

Universal Global Gates for a Fine-Structure Qubit in Strontium-88

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Metastable atomic qubits are a highly promising platform for the realization of quantum computers, owing to their scalability and the possibility of converting leakage errors to erasure errors midcircuit. Here, we demonstrate and characterize a high-fidelity quantum gate set for the metastable fine-structure qubit encoded between the 3P_0 and 3P_2 states in bosonic strontium-88. We find single-qubit gate fidelities of 0.993(1), and two-qubit gate fidelities of 0.9945(6) after correcting for losses during the gate operation. Furthermore, we present a novel state-resolved detection scheme for the two fine-structure states that enables high-fidelity detection of qubit loss. Finally, we leverage the existence of a stable ground state outside the qubit subspace to perform midcircuit erasure conversion using fast destructive imaging. Our results establish the strontium fine-structure qubit as a promising candidate for near-term error-corrected quantum computers, offering unique scaling perspectives.

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Arrays of trapped neutral atoms are emerging as a leading platform for quantum computation [1–4]. Recent milestones include gate fidelities beyond 0.999 for single-qubit gates [5–10] and around 0.995 [7,9,11–13] reaching up to 0.997 [14] for two-qubit gates. Atom arrays have been scaled to thousands of qubits [15–21], and small-scale quantum computations, with both local [6] and nonlocal connectivity, have been demonstrated [22]. This progress, together with recent demonstrations of logical circuits [23–25], has brought quantum error correction to the center of attention.

A major obstacle to realizing logical qubits is the substantial overhead in the number of physical qubits required for their implementation. Noise-biased qubits have recently been proposed as a way to reduce this overhead [26–30]. A particularly useful type of noise bias is toward leakage out of the computational subspace, which can be converted to a detectable error at a known location—thereby significantly increasing the threshold for quantum error correction [31]. Such *erasure-convertible qubits*, first demonstrated in atoms [7,32], have since been adopted by other platforms [33–38].

In atoms, erasure-convertible qubits are naturally implemented in metastable electronic states as found in alkaline-earth(like) species. They were first proposed and realized in neutral ytterbium-171—where a nuclear spin-1/2 qubit is encoded in a metastable state [7,39,40]—and have since been demonstrated in trapped ions [38,41]. Implementing erasure-convertible qubits in other alkaline-earth atoms has proven more challenging. In strontium isotopes, the nuclear spin is either zero for bosonic strontium, or 9/2 in the case of fermions, whose use in quantum computing applications based on qubits requires additional control demonstrated so far only for the electronic ground state [42]. As a result, digital quantum computing with strontium atoms—for which high-fidelity imaging [17,43], continuous atom reloading [18], and state-of-the-art gate fidelities [12,14] have been achieved—still mainly relies on the optical clock qubit [12]. There, scaling to large system sizes and deep circuits may be challenging due to the limited gate speeds and high optical power requirements. Moreover, erasure conversion has so far only been applied to a short-lived qubit in strontium [32] and not yet to any longer-lived encoding, in the context of quantum information processing.

Here, we propose and experimentally demonstrate an erasure-convertible qubit in bosonic strontium-88, encoded in the fine-structure states 3P_0 and 3P_2 separated by 17 THz. Compared to the qubit operating on the ultranarrow clock transition [12], our scheme reduces the gate time by an order of magnitude while significantly lowering the required optical power, enabling straightforward scaling to larger array sizes. While coherence and coherent control [44–46] of the fine-structure qubit have been explored

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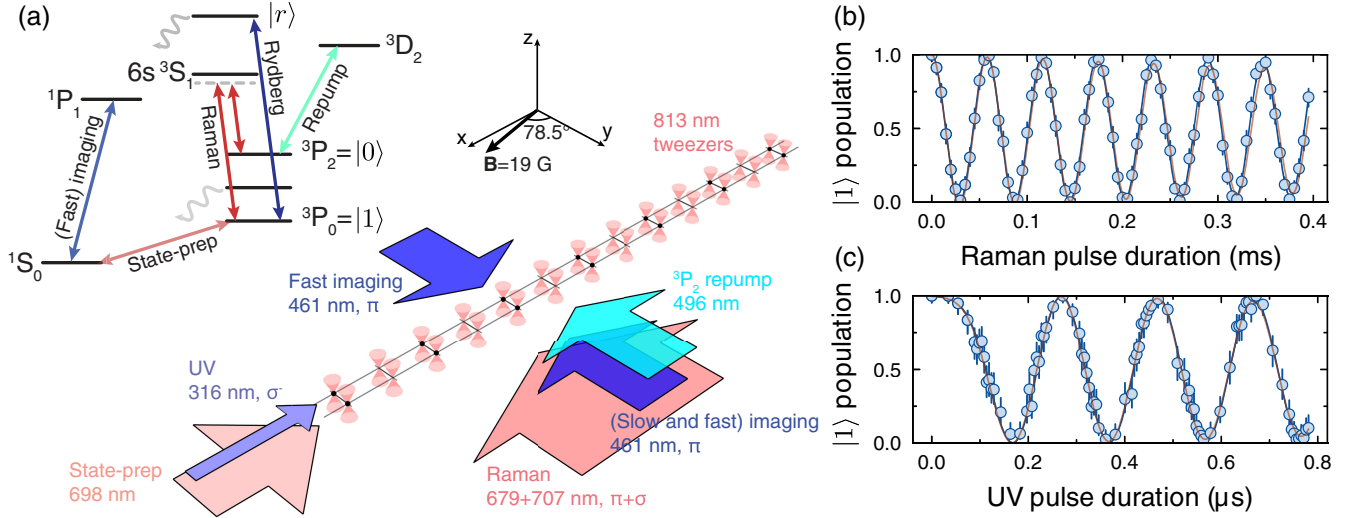


FIG. 1. Experimental setup. (a) Layout of the optical tweezer array, laser beams with their polarization, as well as the level diagram relevant to this Letter. The qubit is encoded in metastable states $|0\rangle \equiv |^3P_{2,m_J=0}\rangle$ and $|1\rangle \equiv |^3P_0\rangle$ in strontium-88. Repumping on the 3P_2 - 3D_2 transition at 496 nm incoherently transfers $|0\rangle$ population to 1S_0 , in the state-sensitive readout scheme. Imaging in general is performed by scattering photons on the broad 1S_0 - 1P_1 transition at 461 nm. For midcircuit erasure detection of leakage out of the qubit subspace, two well-balanced, counterpropagating imaging beams are used. A tightly focused UV beam couples $|1\rangle$ to the Rydberg state $|r\rangle = |47s\ ^3S_{1,m_J=-1}\rangle$ for entanglement generation. (b) Rabi oscillation between $|0\rangle$ and $|1\rangle$ driven by a two-photon Raman process with (blue) and without (orange) erasure conversion (discussed in the main text). (c) Rabi oscillation between $|1\rangle$ and $|r\rangle$ with (blue) and without (orange) erasure conversion. Atoms in $|r\rangle$ are detected via losses induced by a 408 nm autoionization laser [52].

previously, this Letter provides the first demonstration of calibrated, high-fidelity universal gates and loss-tolerant state readout, which are the prerequisites for algorithmic operations. Our erasure protocol further differs from prior strontium-88 demonstrations that relied on short-lived Rydberg states [32]. Here, the protocol operates entirely within the robust metastable manifold, which is essential for midcircuit operation. We first demonstrate coherent manipulation of fine-structure qubits in an atom array via a two-photon transition that couples the qubit states off resonantly through the intermediate 3S_1 state. Next, we implement midcircuit erasure conversion, converting state-preparation and off-resonant scattering errors into erasures and excising them to reach a single-qubit Clifford gate fidelity of 0.993(1). Excluding loss events, we then realize two-qubit gates based on Rydberg blockade with a fidelity of 0.9945(6), and generate Bell states of two fine-structure qubits with a fidelity of 0.983(8). Finally, we describe in detail our novel loss detection scheme employed above, which leverages shelving into the 1S_0 state outside the qubit subspace, combined with controlled, low-leakage depumping, to enable imaging of both qubit states. Taken together, these results establish the fine-structure qubit as a compelling candidate for fault-tolerant circuit-based quantum computing.

Our experiment [17,18,46] consists of strontium-88 atoms trapped in 32 reconfigurable optical tweezers at 813 nm with spacings of 6.5 μm (2 μm) along the x (or y) axis; see Fig. 1(a). After loading atoms from the magneto-optical trap and performing initial imaging to determine

tweezer occupancy, we sort them into a unity-filled pattern of pairs with a 13 μm interpair spacing using an additional mobile tweezer. Subsequently, the atoms are cooled close to their radial motional ground state via resolved sideband cooling on the 1S_0 - 3P_1 transition [47]. The fine-structure qubit is encoded in metastable states $|^3P_0\rangle \equiv |1\rangle$ and $|^3P_{2,m_J=0}\rangle \equiv |0\rangle$. To prepare the state $|1\rangle$, we apply a single, 150 μs -long π pulse on the ultranarrow clock transition at 698 nm at 420G bias field. To achieve magic trapping conditions for the fine-structure qubit, we then ramp the magnetic field to the triple magic configuration where the 1S_0 and the qubit states are magically trapped [46]. For loading and imaging, we typically operate the tweezers at a depth of 700 μK , which is reduced to a shallower depth of 50 μK during gate operations to increase the qubit coherence time [46]. To realize arbitrary single-qubit control, we drive a global two-photon Raman process using lasers at 679 and 707 nm; see Figs. 1(a) and 1(b). To entangle pairs of atoms, a tightly focused 316 nm UV beam couples the state $|1\rangle$ to a highly excited Rydberg state $|r\rangle = |47s\ ^3S_{1,m_J=-1}\rangle$ in free space [Fig. 1(c)], where Rydberg interactions lead to a blockade of nearby excitations. In our array, the interaction shift for pairs of atoms in the Rydberg state is approximately $2\pi \times 114$ MHz, which far exceeds the Rabi coupling strength to the Rydberg state of $\Omega = 2\pi \times 6$ MHz.

Since the 1S_0 ground state lies outside the qubit subspace, it can be used for erasure conversion via fast imaging on the broad 1S_0 - 1P_1 transition. This has been demonstrated

for the metastable, nuclear qubit in ytterbium-171 [7], a short-lived qubit encoded between the 3P_0 state and a Rydberg state in strontium-88 [32] and, more recently, the ground-state hyperfine qubit in strontium-87 [53], but not yet on long-lived qubits in strontium in the context of quantum information processing. In our implementation, we image the 1S_0 population in a 30 μs -long detection block using two pulsed, counterpropagating imaging beams [54,55]; see Fig. 1(a). Based on the thresholding of the erasure image, we identify experimental instances where midcircuit leakage to 1S_0 has occurred, and excise these from the analysis. With a typical classification fidelity of 0.96 for fast imaging in shallow tweezers during qubit operation, we can convert and excise approximately 91% leakage error at the expense of discarding 7% valid data where no error has occurred; see Fig. 2(b) inset and [47]. Here, we show that state-preparation errors arising from imperfect π pulses on the clock transition and from Raman scattering during the idle time atoms spend in traps can be eliminated; see Fig. 2(b). As we lower the classification threshold in the erasure image, the probability of successfully identifying and removing leakage errors increases. As a direct consequence, the state-preparation fidelity increases. As the threshold drops below zero, the state-preparation fidelity reaches a plateau at over 0.996, just 0.002 below our imaging-limited survival probability of 0.998. In the meantime, we observe negligible influence of erasure conversion on the coherence of the fine-structure qubits; see Fig. 2(c). Moreover, our erasure scheme is also effective against leakage errors such as those occurred during the qubit manipulation due to off-resonant scattering off 3S_1 into 3P_1 , which quickly decays to the 1S_0 owing to its 21 μs lifetime. These features establish erasure conversion as a versatile, midcircuit-applicable error-detection scheme for the metastable qubits.

To perform state-sensitive detection of $|1\rangle$, we drive the 496 nm repump transition between 3P_2 and 3D_2 to deplete $|0\rangle$. The branching of 3D_2 into 3P_J is such that 99.965% of the population decays to 1S_0 via 3P_1 , leaving 0.035% in 3P_0 , which amounts to a small detection error [56]. Finally, we push out the population in 1S_0 with an intense 461 nm pulse and image the remaining population, which we assign to $|1\rangle$. To demonstrate control over the fine-structure qubit initialized in $|1\rangle$, we drive highly coherent Rabi oscillations between the two qubit states; see Fig. 1(b). To characterize the single-qubit gate fidelity, we turn to Clifford randomized benchmarking (CRB) [57,58]; see Fig. 2(a). We find the average single-qubit Clifford gate fidelity F_{1q} of 0.992(1) [0.993(1)] without (with) erasure excision, averaged over 16 tweezer sites, at $2\pi \times 17$ kHz Rabi frequency; see Fig. 2(d). To further improve gate performance, the most effective means is by reducing laser phase noise which currently accounts for 4×10^{-3} raw infidelity. In addition, off-resonant scattering into $^3P_{2,m_J \neq 0}$ can in principle be

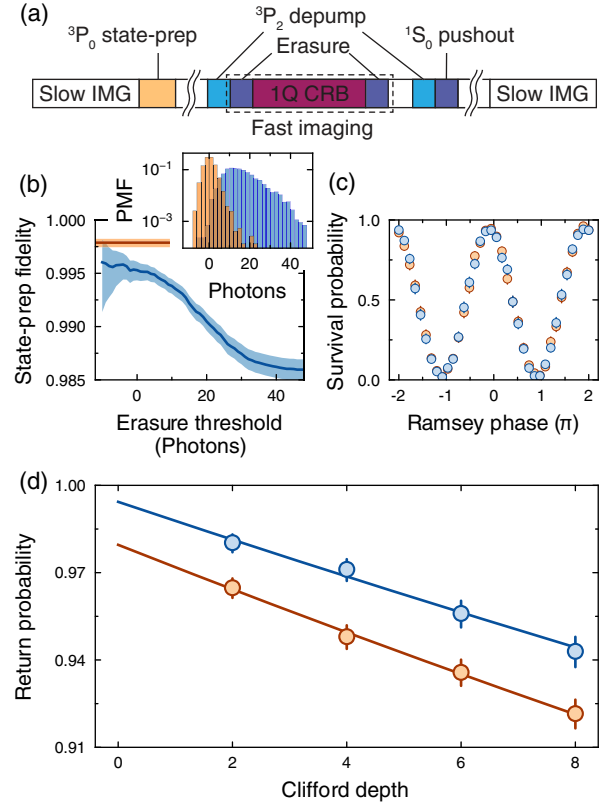
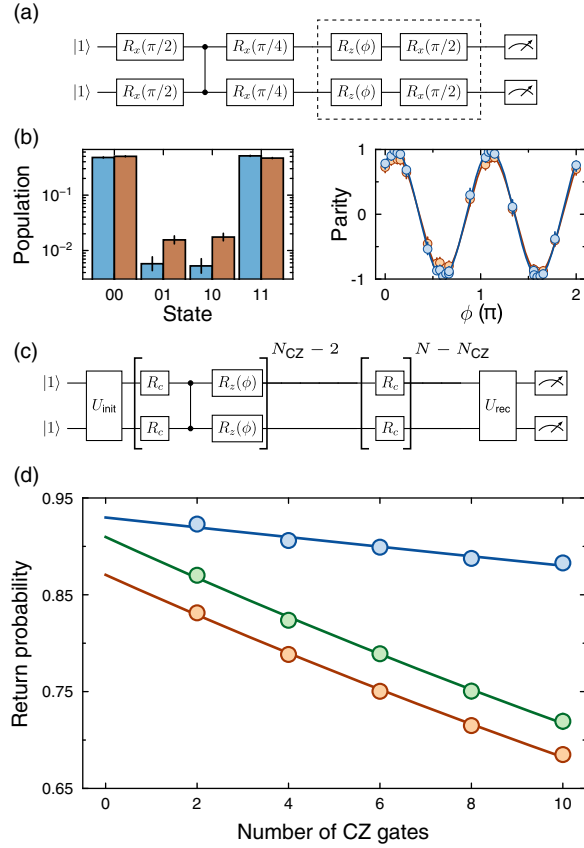


FIG. 2. State-preparation and single-qubit gate benchmarking. (a) Experimental sequence. The cooling-assisted, nondestructive imaging (slow IMG) at the start of the sequence verifies the loading of atoms at the target tweezer sites, and at the end reads out the $|1\rangle$ population after a $|0\rangle$ depletion stage (using 3P_2 depumping and 1S_0 pushout). Two erasure conversion pulses sandwiching the single-qubit Clifford randomized benchmarking (CRB) sub-sequence remove state-preparation error in 3P_0 and off-resonant scattering errors originating from 3P_1 . See main text for details. (b) The $|1\rangle$ state-preparation fidelity (blue) as a function of the erasure conversion threshold, which determines the fraction of state-preparation errors excised. Inset: probability mass function (PMF) of photon counts in an erasure image, binarized using a preceding high-fidelity, low-loss imaging stage. At low erasure threshold, the false negative probability is low, and the state-preparation error (blue) is suppressed to $0.39^{+0.47}_{-0.21}\%$, approaching the error from the imaging loss (orange) alone. Negative photon counts arise solely from a camera bias that we subtract during postprocessing. (c) Ramsey measurement with midcircuit erasure conversion (blue) shows no measurable contrast reduction within the error bar compared to a reference measurement without it (orange). (d) The average Clifford gate fidelity raw (orange) and after erasure conversion (blue) from randomized benchmarking are 0.992(1) and 0.993(1), respectively. Data excision rate is about 16%; see Fig. 5(a). The erasure conversion threshold is chosen at two photon counts.

converted to erasure events by two-photon coupling of 3P_2 to the short-lived 3P_1 state.

An important requirement for universal quantum computers is the realization of high-fidelity entangling gates.



To entangle two fine-structure qubits, we couple the qubit state $|1\rangle$ to the Rydberg state $|r\rangle$, implementing a time-optimal control-Z (CZ) gate by modulating the phase of the laser drive [59]. Embedding the CZ gates in a sequence of single-qubit rotations [see Fig. 3(a)], we benchmark the entanglement by generating two-qubit Bell states. From parity oscillation contrast and population measurements in the $|00\rangle$ and $|11\rangle$ subspace, we extract a Bell-state fidelity of 0.9834 (0.9355) with (without) excising atom loss events using the procedure described below; see Fig. 3(b). To obtain

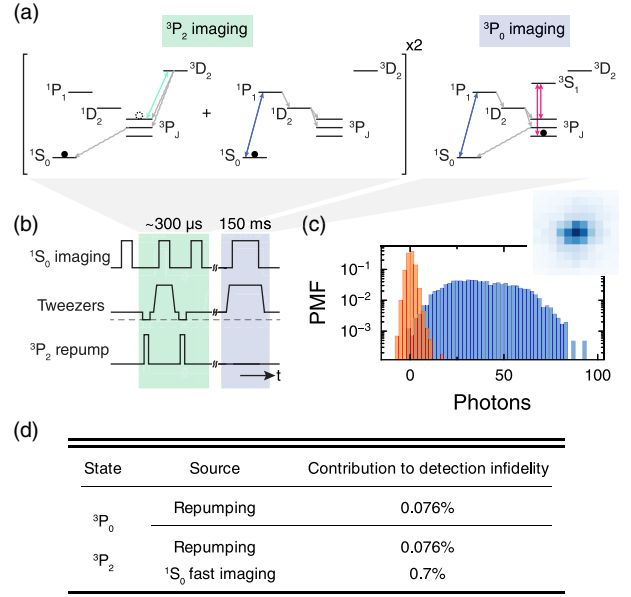


FIG. 4. State-resolved detection. (a) Internal-state dynamics relevant to the detection of $^3\text{P}_2$ (green) and $^3\text{P}_0$ (blue). Prior to detecting $^3\text{P}_2$, population in this state is incoherently transferred to $^1\text{S}_0$ via repumping on the $^3\text{P}_2$ - $^3\text{D}_2$ transition. Then, we perform fast, destructive imaging in deep tweezers to collect sufficient photons for high-fidelity $^3\text{P}_2$ -state reconstruction. Such a state-transfer plus imaging cycle is repeated to ensure complete removal of $^3\text{P}_2$ population, despite small leakage from $^1\text{P}_1$ via $^1\text{D}_2$ into $^3\text{P}_2$. Once $^3\text{P}_2$ is destructively imaged, the remaining population is assigned to $^3\text{P}_0$ using a subsequent slow image with repumping on the 679 and 707 nm transitions. (b) Timing diagram (not to scale) for the $^1\text{S}_0$ imaging beam, $^3\text{P}_2$ repumper, and tweezer trap depth during the state-selective detection. Traps are blinked off (dashed) during the $^3\text{P}_2$ repumping pulse to avoid photo-induced losses. (c) Probability mass function (PMF) of photons emitted by $^1\text{S}_0$ atoms transferred from $^3\text{P}_2$ recorded during fast imaging. The resulting histogram, binarized using a high-fidelity preimage, shows a classification fidelity > 0.993 averaged over all tweezers at the optimal threshold. The orange and blue correspond to zero- and one-atom peak, respectively. Inset: deconvolution mask derived from the averaged fluorescence profile. (d) Dominant infidelity contributions to state-resolved imaging.

a CZ-gate fidelity F_{2q} , we implement the recently proposed symmetric stabilizer benchmarking (SSB) sequence [12,14], which is only weakly sensitive to single-qubit gate errors. By fitting the decaying $|11\rangle$ return probability as a function of number of CZ gates as in $P_{11} = aF_{2q}^{N_{\text{CZ}}}$, we measure $F_{2q} = 0.9945(6)$ [0.9759(5)] with (without) correction for atom loss events; see Figs. 3(c) and 3(d).

To decouple the entangling gate fidelity from qubit loss (i.e., due to ionization of $^3\text{P}_2$ by the 316 nm Rydberg excitation laser [47]), we present a new, partially destructive, state-resolved detection (SRD) scheme for the fine-structure qubit. Contrary to the previous work focusing on imaging one of the two states in a qubit [60–63], the SRD

yields population in both qubit states and can thus identify atom loss events. In alkali species, direct imaging of both qubit states has been achieved by spatially separating spin states in strong magnetic field gradients [64,65] or state-dependent traps [66]. In alkaline-earth(-like) atoms, SRD has recently been demonstrated for ground-state hyperfine qubits using narrow-line imaging transitions [67] and by shelving population into metastable clock states [40]. By contrast, our protocol exploits the large energy splitting between qubit states together with the species-specific advantage of low-leakage, state-selective repumping, while remaining compatible with erasure conversion and post-selection on lossless experimental events. To convert the state-sensitive detection scheme including the 3P_2 -repumper into the SRD, we collect the photons emitted during the push of 1S_0 using fast imaging techniques following the 3P_2 - 3D_2 repumping step; see Figs. 4(a) and 4(b). Compared to the fast imaging used for erasure conversion, the photon count here is increased by operating at a significantly higher tweezer trap depth. We achieve > 0.9931 detection fidelity of 1S_0 atoms in ~ 50 μ s, which significantly exceeds the fidelity achieved in shallow traps for state-preparation erasure conversion; see Fig. 4(c). Meanwhile, fast imaging removes $> 99.92\%$ of the population from $|0\rangle$, and ensures high-fidelity assignment of the remaining atoms to $|1\rangle$ in a subsequent conventional imaging step. As a result, we find a $|0\rangle$ ($|1\rangle$) detection fidelity > 0.993 (0.998); see Fig. 4(d). Note that our scheme is minimally sensitive to bit-flip errors originating from trap-induced Raman processes. This is a consequence of the short timescale and relatively shallow traps during which the SRD operates, in contrast to alternative cooling-dependent schemes [67].

In summary, we have demonstrated high-fidelity quantum control of the 17 THz fine-structure qubit in strontium-88. In addition to the demonstrated erasure conversion, this qubit has several distinct advantages over existing approaches. First, by employing larger intermediate-state detunings and higher optical powers, single-qubit gate times could be driven well below those demonstrated in our proof-of-principle experiment—potentially into the sub- μ s regime in future implementations. Compared to the hyperfine or nuclear qubits, in particular the metastable nuclear qubit in ytterbium-171, the fine-structure qubit permits larger intermediate-state detunings and thus in principle proportionally smaller error per gate. Second, we expect that the fine-structure qubit is compatible with coherent transport [22], paving the way for universal quantum computation and error correction [23] enhanced by erasure conversion [68]. Local qubit addressing can be conveniently realized via a coherent movement of qubits through the laser phase grating [12], using the same optical tweezers employed for atom rearrangement. Such a scheme would greatly reduce the experimental complexity and errors associated with additional addressing beams and is expected to scale more favorably to larger qubit numbers

compared with similar implementations based on clock qubits. Third, we expect that our state-resolved detection will facilitate monitoring inevitable atom loss in quantum computation—for example, during error-correction cycles [69–71]. To this end, the residual infidelity in our state-resolved detection scheme could be mitigated by adding repumping lasers on the 1D_2 or by deploying a more efficient imaging system. Finally, we anticipate that combining our state-resolved detection scheme with fast, MHz-scale fine-structure qubit manipulation will unlock a broader range of applications. For example, this combination enables readout of population in short-lived transitions to 3P_2 , such as the decay of 3D_3 to 3P_2 on the long-wavelength 2.9 μ m transition relevant for free-space quantum optics experiments [72]. Another application is the detection of both qubit states of short-lived qubits in Rydberg-based quantum simulators, enabling high-fidelity quantum simulation that is robust to atom loss [32,73–75].

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Data availability—The data supporting this study are available in [76].

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End Matter

Appendix A: Data excision in postprocessing—In single-qubit and two-qubit benchmarking, instances in which an erasure error is detected are discarded. In two-qubit result, postselection based on the state-resolved imaging leads to additional data excision. Generally, the classification threshold in fast imaging for erasure conversion and loss detection is chosen to maximize the classification fidelity. The optimal threshold is around seven photons in the deconvolved images, which is subject to slow drift in the imaging condition. The excision fraction for both single- and two-qubit gate benchmarking results are shown in Figs. 5(a) and 5(b). In the loss-excised dataset in Fig. 3(d), additional classification of data can be made, thanks to the density information before the state preparation and full state resolution after the benchmarking sequence.

Appendix B: Error budget—We estimate the contributions to the infidelity of our gate using the effective super-operator associated with each error source. The super-operator is obtained, for each error source, by solving the associated master equation, taking into account the coherent error sources in the Hamiltonian and the collapse operators for spontaneous decay, pure dephasing on the Rydberg transition, and 3P_2 ionization. The infidelity is calculated in two ways, through the process fidelity between the simulated super-operator with the ideal one, and using a simulated SSB sequence with the obtained superoperator. We observe no notable difference in results between the two methods. For gate infidelity originating from laser phase noise, we compared our result to the one derived from the recently proposed linear response calculation [14] and find good agreement. Numerically, aside from the

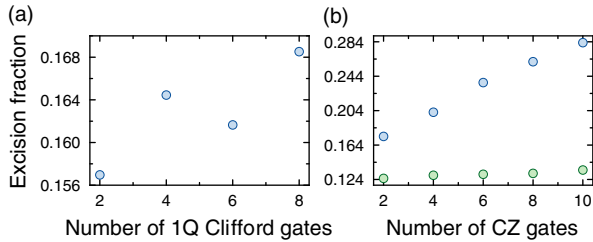


FIG. 5. Data excision fraction in randomized benchmarking result. (a) The data excision fraction in the erasure-excised measurement shown in Fig. 2(d). The data discarded are believed to contain state preparation and off-resonant scattering error (see main text). (b) The data excision fraction in the erasure-excised (green) and loss-excised (blue) measurement shown in Fig. 3(d). The color coding is consistent between identical measurements. The blue (green) markers are analyzed on data processed exercising atom loss (erasure errors). See main text for details.

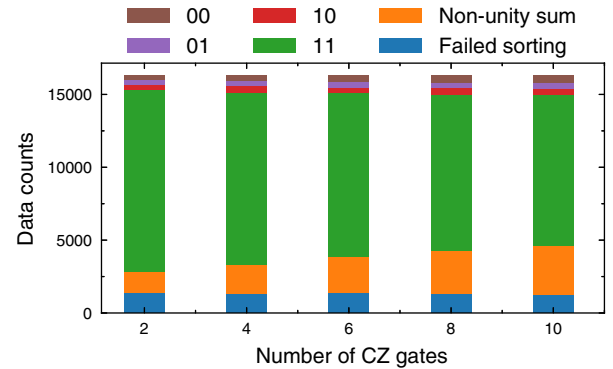


FIG. 6. A breakdown of loss-excised dataset reported in Fig. 3(d) into various labeled groups. Data marked as “failed sorting” contains defects in atom pairs before the state preparation. After the benchmarking sequence, the state-resolved imaging reveal data containing atom loss (labeled as “non-unity sum”). Among the remaining data, logical states can be classified further.

qubit and Rydberg states, we define an additional “bucket” state for each atom to which it is assumed to be transferred in the case of either Rydberg decay to outside the qubit manifold or 3P_2 ionization loss; see Fig. 7(a).

To estimate infidelities taking the loss-correcting SRD into account, we use the simulated SSB sequence once more, but only consider the valid computational states. Population decayed from Rydberg states into $m_J \neq 0$ states of 3P_2 which are not qubit states but nevertheless manifest as if they are, are also taken into account. We identify Rydberg state decay, 3P_2 ionization (see above), and gate parameter estimation errors as the most prominent, known, error sources in our two-qubit gate. The effect of other known noise sources are presented in Fig. 7(b). The modeled noise sources give rise to a total raw infidelity of 1.84% and loss-corrected infidelity of 0.16%. We attribute the higher infidelities measured in the experiment to experimental drifts such as in Rabi frequency and UV pulse area, phase, and shape. Note that the ionization loss will be eliminated with a UV laser system coupling 3P_2 to the Rydberg state, and the infidelity from Rydberg decay can be further reduced by increasing the laser power.

To improve the entangling gate fidelity, experimental changes such as employing Rydberg transition on the $|^3P_{2,m_J=0}\rangle \rightarrow |r\rangle$ for entanglement generation would be

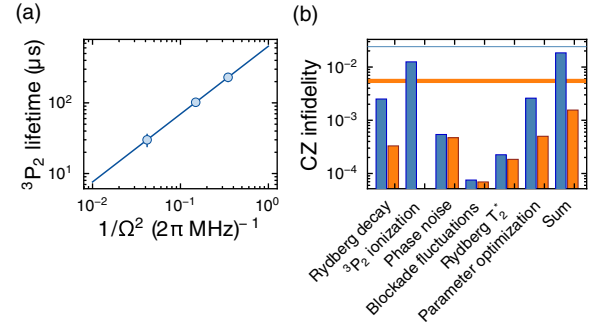


FIG. 7. 3P_2 loss in the presence of 316 nm light and CZ gate error budgeting. (a) 3P_2 lifetime τ scales with UV rabi frequency Ω as $\tau = A/\Omega^2$ with a proportionality constant $A = 610/\mu\text{s}$. (b) Leading contributions to the infidelity of the CZ gate with (orange) and without (blue) loss correction at a Rabi frequency of $2\pi \times 6$ MHz. The experimental infidelities are indicated by the corresponding horizontal lines. T_2^* refers to measurement on the $|1\rangle\text{--}|r\rangle$ transition.

necessary as it avoids entirely the ionization loss which stands at the moment at about 1% [47]. In addition, higher optical power on the UV can mitigate the errors due to phase noise, finite Rydberg lifetime, and coherence time. At $2\pi \times 10$ MHz, the collective infidelity drops to 0.18% based on numerical simulations.