

Extended Rydberg Lifetimes in a Cryogenic Atom Array

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We report on the realization of a ^{133}Cs optical tweezer array in a cryogenic blackbody radiation (BBR) environment. By enclosing the array within a 4 K radiation shield, we measure long Rydberg lifetimes, up to 406(36) μs for the $55P_{3/2}$ Rydberg state, a factor of 3.3(3) longer than the room-temperature value. We employ single-photon coupling for coherent manipulation of the ground-Rydberg qubit. We measure a small differential dynamic polarizability of the transition, beneficial for reducing dephasing due to light intensity fluctuations. Our results pave the path for advancing neutral-atom two-qubit gate fidelities as their error budgets become increasingly dominated by T_1 relaxation of the ground-Rydberg qubit.

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Neutral atoms in optical tweezer arrays are a competitive platform for the realization of large-scale fault-tolerant quantum computers. Recent progress has included the demonstration of dynamical reconfigurability [1], large-scale arrays containing thousands of qubits with long coherence times [2], continuous operation with atom reloading [3,4], and logical and mid-circuit operations [5–9]. In particular, two-qubit gate fidelities, the bottleneck for quantum error correction, have been improved beyond the surface code threshold for fault-tolerant quantum computation [10–15], reaching up to 99.85% [16]. Further increases in the gate fidelity can significantly reduce the overhead for quantum error correction [17].

While qubits are usually encoded in a pair of long-lived hyperfine ground states, two-qubit gates rely on coupling a ground state to a Rydberg state. Focusing on the ground-Rydberg subspace, errors are primarily due to population relaxation (characterized by lifetime T_1) and coherence decay (characterized by coherence time T_2^*) and off-resonant couplings to Rydberg Zeeman sublevels outside the subspace [10]. As gate fidelities have improved, T_1

relaxation is rapidly becoming the dominant error source. It is determined by spontaneous emission from the Rydberg state, BBR-induced transitions to nearby Rydberg states and intermediate state scattering in commonly used two-photon excitation schemes [10,12]. In state-of-the-art optical tweezer array experiments, the relaxation time T_1 is typically below 65 μs [10,11,14,15]. A promising route to extend T_1 is the suppression of BBR-induced transitions using a cryogenic environment [18–21].

Previous experiments have prepared atom arrays inside low-temperature cryostats, demonstrating improved trapping lifetimes of the atoms as well as excitation to Rydberg states [22–24]. Long vacuum lifetimes are advantageous for assembling large defect-free arrays and increasing imaging fidelity for mid-circuit detection. However, a demonstration of the other advantage of cryogenic tweezer array experiments, the extended Rydberg lifetimes due to suppressed BBR-induced transitions, has remained outstanding.

In this work, we demonstrate the extension of Rydberg state lifetimes for cesium atom arrays prepared in a cryogenic blackbody radiation environment. For the state $55P_{3/2}$, we measure a lifetime of 406(36) μs , corresponding to an effective BBR temperature of less than 25 K at the 1σ uncertainty level. In this temperature range, BBR-induced transitions are suppressed by more than one order of magnitude compared to room temperature. We also demonstrate coherent manipulation of the ground-Rydberg qubit using single-photon coupling, which avoids intermediate state scattering present in two-photon coupling schemes. Together, these features of our experiment push T_1 toward the fundamental limit set by spontaneous emission of the Rydberg state.

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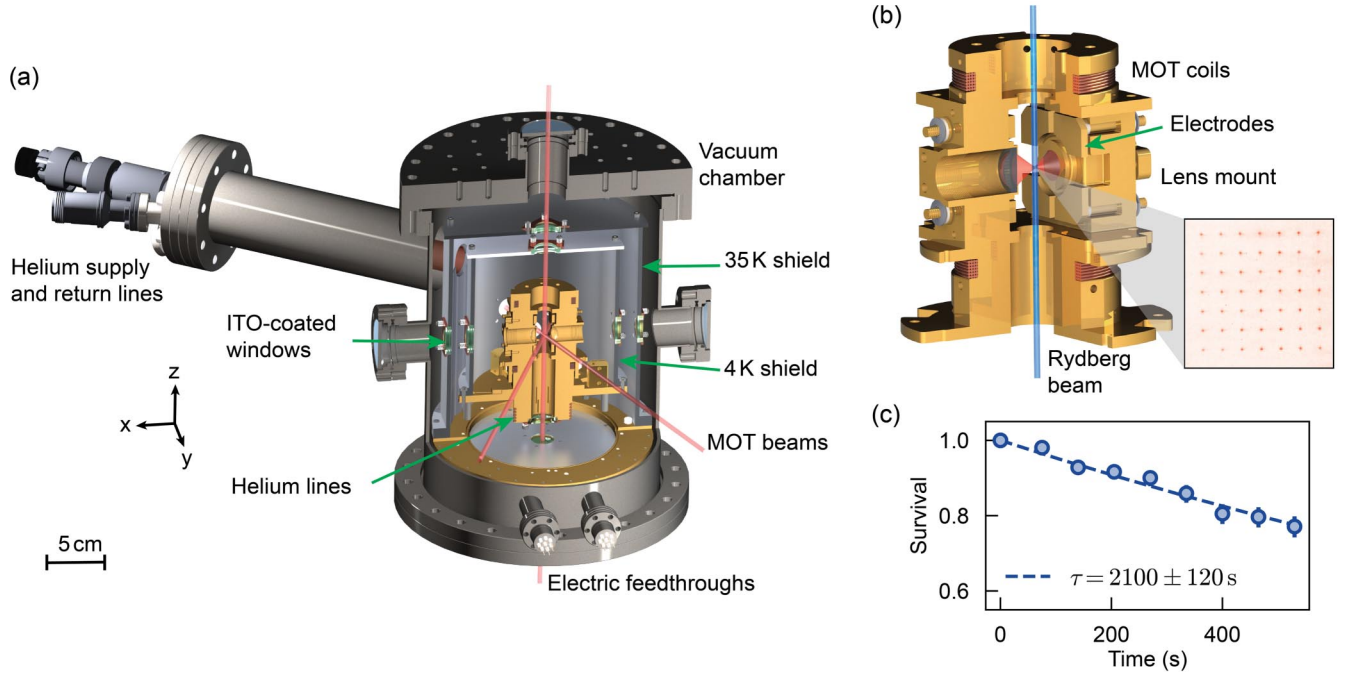


FIG. 1. (a) UHV cryostat with 4 and 35 K radiation shields inside a room-temperature vacuum chamber. The atomic beam (not shown) is directed along the y -axis. (b) Assembly inside the 4 K radiation shield, integrating aspheric lenses, electrodes and MOT coils. Inset: averaged fluorescence image of a 7×7 atom array, with a tweezer spacing of $12 \mu\text{m}$. (c) Vacuum trapping lifetime measurement.

Our apparatus consists of two vacuum chambers connected by a differential pumping tube: a room-temperature atom-source chamber and a cryogenic science chamber [see Fig. 1(a)]. A beam of cesium-133 atoms is produced from a 2D magneto-optical trap (MOT) in the room-temperature chamber and delivered to the ultra-high vacuum (UHV) cryostat using a push beam. There, the atoms are trapped in a 3D MOT and stochastically loaded into an optical tweezer array. The core assembly features a pair of aspheric lenses (0.5 numerical aperture and 10 mm focal length, mounted following the design in Ref. [22]) for projecting optical tweezers and imaging the atom array, superconducting coils for producing the magnetic field for the MOT, and electrodes for controlling the electric field environment [see Fig. 1(b)]. This assembly is mounted on a 4 K baseplate. Helium gas flows through copper tubing brazed on the baseplate, providing a cooling power of 0.4 W at the base temperature. We use a closed-cycle system (ColdEdge Technologies), where the helium gas circulates between a Gifford-McMahon cryocooler and the cryostat, with the flexible helium line damping mechanical vibrations at the baseplate.

To ensure a low-BBR environment, two radiation shields surround the assembly, at 35 and 4 K, respectively. Both shields have windows for laser beams and a small opening for the atomic beam. Blackbody radiation from the room-temperature walls of the cryostat chamber can leak through cold windows on the shields, increasing the effective BBR temperature at the location of the atoms. To

address this issue, we coat the windows on the 4 K shield with a 120-nm-thick layer of indium tin oxide (ITO) with sheet resistance $R_{\square} \sim 20 \Omega/\text{sq}$, which transmits optical beams (transmission coefficient $T \approx 95\%$) while suppressing microwaves in the 10–300 GHz frequency range, relevant for transitions between Rydberg states ($T \lesssim 3\%$) [25]. For the UV-beam path for Rydberg excitation, we leave the central region of the windows uncoated since the ITO coating has a strong absorption of UV light. For the tweezer-beam path which has a higher laser power, we use a 30-nm-thick ITO coating ($R_{\square} \sim 100 \Omega/\text{sq}$) and put the coating on the 35 K windows since the cooling power at that temperature is higher, and can handle the 1% laser power absorbed per window from the ITO coating.

Electric field control is crucial for manipulating Rydberg atoms, especially for nP Rydberg states used in this experiment, which have a larger dc polarizability than nS Rydberg states accessible with two-photon excitation. For example, the polarizability of the $|55P_{3/2}, m_J = \pm 1/2\rangle$ state is $2740 \text{ MHz cm}^2/\text{V}^2$, a factor of 26 larger than the $|55S_{1/2}, m_J = \pm 1/2\rangle$ state [26]. We use eight electrodes connected to vacuum feedthroughs using twisted-pair cables. These cables allow the transmission of dc voltages for compensating stray electric fields, as well as RF signals with frequencies up to a few hundred MHz, while strongly attenuating GHz thermal noise from the 300 K environment that can drive BBR-induced transitions. The wires are heat sunk at both 4 and 35 K stages. Although RF signals are not used in the current

experiment, this design adds flexibility for future experiments with circular Rydberg atoms, where RF drives with well-defined polarization are needed for transfer to circular states. Compared to the nP Rydberg states used in this work, atoms in circular states can exhibit even more dramatic lifetime enhancements at cryogenic temperatures [21,27,28].

We start our experiments by loading atoms from the 3D MOT into a tweezer array [see Fig. 1(b) inset]. Then, we apply two stages of polarization gradient cooling (PGC), between which we adiabatically ramp down the tweezer trap depth and image the initial tweezer occupancies (see Appendix A).

We first characterize the improvement in vacuum-limited atom lifetimes. An ion gauge located at the room-temperature region of the cryostat reads 2×10^{-10} Torr after cooldown. However, the 4 and 35 K surfaces provide a strong cryopumping effect, further reducing the pressure inside the radiation shields. During the lifetime measurement, we hold the atoms at a depth of 210 μ K and apply pulsed PGC with a detuning of -23 Γ for 10 ms every 2 s [2,22], where $\Gamma = 2\pi \times 5.22$ MHz is the natural linewidth of the $|6S_{1/2}, F=4\rangle \rightarrow |6P_{3/2}, F'=5\rangle$ transition. Atoms are imaged every 65 s. A $1/e$ lifetime of 2100s is extracted in Fig. 1(c) after accounting for the 5×10^{-3} loss per imaging step, obtained from a separate measurement. We note that this lifetime is obtained with an unbaked vacuum chamber, only utilizing a 150 L/s ion pump in combination with cryopumping. Further improvements may be achievable by baking the system and firing an integrated titanium sublimation pump.

Next, we demonstrate coherent manipulation of the ground-Rydberg qubit. We employ single-photon excitation to nP Rydberg states [29,30], avoiding the reduction of T_1 associated with intermediate state scattering in two-photon excitation schemes [16]. The excitation light at 319 nm is generated via sum-frequency generation of a 1560.5 nm fiber laser and a 1080 nm external-cavity diode laser (ECDL), followed by second-harmonic generation, producing up to 300 mW out of a solarization-resistant UV fiber [31]. The UV frequency can be tuned over a wide range of Rydberg states by adjusting the ECDL frequency.

The relevant energy levels and beam configuration for Rydberg excitation are shown in Figs. 2(a) and 2(b). After the two stages of PGC, we optically pump the atoms into the stretched state $|g\rangle = |6S_{1/2}, F=4, m_F=4\rangle$ at a reduced trap depth of 50 μ K, with a 3 G bias magnetic field defining the quantization axis along the y direction. We then lower the trap depth adiabatically to further cool the atoms. Subsequently, we turn off the optical tweezer light, use the Rydberg beam to drive the transition between $|g\rangle$ and $|r\rangle = |nP_{3/2}, m_J=1/2\rangle$, and then turn the tweezer light back on for detection. The Rydberg beam propagates along the vertical z direction perpendicular to the

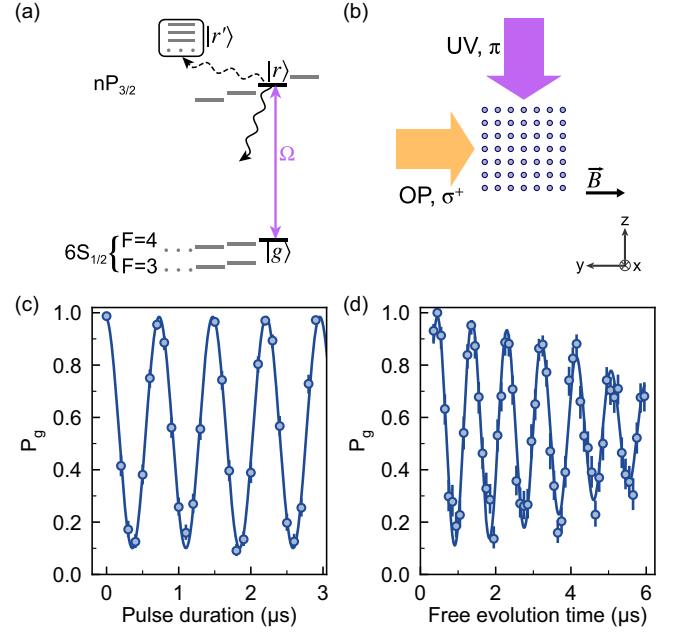


FIG. 2. Coherent control of the ground-Rydberg qubit. (a) Relevant energy levels and decay pathways. Atoms are initialized into $|g\rangle = |6S_{1/2}, F=4, m_F=4\rangle$ via optical pumping and excited to the Rydberg state $|r\rangle = |nP_{3/2}, m_J=1/2\rangle$ using single-photon excitation at 319 nm. The Rydberg state can undergo BBR-induced transitions to other Rydberg states $|r'\rangle$ or spontaneous decay to low-lying states, indicated by curly arrows. (b) Configuration of the UV excitation and optical pumping (OP) beams relative to the atom array. The UV and OP beams have π and σ^+ polarizations, respectively. The quantization axis is defined by the magnetic field B along the y axis. (c) Rabi oscillation between $|g\rangle$ and $|r\rangle$ for the $55P_{3/2}$ Rydberg state, averaged over atoms in the central column along the z direction. P_g denotes the ground-state fraction. (d) Ramsey measurement for a single atom at the center of the array, yielding a fitted coherence time $T_2^* = 6.2(4)$ μ s, the $1/e$ time constant of the Gaussian decay of the oscillation amplitude.

quantization axis and is focused to a waist ($1/e^2$ radius) of 80 μ m at the position of atoms. We initially observed a strong spatial gradient of the transition frequencies from background electric fields. By applying compensating fields with the electrodes, we suppressed the frequency variation across the array to less than 100 kHz for $n=55$, corresponding to a field variation of 9 mV/cm.

Figure 2(c) shows Rabi oscillations between $|g\rangle$ and $|r\rangle = |55P_{3/2}, m_J=1/2\rangle$ at a Rabi frequency $\Omega = 2\pi \times 1.35$ MHz. We detect ground-state atoms, while Rydberg atoms are ejected by the ponderomotive potential of the tweezer, with the contrast of the oscillation determined by imperfect ejection due to spontaneous Rydberg decay during the process. We also use a Ramsey sequence to characterize the coherence of the ground-Rydberg qubit [Fig. 2(d)]. The Gaussian decay of the envelope of the oscillations gives a Doppler-limited coherence time $T_2^* = 6.2(4)$ μ s, corresponding to a temperature of 2.2(3) μ K.

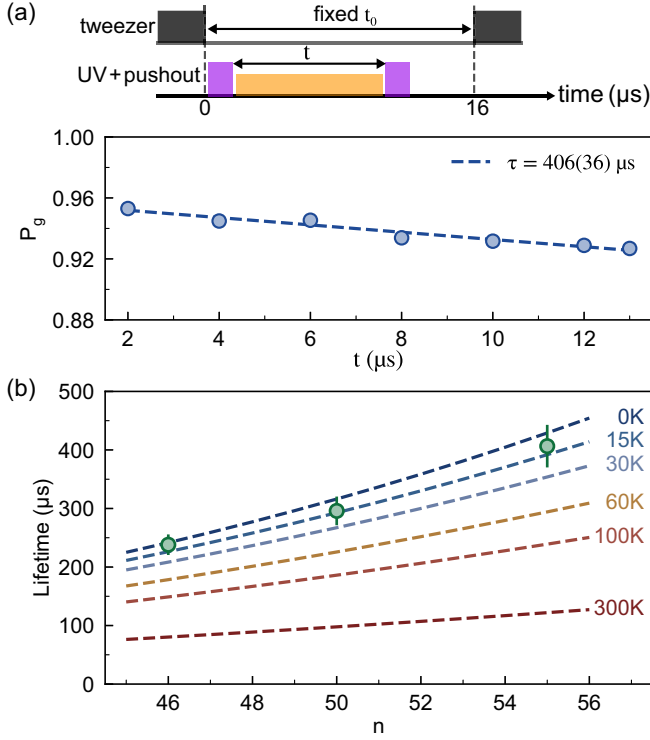


FIG. 3. Extended T_1 lifetimes. (a) Experimental sequence and lifetime measurement of the $55P_{3/2}$ Rydberg state. $P_g(t)$, with t being the gap time between two UV π pulses, is fitted to an exponential decay with no offset. The fitted $1/e$ lifetime is $406(36) \mu\text{s}$. (b) Lifetimes of different $nP_{3/2}$ Rydberg states at different BBR temperatures. Green circles with error bars (1σ) denote experimental values measured for $n = 46, 50, 55$. Dashed lines serve as guides to the eye connecting results calculated using ARC [26].

Having established control over the ground-Rydberg qubit, we proceed to measure the extension of the Rydberg state lifetime at cryogenic temperatures using the protocol illustrated in Fig. 3(a). The tweezer light is extinguished for a fixed duration of $t_0 = 16 \mu\text{s}$, chosen such that in the absence of any light pulses, the atoms are recaptured in the tweezers with almost unit probability. During the tweezer off time, a π pulse is applied to transfer the population from $|g\rangle$ to $|r\rangle$ and after a variable delay t , a second π pulse is applied to transfer the population back to $|g\rangle$. The transfer efficiency of each Rydberg π pulse is 98%–99%, limited by residual intensity fluctuations of the Rydberg light and its inhomogeneity across the array. In between the two π pulses, we apply a strong pushout beam to continuously blow away any population in the $6S_{1/2}$ manifold from decay of the Rydberg state. The pushout beam is resonant with the $|6S_{1/2}, F=4\rangle \rightarrow |6P_{3/2}, F'=5\rangle$ transition, and a repump beam resonant with $|6S_{1/2}, F=3\rangle \rightarrow |6P_{3/2}, F'=4\rangle$ is applied simultaneously (see Appendix B). A lifetime measurement curve for $|55P_{3/2}, m_J = 1/2\rangle$ is shown in Fig. 3(a). Each data point is averaged over about 2400 repeated measurements.

The measured lifetime, obtained from an exponential decay fit, is $406(36) \mu\text{s}$. This is a factor of 3.3(3) longer than the room-temperature lifetime of $122 \mu\text{s}$ and approaches the spontaneous-decay-limited lifetime of $429 \mu\text{s}$, both calculated using ARC [26]. Comparison with ARC calculations indicates that this lifetime corresponds to an effective BBR temperature of 10_{-10}^{+13} K , indicating a strong suppression of BBR-induced transitions. At 10 K, we calculate that the BBR-induced decay rate of the $55P_{3/2}$ state is suppressed by a factor of 40 compared to room temperature.

Our measured lifetimes for $n = 55, 50, 46$, shown in Fig. 3(b), are all about three times longer than the room-temperature values and consistent with an effective BBR temperature of $\lesssim 25 \text{ K}$. Further reduction of the BBR temperature would only lead to marginal lifetime improvement, as it is primarily limited by spontaneous decay. Even longer lifetimes are expected for higher n states, given the n^3 scaling of the radiative lifetime. However, we restrict our attention to states in this range of n because of their utility for implementing two-qubit gates in future work. The n^7 scaling of the dc polarizability of Rydberg states rapidly degrades T_2^* at higher n due to coupling to stray electric fields.

The extended Rydberg lifetime is expected to directly translate into improved two-qubit gate fidelity. In state-of-the-art experiments, the T_1 contribution to two-qubit gate infidelity is at the $(1\text{--}3) \times 10^{-3}$ level [10,11,15] and is becoming the dominant error source. Because this infidelity scales as $1/(\Omega T_1)$, extending the lifetime reduces the gate error for any given drive strength. Even with the modest Rabi frequency $\Omega = 2\pi \times 1.35 \text{ MHz}$ used here, we project the T_1 contribution to infidelity to be 6.4×10^{-4} for a time-optimal gate [32,33], already below the typical floor of room-temperature experiments. By reducing the beam waist to $20 \mu\text{m}$ to increase the Rabi frequency, a typical size balancing drive strength against intensity noise [10,11,15], this contribution would be further suppressed to 1.6×10^{-4} . In the context of quantum error correction [34–36], such a reduction in physical error rates of two-qubit gates leads to strong suppression of the logical error rates. For instance, considering physical two-qubit gates limited by T_1 and a moderate size surface code with distance $d = 7$ [5], our improvement of the Rydberg lifetime by a factor of 3.3 relative to room temperature would lead to an approximately two-orders-of-magnitude reduction in the logical error rate [37].

Achieving high Rabi frequencies to suppress the contribution of T_1 to gate errors requires management of light shifts associated with Rydberg excitation light. In two-photon excitation schemes used in alkali atom quantum processors, off-resonant coupling to the intermediate states induces strong differential light shifts between the ground and Rydberg states [10]. Therefore, temporal noise and spatial inhomogeneities in the Rydberg beam intensity are

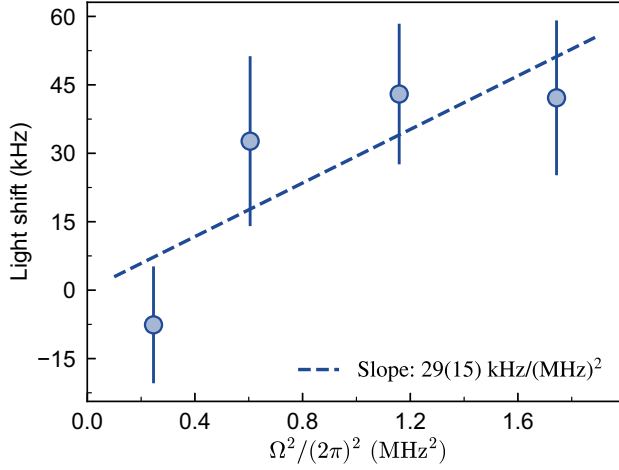


FIG. 4. Light shift of the $55P_{3/2}$ Rydberg transition as a function of $(\Omega/2\pi)^2$. A linear fit (dashed line) to the data gives a light-shift coefficient $\kappa = 29(15)$ kHz/MHz².

converted into effective frequency noise, introducing a dephasing channel that grows with Rabi frequency and limits gate fidelity. We verify that our use of single-photon excitation significantly mitigates this issue. Performing spectroscopy of the Rydberg transition frequency at different Rabi coupling strengths, we measure a light-shift coefficient of $\kappa = 29(15)$ kHz/MHz² (Fig. 4). Similar to observations with alkaline earth qubits [8,38], the light shift is negligibly small at our current Rabi frequency and should remain well below the Rabi frequency even when reducing the beam waist as described above.

Beyond the absolute extension of T_1 , the specific suppression of BBR-induced transitions is beneficial for reducing correlated errors in quantum circuits. Compared to spontaneous emission, BBR-induced transitions can be more detrimental due to collective effects. Consider, for example, a transversal entangling gate between logical qubits, as demonstrated in [5]. A BBR transition transfers an atom to a different Rydberg state that couples to the rest of the excited atoms via long-range dipole-dipole interactions, inducing correlated dephasing and loss [9,39–42]. In fact, even at our cryogenic temperatures, we have observed collective effects in our lifetime measurements. To extract single-atom Rydberg lifetimes, we use a 3×3 tweezer array with 24 μm spacing to perform the measurements. In contrast, for a 7×7 tweezer array with 12 μm spacing, we observe accelerated and non-exponential decay of the probability to be in the ground state at the end of the lifetime measurement protocol (see Appendix C).

In summary, we have realized a cryogenic neutral-atom-array platform engineered to suppress blackbody radiation. Using this platform, we demonstrated a substantial lifetime extension of low-angular-momentum Rydberg states, with BBR-induced transition rates reduced by more than an order of magnitude. The extension of Rydberg lifetimes

directly addresses the dominant error mechanism in two-qubit gates in neutral-atom quantum computers and provides a pathway for higher-fidelity Rydberg gates. Furthermore, our platform opens new possibilities for other Rydberg-based quantum applications. For instance, the low-BBR environment can reduce collective avalanche loss that currently limits Rydberg-dressing schemes for quantum simulation and metrology [29,43,44]. It also enables extended lifetimes for circular Rydberg states [21,45–47], a promising resource for quantum simulation and computation applications [27,28], although their state preparation, manipulation, and detection are not yet as mature as those of low-angular-momentum Rydberg states.

Looking forward, it would be interesting to demonstrate extended Rydberg lifetimes in much larger arrays with thousands of tweezers. The aspheric lenses used in the current iteration of our apparatus limit the field of view, restricting array sizes to ~ 400 tweezers at a spacing of 4 μm . In this regard, cryogenic setups using large field of view objectives are very promising [23,24].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication but are available from the authors upon reasonable request.

APPENDIX A: EXPERIMENTAL SEQUENCE

The 3D MOT beams consist of two pairs of counter propagating horizontal cooling beams with 1.6 mm waist ($1/e^2$ radius), and a retroreflected vertical cooling beam with 3 mm waist. For each cooling beam, there is a co-propagating repump beam. The cooling beams have a detuning of $\Delta = -3 \Gamma$ relative to the bare $|6S_{1/2}, F = 4\rangle \rightarrow |6P_{3/2}, F' = 5\rangle$ atomic transition frequency, where $\Gamma = 2\pi \times 5.22$ MHz is the natural linewidth of this transition. The repump beam is at the resonance of the bare $|6S_{1/2}, F = 3\rangle \rightarrow |6P_{3/2}, F' = 4\rangle$ transition. The magnetic field of the MOT is generated by a pair of superconducting coils inside the 4 K radiation shield. We apply a current of

1.2 A through both coils, producing a magnetic field gradient of 8.4 G/cm.

Atoms are first loaded from a 3D MOT into optical tweezers with 1.15 μm waist, 700 μK trap depth and 57 kHz radial trap frequency. Using a loading time of 600 ms, we achieve a typical array filling fraction of ~ 0.5 . The tweezer light is at 936 nm, a magic wavelength for the cesium D2 line. Following loading, we apply the first stage of polarization gradient cooling (PGC) by increasing the detuning of the cooling beams to $\Delta = -17 \Gamma$ and reducing the cooling beam power. The tweezer trap depth is then ramped down to 210 μK , where atoms are imaged with a 60 ms exposure time at $\Delta = -15 \Gamma$. Subsequently, we apply the second stage of PGC with $\Delta = -23 \Gamma$. After lowering the trap depth to 50 μK , we optically pump atoms for 3 ms using a σ^+ -polarized beam resonant with the $|6S_{1/2}, F=4\rangle \rightarrow |6P_{3/2}, F'=4\rangle$ transition, alongside a co-propagating σ^+ -polarized repump beam. A 3 G bias field along the y-axis defines the quantization axis. Finally, the trap depth is adiabatically lowered to 16 μK . The resulting state-preparation infidelity is $< 0.5\%$.

After adiabatic cooling, we turn off the tweezer trap to apply the Rydberg pulses for Rydberg excitation and T_1 lifetime measurements.

APPENDIX B: LIFETIME MEASUREMENTS

We first measure the atom loss after different release times, without applying Rydberg pulses. The loss remains negligible for release times up to 24 μs as shown in Fig. 5(a). The observed loss of about 0.5% is consistent with the imaging loss. We use a fixed release time of 16 μs in the lifetime measurements to provide a conservative safety margin, ensuring recapture in the presence of effects on the atomic motion induced by UV photons.

We measure the lifetime by first exciting all atoms to the Rydberg state using a π pulse. Then the Rydberg state

undergoes spontaneous decay to the ground state or BBR-induced transitions to other Rydberg states. To determine the population remaining in the original Rydberg state after a certain amount of time, we apply a second π pulse to transfer the population back to the ground state for detection. Between the two π pulses, a strong pushout beam is continuously applied to blow out any atoms that decay to ground states. We characterize the efficiency of the pushout beam by removing the Rydberg pulses and optical pumping process to verify that all ground state hyperfine levels can be efficiently pushed out. A pushout curve measuring the recaptured population versus the pushout time is shown in Fig. 5(b). In the Rydberg lifetime measurements (Fig. 3 of the main text), the data are taken with gap times $t \geq 2 \mu\text{s}$ between two Rydberg π pulses, and with the pushout pulse duration set to about $t - 1 \mu\text{s}$.

We comment on the fact that an atom in the Rydberg state can be falsely detected as a ground state with nearly 10% probability as seen from the lowest value in the Rabi oscillations in the main text. This false detection has negligible contribution to our measurement since atoms in the target Rydberg state are transferred to the ground state for detection at the end of the protocol.

APPENDIX C: COLLECTIVE EFFECTS

For the lifetime measurements, we operate with a reduced density array, using a 3×3 tweezer array with 24 μm spacing. When using a 7×7 array with 12 μm spacing, the ground-state fraction decreases significantly faster and cannot be described by an exponential fit (Fig. 6). We attribute this to collective effects induced by the transition of one Rydberg atom into a different Rydberg state. The resulting dipolar interaction perturbs the energies of nearby Rydberg atoms, reducing the fidelity of the second π pulse and thereby lowering the transfer efficiency back to the ground state. For instance,

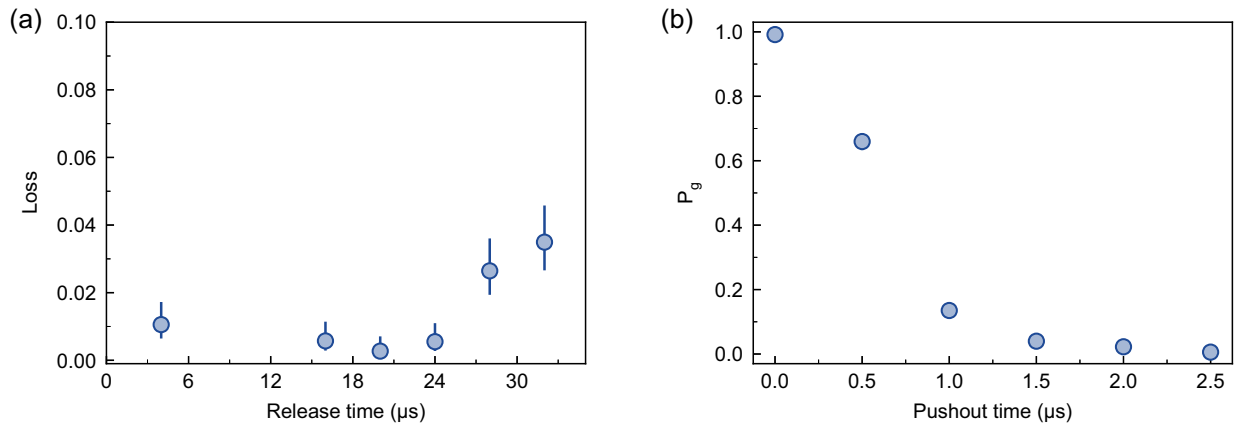


FIG. 5. (a) Atom loss after different release times. When the release time is less than 24 μs , there is essentially no loss during the release-recapture sequence. The approximately 0.5% loss observed is consistent with imaging loss. (b) Pushout of atoms in the ground states. The atoms are not optically pumped into the stretched state before the pushout. The experimental protocol used is the same as that shown in Fig. 3(a) of the main text, except that the Rydberg beam remains off.

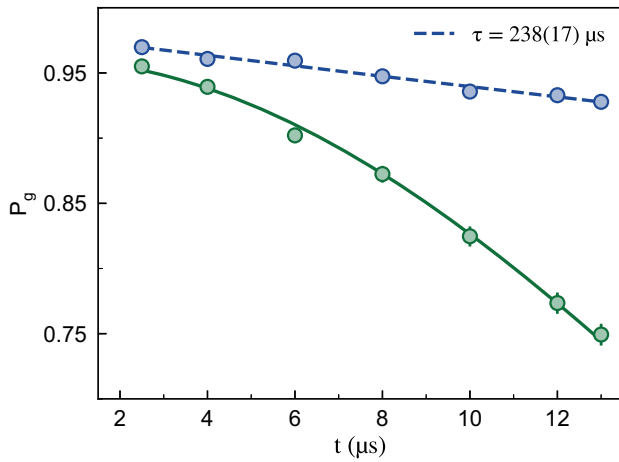


FIG. 6. Ground-state fraction P_g versus the gap time between two Rydberg π pulses for the $|46P_{3/2}, m_J = 1/2\rangle$ state. Blue and green data points correspond to a 3×3 tweezer array with $24 \mu\text{m}$ spacing and a 7×7 array with $12 \mu\text{m}$ spacing, respectively. The dashed line shows an exponential fit to the blue data. The fitted lifetime is $238(17) \mu\text{s}$. The green solid line is a guide to the eye.

the dipolar interaction between an atom in $|46P_{3/2}, m_J = 1/2\rangle$ and an atom in a Rydberg state of opposite parity can reach up to 1 and 0.35 MHz for nearest and next-nearest neighbors, respectively. Such interaction strengths are non-negligible compared to the Rabi frequency of the Rydberg π pulses. A more detailed investigation of the collective effects is left for future work.

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