to $S_{1/2}$, then apply a resonant 370-nm laser to prepare the desired state, initialization. After an attempted population transfer to $F_{7/2}$, rather than first encoding the qubit in the $S$-type and then coherently converting the $F$-type, we repeat this initialization–verification cycle for several rounds to achieve 0.97 ± 0.05% round-trip transfer error, as reported in the main text using $0.54 \pm 11$ μm × pulses and $0.39 \pm 132$ 3.432-nm × pulses.

Detection through electron shelving. In our experiment, the F-qubit is detected by electron shelving, as shown in the main text, with a detection fidelity of 99.86 ± 0.03% with a detection time of 0.25 ms, which can be further improved to 99.96 ± 0.004% at 2.5 ms detection time. The S-qubit can be detected by the round-trip 370-nm laser with a detection fidelity of 98.3 ± 0.2%, or by the electron shelving method’ with a detection fidelity of 99.913 ± 0.007%.

For F-qubit detection, we can transfer the population in $|0 \rangle$ of the S-qubit to the $|F_{2J/2}, F_m = 3, m = 0 \rangle$ state via 411-nm and 3,432-nm × pulses. However, this population transfer is not perfect, so we further transfer the population in $|0 \rangle$ to several Zeeman levels of the $|F_{2J/2}, F = 4, m_0 = 0, \pm 1 \rangle$ states, sequentially, using 3.62 GHz microwave transitions. We thus achieve a detection fidelity of around 99.913 ± 0.007% for the S-qubit within a detection time of ~2.5 ms.

Microwave single-qubit gates. We use 12.6428-GHz microwave fields to implement single-qubit gates for the S-qubit, and 3.62057-GHz microwave fields for the F-qubit. We characterize the gate fidelity via the standard randomized benchmarking method$^3$. The results are shown in Extended Data Fig. 3, with a measured average gate fidelity of 99.98 ± 0.04% for the S-qubit and 99.99 ± 0.04% for the F-qubit. We can thus ignore the error in the microwave operations in the initialization and measurement stages compared with the other SPAM errors.

Fitting model for average fidelity versus number of repetitions. The decay of the average state fidelity versus the number of coherent conversions or that of S-qubit operations can be modelled by an exponential decay $F = A \times e^{-B}$, where $A$ and $B$ are fitting parameters. If leakage error outside the qubit subspace dominates, we have $F = 0$ as $N \rightarrow \infty$, so that $C = 0$. On the other hand, if dephasing or depolarization error within the qubit space dominates, one would expect the fidelity to approach zero. Given that both errors are possible in this experiment, we consider the general fitting model and rewrite it as $F = A(1 - e^{-B}) + C$, where we have rearranged the fitting coefficients such that the initial part of the curve can be expanded as $F = F_1 - C \times e^{-N}$. Including correction to the next order, we therefore use $F = F_1 - C \times e^{-N} + C \times e^{-2N}$ as our fitting model, which is valid for the data shown in Figs. 2–4 because the fidelity does not decrease much from unity. The SPAM error is now given by $1 - F_2$, and the ion incoherence or crossstalk is reduced by using a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser to average a 4-nm laser.
where \( \eta_i \) is the Lamb–Dicke parameter for mode \( i \) and \( L_n(x) \) is the Laguerre polynomial of degree \( n \). In the above expression, we have dropped the higher-order terms of \( n \eta_i^2 \), as in our case \( \eta \approx 0.024 \).

Now, if we initialize the ion in the \( S_{1/2} \) state, its probability to remain in \( S_{1/2} \) is

\[
P_{S}(t) = \sum_{\{n_i\}} P_{\{n_i\}} \frac{1 + \cos \Omega \{n_i\} t}{2} = \frac{(1 + \text{Re}(f(t)))/2}{2}
\]

where

\[
f(t) = e^{i\Omega_0 t(1 - \sum \eta_i^2/2)} \prod_i \frac{1}{\eta_i + 1} \frac{\eta_i e^{-i\eta_i^2/2}}{\eta_i^2}.
\]

We use it to fit the two parameters \( \Omega_0 \) and \( T \) from the carrier Rabi oscillation. An example is shown in Extended Data Fig. 4.

**Data availability**

The data that support the findings of this study are available from the authors upon request. Source data are provided with this Paper.

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**Author contributions**

L.-M.D. proposed and supervised the experiment. H.-X.Y., J.-Y.M., Y.W., M.-M.C., W.-X.G., Y.-Y.H., L.F., Y.-K.W. and Z.-C.Z. carried out the experiment. H.-X.Y., J.-Y.M., Y.-K.W. and L.-M.D. wrote the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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Extended Data Fig. 1 | Detailed time sequence for measuring the crosstalk of S-qubit operations on the F-qubit. Detailed time sequence for measuring the crosstalk of S-qubit operations on the F-qubit. 

**a**. Time sequence for the S-qubit and the F-qubit (which also starts from an S-qubit). During the verification step of the F-qubit, resonant 370-nm laser is applied, so the S-qubit needs to be reinitialized after that. 

**b**. Specific S-qubit operations for Fig. 3b to measure crosstalk errors of Raman Rabi oscillation using 355-nm laser. 

**c**. Specific S-qubit operations for Fig. 3c to measure crosstalk errors of preparation and detection of |0⟩. 

**d**. Specific S-qubit operations for Fig. 3d to measure crosstalk errors of preparation and detection of |1⟩.
Extended Data Fig. 2 | Carrier Rabi oscillation of the 411-nm laser and 3,432-nm laser. Carrier Rabi oscillation of a, the 411-nm laser and b, 3,432-nm laser. The 411-nm laser has an optical power of about 0.8 mW and a beam diameter of about 8 µm, which generates a Rabi frequency of about $2\pi \times 859.4$ kHz. The 3,432-nm laser has an optical power of about 0.5 mW and a beam diameter of about 73 µm, which gives a Rabi frequency of about $2\pi \times 1.2$ MHz.
Extended Data Fig. 3 | Randomized benchmarking of the microwave-driven single-qubit gates. Randomized benchmarking of the microwave-driven single-qubit gates for a, the S-qubit and b, the F-qubit. The average gate fidelity is $(99.98 \pm 0.04)\%$ for the S-qubit and $(99.99 \pm 0.04)\%$ for the F-qubit.
Extended Data Fig. 4 | Carrier Rabi oscillation of 411-nm laser after 500 μs sympathetic cooling. Carrier Rabi oscillation of 411-nm laser after 500 μs sympathetic cooling. The fitted effective temperature is (9.2 ± 0.2) mK.