High-resolution spectroscopy and single-photon Rydberg excitation of reconfigurable ytterbium atom tweezer arrays utilizing a metastable state

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We present an experimental system for Rydberg tweezer arrays with ytterbium (Yb) atoms featuring internal state manipulation between the ground \(^1S_0\) and the metastable \(^3P_2\) states, and single-photon excitation from the \(^3P_2\) to Rydberg states. In the experiments, single Yb atoms are trapped in two-dimensional arrays of optical tweezers and are detected by fluorescence imaging with the intercombination \(^1S_0 \leftrightarrow ^3P_1\) transition, and the defect-free single atom arrays are prepared by the rearrangement with the feedback. We successfully perform high-resolution \(^1S_0 \leftrightarrow ^3P_2\) state spectroscopy for the single atoms, demonstrating the utilities of this ultranarrow transition. We further perform single-photon excitation from the \(^3P_2\) to Rydberg states for the single atoms, which is a key for the efficient Rydberg excitation. We also perform a systematic measurement of a complex energy structure of a series of \(D\) states including newly observed \(^3D_1\) states. The developed system shows feasibility of future experiments towards quantum simulations and computations using single Yb atoms.

I. INTRODUCTION

Individually trapped neutral atoms in optical tweezer arrays offer a promising platform for quantum simulation and computation [1,2]. Combination of high flexibility of the trap geometry and high tunability of interactions using Rydberg states enables a variety of experiments, ranging from observation of quantum phase transitions [3-5] to gate operations on multiple qubits [6-9].

Two-electron atoms, or alkaline-earth-like atoms, such as Sr and Yb have several advantages over alkali atoms widely used in single atom array experiments, and some unique features have been demonstrated such as trapping of Rydberg states [10] and the utility of the autoionization process [11,12]. An important feature is the absence of the electron spins in the \(^1S_0\) and \(^3P_0\) electronic states, which makes it possible to realize nuclear spin qubits with fermionic isotopes robust against environmental magnetic field fluctuations [13]. The advantage of the nuclear spin degree of freedom of \(^{174}\)Yb, in particular, in quantum information processing was discussed in [14-19]. Coherent nuclear spin control between two out of ten spin components in \(^{87}\)Sr [17] and between the two spin components in \(^{171}\)Yb [18,19] in optical tweezers were experimentally demonstrated recently.

The existence of the metastable \(^3P_0\) and \(^3P_2\) states is also an important property of the two-electron atoms. Quantum gate operations [11,20] and quantum metrology [21,22] in tweezer array systems using the clock \(^3P_0\) state have been demonstrated, while there are little investigations with the \(^3P_2\) state in spite of its comparable lifetime and linewidth to those of the \(^3P_0\) state. There are also several unique features of the \(^3P_2\) state compared to \(^3P_0\) [11,24]: First, the polarizability of the trapping light for the \(^3P_2\) state can be widely tuned by the magnetic field orientation and thus the magic-like condition is achievable without choosing any special wavelengths. Second, the Zeeman shift of the \(J = 2\) electronic spin enables individual addressing of the atoms in different tweezer sites with a modest strength of the magnetic field gradient, as demonstrated for the atoms in an optical lattice [25]. Third, the \(m_J = 0\) state of the bosonic isotopes is expected to be less sensitive to the magnetic field fluctuations than the \(^3P_0\) state as the second-order Zeeman coefficients for the \(^3P_0\) and \(^3P_2\) states are calculated to be \(-6.0\) Hz/G\(^2\) and \(1.2\) Hz/G\(^2\), respectively [26]. This implies that the \(^1S_0 - ^3P_2\) \((m_J = 0)\) system of the bosonic isotopes can be a promising qubit as well as a good resource for precision measurements.

The metastable states also offer a possibility of coherent, loss-less excitation to Rydberg states by single-photon process. Rydberg state excitation of alkali atoms is usually performed by two-photon process with an intermediate state with a short lifetime. Spontaneous decays from the intermediate state causes short coherence time even with a large detuning. Two-electron atoms, on the other hand, can be excited to Rydberg states with single-photon process from the metastable states. Coherent driving between the \(^3P_2\) and a Rydberg state was indeed demonstrated with \(^{88}\)Sr [11].

In this paper, we present an experimental system for Rydberg atom arrays with Yb atoms featuring internal state manipulation between the ground \(^1S_0\) and the metastable \(^3P_2\) states, and single-photon excitation from the \(^3P_2\) to Rydberg states. We trap single \(^{174}\)Yb atoms in arrays of optical tweezers generated by a pair of acousto-optic deflectors (AODs). High-sensitive imaging of trapped single atoms is performed using the narrowline \(^1S_0 \leftrightarrow ^3P_1\) transition, yielding 95% of imaging fi-
delity. The trapped single atoms in one dimension (1D) and two dimension (2D) are dynamically rearranged to defect-free single atom arrays with a fast feedback system. Using this system, we succeed in high-resolution \(^1S_0 \leftrightarrow \(^3P_2\) laser spectroscopy for single Yb atoms. We also successfully demonstrate single-photon excitation to a Rydberg state from the metastable \(^3P_2\) state for single atoms in optical tweezers. In addition, we perform a systematic laser spectroscopy for Rydberg states using evaporatively cooled atoms, in which we newly observe a series of \((6s)(nd)^3D_3\) states ranging \(n = 65–80\). This work offers an important step towards the realization of scalable systems for versatile quantum simulation and computation applications using Yb atom tweezer arrays.

This paper is structured as follows: We present in section II the overview of the apparatus including the vacuum chamber system integrating electrodes and a micro-channel plate (MCP), an optical tweezer array generation system and laser sources for internal state control and probing. In section III we show the result of single atom trapping and imaging in optical tweezer arrays, as well as tweezer array rearrangement by a feedback program. In section IV we describe the \(^1S_0 \leftrightarrow \(^3P_2\) laser spectroscopy for single atoms in an optical tweezer array. In section V we show the result of single-photon Rydberg state spectroscopy from the \(^3P_2\) state with both single atoms and an ensemble of evaporatively cooled atoms. Finally in section VI we conclude our work with perspectives using the developed system towards quantum simulation and computation.

II. EXPERIMENTAL APPARATUS

A. Vacuum chamber

Our vacuum chamber system is based on a rather standard system for producing Yb quantum gases, and it comprises four sections: oven chamber, Zeeman slower pipe, science chamber, and pumping chamber, as depicted in Fig. 1(a). In particular, the science chamber is specially designed for experiments of the Rydberg atom detection and optical tweezer arrays, based on a commercial chamber (Kimball Physics, MCF800-ExtOct-G2C8A16) with two ICF203, eight ICF70 and sixteen ICF34 flanges. Two reentrant viewports are mounted on the ICF203 flanges on top and bottom, hosting high-NA objective lenses for high-resolution imaging, optical tweezer arrays, and site-resolved manipulation. Electrical feedthroughs and a MCP (Hamamatsu photonics F4655-11) for Rydberg state detection are attached to the chamber. Many viewports allow optical access for laser cooling, internal state excitation, absorption and fluorescence imaging, and further optical trapping.

In addition, the science chamber is equipped with eight electrodes as shown in Fig. 1(b) and (c) in order to compensate for stray electric fields at the position of the atoms as well as to ionize Rydberg atoms, enabling high-sensitive detection of Rydberg states by the MCP. The electrodes are connected to a digital-analog converter through the feedthroughs, which outputs ±1 V with 16-bit resolution, corresponding to 0.9 \(\mu\)V/mm, 1.2 \(\mu\)V/mm, and 0.7 \(\mu\)V/mm resolution along the \(x, y,\) and \(z\) directions, respectively. The atoms are shielded from electric fields created by the MCP and the feedthroughs, respectively. A grounded mesh and an aluminum plate placed next to the electrodes shield atoms from electric fields created by the MCP and the feedthroughs, respectively. (c) Photograph of the electrodes and the mesh assembled on the bottom viewport prior to installation in the vacuum system.
B. Laser sources

![Energy levels of Yb relevant for the experiment. The strong $^1S_0 \leftrightarrow ^3P_1$ transition (399 nm) is used for the Zeeman slower and absorption imaging. The narrow-line $^1S_0 \leftrightarrow ^3P_1$ transition (556 nm) is used for the MOT and fluorescence imaging for single atoms. Atoms in the metastable $^3P_2$ state are prepared by direct excitation from the ground state with a 507 nm light. The atoms in the $^3P_2$ state are excited to Rydberg states by single-photon excitation with a 325 nm laser. For high-resolution spectroscopy of the $^1S_0 \leftrightarrow ^3P_2$ transition, the $^3P_2$ atoms are repumped to the ground state through the $^3S_1 \rightarrow ^3P_1 \rightarrow ^1S_0$ process by applying a 770 nm laser.

We utilize five optical transitions shown in Fig. 2. The Zeeman slowing beam operating on the $^1S_0 \leftrightarrow ^1P_1$ transition with a wavelength of 399 nm is generated by a second harmonic generation (SHG) of a 798 nm laser beam derived from a tapered-amplified diode laser (Toptica, TA-pro). The frequency of which is stabilized with a wavemeter (High Finesse, WS-8 10). The magneto-optical trapping (MOT) and fluorescence imaging are operated on the $^1S_0 \leftrightarrow ^3P_1$ transition with a wavelength of 556 nm. They are also derived from a SHG of a tapered-amplified diode laser (Toptica, TA-pro) with a wavelength of 1112 nm. The diode laser is frequency-stabilized with the Pound–Drever–Hall (PDH) technique to an ultra-low expansion (ULE) glass cavity with a finesse of about 20,000 at this wavelength.

Towards a qubit operation and subsequent Rydberg excitation, the atoms in the ground state $^1S_0$ are directly excited to the $^3P_2$ state with a resonant 507 nm light. We generate the 507 nm light from a SHG of a home-built external cavity diode laser (ECDL)–tapered amplifier (TA) system at 1014 nm. We obtain 15 mW, which is enough for us to perform a Rabi oscillation at about several kHz. The frequency of the ECDL is also stabilized to the same ULE glass cavity with a finesse of about 500,000 at this wavelength. The linewidth is estimated to be 200 Hz from the PDH error signal at 1014 nm. The 507 nm beam propagates along the radial direction of the optical tweezers and has a horizontally elongated shape of 60 µm × 530 µm at the position of the atoms to ensure uniform intensity over the array. In the $^1S_0 \leftrightarrow ^3P_2$ spectroscopy, we apply repumping light resonant with the $^3P_2 \leftrightarrow ^3S_1$ transition with a wavelength of 770 nm for the $^3P_2$ atoms to return to the ground state via the $^3P_1$ state. The light is derived from an interference filter diode laser, frequency-stabilized with the wavemeter. The atoms in the $^3P_2$ state are transferred to Rydberg states by a 325 nm light generated by a SHG of a home-built ECDL–TA system at with a wavelength of 650 nm, the frequency of which is stabilized with the wavemeter. We obtain 30 mW with this system.

C. Optical tweezer array system

The optical tweezers with a wavelength of 532 nm are derived from a diode-pumped solid-state laser (Coherent, Verdi V-10). The laser beam is arranged into two-dimensional arrays of optical tweezers by two orthogonally oriented AODs (AA opto-electronic, DTSX-400-532) in the 4f configuration (see Fig. 3). We apply multi-tone radio-frequencies (RFs) generated by an arbitrary waveform generator (Spectrum, M4i.6622-x8) to the AODs. Relative phases of the RF components are designed to reduce the peak-to-average power ratio using the Kitayoshi algorithm [27].

The deflected beams are magnified and pass through an objective lens below the science chamber. The objective lens has an NA of 0.6 and a working distance of 20.25 mm and it is designed to be diffraction-limited for 532 nm and 556 nm light, corresponding to the tweezer and imaging wavelengths, respectively. The tweezers are focused down to a waist of 0.89 µm, determined by the sideband-resolved $^1S_0 \leftrightarrow ^3P_2$ spectroscopy as described in section IV. The deflection angle of the AOD is 0.8 mrad/MHz, resulting in a 2.4 µm/MHz shift at the position of the atoms.

III. SINGLE ATOM TRAPPING AND IMAGING

The experiment starts from loading atoms in a MOT from a Zeeman-slowed atomic beam for 500 ms. The atoms collected in the MOT are then compressed by increasing the magnetic field gradient and further cooled by decreasing the detuning and the power of the MOT beams. Typical temperature and the number of atoms at this stage are $\sim 20 \mu K$ and $10^5$, respectively. Optical tweezers are overlapped with the MOT cloud, and some of the atoms are trapped in the optical tweezers after turning off the MOT beams. Typical power of each tweezer is 18 mW, corresponding to the potential depth of $k_B \times 660 \mu K$, where $k_B$ is the Boltzmann constant. We apply a red-detuned 556 nm light to induce losses of pairs of atoms by light-assisted collisions, yielding zero or one atom in each tweezer reflecting the parity of the initial number of atoms [28].

Single atoms are detected with fluorescence imaging with the $^1S_0 \leftrightarrow ^3P_1$ transition. The imaging light is tilted by 16° from the horizontal plane and horizontally polarized. Photons emitted from the atoms are collected for 60 ns on a charge-coupled device camera (Andor, iXon-
FIG. 3. Sketch of the optical system for the optical tweezers and fluorescence imaging. Two AODs are placed horizontally (AOD(H)) and vertically (AOD(V)) on the imaging planes of the standard 4f configuration to generate two-dimensional tweezer arrays. The deflected 532 nm beams pass through the dichroic mirror and the objective lens with NA = 0.6 and focused onto the atoms. 556 nm fluorescence from the atoms are collected on the EMCCD camera through the objective lens.

FIG. 4. (a) Single-shot and (b) 400-average image of atoms in a 5 × 5 tweezer array with the spacing 4.8 μm (60 ms exposure time). (c) Histogram of photons detected by the CCD camera in each 3 × 3 pixel region around the atom positions. The dashed line represents the fitted curve by a double gaussian distribution. The dark count is set to be zero for clarity.

### FIG. 5. Recapture probability as a function of the release time

To obtain defect-free atom arrays, we apply a rearrangement protocol in 1D and 2D arrays. We first prepare a sample randomly loaded in a 1D array of 25 sites and take an image. At this stage, we identify the filled and empty sites. We then turn off the RF components applied to the AODs corresponding to the empty trap sites, and move the remaining sites to the left by dynamically changing the multi-tone RF in 0.64 ms. To confirm the successful rearrangement, we finally take the second image. Figure 6(a) shows typical images before and after the rearrangement.
and after the rearrangement.

Figure 6(b) shows the probability to find an atom in each site obtained by 200 experimental runs before (blue circles) and after (red squares) the rearrangement. The probability to find an atom in the i-th site from the left edge after the rearrangement is given by

\[ P_i = (1 - q) \times \sum_{i \leq j \leq N} \binom{N}{j} p^j (1-p)^{N-j}. \] (1)

Here \( N \) is the number of total trap sites before the rearrangement, \( p \) is the loading probability, and \( q \) is the loss probability between the two images. The fit of Eq. (1) gives \( p = 0.61 \) and \( q = 0.07 \). The obtained value of \( p \) and \( 1 - q \) are close to the fully random case of \( 1/2 \), and the survival probability of 0.95, which indicates the rearrangement process is performed with negligibly small error.

This rearrangement method using the AODs is not limited to 1D arrays. Figure 6(c) shows an example for a 2D array. By only collecting defectless vertical lines of sites in a \( 3 \times 8 \) array, we successfully prepare a defect-free \( 3 \times 5 \) array of single atoms. As far as we know, this is the first demonstration of creating a defect-free 2D array only by AODs.

IV. EXCITATION OF THE SINGLE ATOMS TO THE METASTABLE \( ^3P_2 \) STATE

We perform high-resolution laser spectroscopy for the transition between the \( ^1S_0 \) and \( ^3P_2 \) states of single atoms in an optical tweezer array. Unlike the \( ^1S_0 \leftrightarrow ^3P_0 \) transition, the differential light shift between the \( ^1S_0 \) and \( ^3P_2 \) states can be controlled by tuning the angle between the polarization of the tweezers and the magnetic field direction. For the \( ^{174}\text{Yb} \) isotope in 532 nm light, the difference of the light shifts between \( ^3P_2 \) \((m_J = 0)\) and \( ^1S_0 \) is minimized such that the ratio of their polarizabilities is 1.016 when the magnetic field is aligned to the light polarization. We apply 2.8 G in order to lift the degeneracy along the direction of tweezer light polarization.

We perform spectroscopy of the \( m_J = 0 \) state of single atoms in a \( 5 \times 5 \) array. The experimental sequence proceeds as shown in Fig. 7(a). We first take an image of single atoms randomly loaded in a \( 5 \times 5 \) array followed by the cooling as described in section III. The potential depth at this stage is 690 \( \mu \text{K} \). The tweezer potential is adiabatically ramped down to \( 1/10 \) to further reduce inhomogeneous broadening of the \( ^1S_0 \leftrightarrow ^3P_2 \) resonance. We apply a 507 nm laser pulse for 4 ms followed by a 556 nm laser pulse for 10 ms to remove the remaining atoms in the ground state over the array. After the 507 nm excitation, we ramp the tweezer potential back to the initial value and apply a 770 nm light for 5 ms. We note that the \( ^3S_1 \) state spontaneously decays into all the \( ^3P_J \) \((J = 0, 1, 2)\) states but majority of the \( ^3P_2 \) atoms return to the \( ^1S_0 \) state through the \( ^3P_1 \) without the other repumper \( ^3P_0 \leftrightarrow ^3S_1 \). Finally, we take the second fluorescence image and obtain the return fraction by comparing with the first image.

Figure 7(b) shows a typical spectrum. The carrier resonance and the blue and red sidebands are well resolved, promising for the sideband cooling to the vibrational ground state in the optical tweezers. The radial trap frequency \( \Omega_r/(2\pi) \) deduced from the sidebands is \( 20.7 \pm 0.3 \text{ kHz} \), from which we evaluate the waist of the tweezer beams to be 0.89 \( \mu \text{m} \). The ratio of the peak heights of the red sideband \( A_R \) to the blue \( A_B \) gives the temperature \( T \) and the mean vibrational number occupation \( \bar{n} \) by a relation \( A_R/A_B = \exp(-\hbar\Omega_r/(k_B T)) = \bar{n}/(1 + \bar{n}) \) where \( \hbar \) denotes the reduced planck constant, and we find \( T = 1.90 \pm 0.02 \mu\text{K} \) and \( \bar{n} = 1.46 \pm 0.01 \). The obtained value of \( \bar{n} \) is in agreement with the theoretical expectation that \( \bar{n} \) is reduced to 1.05 at most by the cooling process taking into account the sideband transitions, using Eq. (121) of [31]. The assumption of the same distribution of the occupation for trap depth before the ramping down of the potential suggests the temperature of 6.01 \pm 3.24 \mu\text{K}. We attribute the difference between the value obtained with the release-and-recapture method in the previous section to the assumption of isotropic temperatures in the Monte-Carlo simulation. Note that the saturation effect would contribute to reduction of the peak height of the carrier resonance.
of 5 μK. We first apply a 507 nm pulse resonant to the \(^{1}\text{S}_0 \leftrightarrow ^{3}\text{P}_2\) \((m_J = 2)\) transition for 18.75 ms followed by a 325 nm pulse for 250 μs. Immediately after the 325 nm pulse we ramp up the electric field to 17 V/cm to detect the Rydberg states on the MCP by the field ionization method. The MCP signal is amplified and acquired by a field-programmable gated array with a 2 μs time resolution. This excitation and ionization process is repeated for 10 times and the MCP signals are averaged. Figure 8(a) and (b) shows the pulse sequence and a typical averaged MCP signal, respectively. The integral of the MCP signal corresponds to the number of the ionized Rydberg state atoms.

We perform spectroscopy around the D series of Rydberg states from \(^{3}\text{P}_2\) to \(^{1}\text{S}_0\) state atoms. (a) Pulse sequence for the Rydberg spectroscopy from the \(^{3}\text{P}_2\) state for single atoms. (b) A spectrum of the \(^{3}\text{P}_2\), \(m_J = 0 \leftrightarrow (6s)(78d)^{3}\text{D}_3\) transition for single atoms in the \(5 \times 5\) tweezer array. Rydberg states are ionized by an electric field before the repumping of \(^{3}\text{P}_2\) state and observed as a loss of the \(^{1}\text{S}_0\) state.

V. RYDBERG STATE SPECTROSCOPY

We perform single-photon Rydberg state excitation spectroscopy from the \(^{3}\text{P}_2\) state in single atom arrays. The \(^{3}\text{P}_2\) state atoms are prepared by applying a 507 nm laser pulse for 20 ms on the carrier resonance in the shallow trap, yielding the excitation probability of 40%. After ramping back the trap potential we apply a 325 nm laser pulse for 10 ms followed by ionization. We then take the second image after a 5 ms pulse of the 770 nm laser (see Fig. 8 a). Successful excitation to a Rydberg state is observed as a decrease of the return probability as shown in Fig. 8(b). The observed resonance corresponds to the \((6s)(78d)^{3}\text{D}_3\) state. This is the first demonstration of the single-photon Rydberg excitation of a single Yb atom array.

In addition, the spectroscopic information on the accessible Rydberg states is crucially important, and thus we further perform systematic spectroscopic measurements of the transition between the \(^{3}\text{P}_2\) and Rydberg states. In this measurement, different from the previous experiments, we use an ensemble of atoms in an optical dipole trap (ODT) with a wavelength of 1070 nm for the sake of high signal intensity. Atoms loaded in a MOT for 10 s are transferred into the ODT and evaporatively cooled. Finally we obtain \(10^3\) atoms with a temperature close to the quantum defect of each resonance and plot them against the principal quantum number in the two-level system.
FIG. 9. (a) Pulse sequence for the Rydberg state ionization spectroscopy. (b) Typical MCP signal averaged for 10 pulses. The area of the trace corresponds to the number of ions detected by the MCP. (c) Spectra around the $^3P_2$ ($m_J = 2$) $\leftrightarrow$ $^3D$ transition for $n = 65$–80. We label the resonances by numbers from lower to higher energies in the $n = 80$ spectrum. The horizontal axis is relative frequency from the strongest resonance 7. The resonances 3, 5 and 8 correspond to $^3D_1$, $^3D_2$ and $^1D_2$ states, respectively. The peaks 2 and 7 are the new observations, and 7 is assigned as (6s)(nd)$^3D_3$. Note that the peaks of 1, 4, and 6 were also observed in [35] but not assigned. (d) The quantum defect $\delta$ of the resonances against the principal quantum number.
where \( I = 50,443,070.41 \text{ cm}^{-1} \) and \( R_{\text{Yb}} = 10,973.696,959 \text{ cm}^{-1} \) are the energy of the first ionization limit and the Rydberg constant of \( ^{174}\text{Yb} \), respectively [36]. The quantum defects for the low-lying \( ^3\text{D}_3 \) state of \( n = 10 \) and \( 12–15 \) were deduced in [37]. We confirm that the deduced quantum defects for the high-lying \( ^3\text{D}_3 \) Rydberg states are in good agreement with the values for the low-lying ones. Table I summarizes the energies and the quantum defects obtained by our measurement.

VI. CONCLUSION

In conclusion, we demonstrate core capabilities for quantum information processing based on single neutral Yb atoms — trapping and imaging of single atoms in optical tweezer arrays, the preparation of defect free arrays in 1D and 2D by atom rearrangement through the measurement and feedback, the direct optical excitation to the long-lived metastable state of \(^3\text{P}_2\), and the demonstration of the single-photon excitation to Rydberg states within a tweezer array. In addition, our results of Rydberg state spectroscopy show new observation of the \(^3\text{D}_3\) series thanks to our choice of \( J = 2 \) as the initial state. With the present work, the single qubit operation utilizing the rich internal degrees of freedom of nuclear spin and orbital degrees of freedom, two-qubit operation via a Rydberg state [1], and the single site addressing with a magnetic field gradient [14], are well within the reach.

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[1] M. Saffman, T. G. Walker, and K. Mølmer, Reviews of Modern Physics 82, 2313 (2010), 0909.4777
[2] D. S. Weiss and M. Saffman, Physics Today 70, 44 (2017)
[3] A. Browaeys and T. Lahaye, Nature Physics 16, 132 (2020), 2002.07413
[4] S. Ebadi, T. T. Wang, H. Levine, A. Keessing, G. Semeghini, A. Omran, D. Bluvstein, R. Samajdar, H. Pichler, W. W. Ho, S. Choi, S. Sachdev, M. Greiner, V. Vuletić, and M. D. Lukin, Nature 595, 227 (2021)
[5] P. Scholl, M. Schuler, H. J. Williams, A. A. Eberharter, D. Barredo, K.-N. Schymik, V. Lienhard, L.-P. Henry, T. C. Lang, T. Lahaye, et al., Nature 595, 233 (2021).
[6] H. Levine, A. Keessing, A. Omran, H. Bernien, S. Schwartz, A. S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M. D. Lukin, Physical Review Letters 121, 123603 (2018), 1806.04682
[7] H. Levine, A. Keessing, G. Semeghini, A. Omran, T. T. Wang, S. Ebadi, H. Bernien, M. Greiner, V. Vuletić, H. Pichler, and M. D. Lukin, Physical Review Letters 123, 170503 (2019), 1908.06101
[8] D. Bluvstein, H. Levine, G. Semeghini, T. T. Wang, S. Ebadi, M. Kalinowski, A. Keessing, N. Maskara, H. Pichler, M. Greiner, V. Vuletić, and M. D. Lukin, arXiv (2021), 2112.03923
[9] T. M. Graham, Y. Song, J. Scott, C. Poole, L. Phutti-tarn, K. Jooya, P. Eichler, X. Jiang, A. Marra, B. Grinkee-meyer, M. Kwon, M. Ebert, J. Cereck, M. T. Lichtman, M. Gillette, J. Gilbert, D. Bowman, T. Ballance, C. Campbell, E. D. Dahl, O. Crawford, T. Noel, and M. Saffman, arXiv (2021), 2112.14580
[10] J. T. Wilson, S. Sasaki, Y. Meng, S. Ma, R. Dilip, A. P. Burgess, and J. D. Thompson, Physical Review Letters 128, 033201 (2022)
[11] I. S. Madjarov, J. P. Covey, A. L. Shaw, J. Choi, A. Kale, A. Cooper, H. Pichler, V. Schkolnik, J. R. Williams, and M. Endres, Nature Physics 16, 857 (2020).
[12] A. P. Burgess, S. Ma, S. Sasaki, J. Wilson, M. A. Alarcón, C. H. Greene, and J. D. Thompson, arXiv (2021), 2110.06902.
[13] A. V. Gorshkov, A. M. Rey, A. J. Daley, M. M. Boyd, J. Ye, P. Zoller, and M. D. Lukin, Physical Review Letters 110, 110503 (2009), 0812.3660.
[14] K. Shibata, S. Kato, A. Yamaguchi, S. Uetake, and Y. Takahashi, Applied Physics B 97, 753 (2009), 0904.4523.
[15] T. Takei, M. Takeuchi, Y. Eto, A. Naguchi, P. Zhang, M. Ueda, and M. Kozuma, Physical Review A 81, 043201 (2010), 0912.4948.
[16] K. Barnes, P. Battaglino, B. J. Bloom, K. Cassella, R. Coxe, N. Crisosto, J. P. King, S. S. Kondov, K. Kotru, S. C. Larsen, J. Lasuign, B. J. Lester, M. McDonald, E. Megidish, S. Narayanaswami, C. Nishiguchi, R. Notermans, L. S. Peng, A. Ryou, T.-Y. Wu, and M. Yarwood, arXiv (2021), 2108.04790.
[17] S. Ma, A. P. Burgess, G. Liu, J. Wilson, B. Zhang, and J. D. Thompson, arXiv (2021), 2112.06799.
[18] A. Jenkins, J. W. Lis, A. Senoo, W. F. McGrew, and A. M. Kaufman, arXiv (2021), 2112.06732.
| n  | index | $\delta$ E/h (MHz) | n  | index | $\delta$ E/h (MHz) |
|----|-------|-------------------|----|-------|-------------------|
| 65 | 3     | 2.753 118 00      | 74 | 6     | 2.732 881 65      |
|    | 4     | 2.749 201 30      |    | 7     | 2.728 919 37      |
|    | 7     | 2.728 954 75      |    | 8     | 2.713 498 12      |
| 66 | 3     | 2.753 233 55      | 75 | 1     | 2.757 558 00      |
|    | 4     | 2.749 123 37      |    | 3     | 2.754 396 71      |
|    | 7     | 2.729 019 84      |    | 4     | 2.751 617 38      |
| 67 | 3     | 2.752 989 91      |    | 5     | 2.749 453 21      |
|    | 4     | 2.749 030 83      |    | 6     | 2.734 156 93      |
|    | 6     | 2.710 514 77      |    | 7     | 2.728 839 26      |
|    | 7     | 2.728 676 00      |    | 8     | 2.713 498 12      |
|    | 8     | 2.713 271 53      |    | 1     | 2.757 558 00      |
| 68 | 3     | 2.753 556 14      |    | 2     | 2.756 319 39      |
|    | 4     | 2.749 545 81      |    | 3     | 2.754 123 63      |
|    | 7     | 2.729 072 10      |    | 4     | 2.751 338 22      |
|    | 8     | 2.713 037 07      |    | 5     | 2.748 931 06      |
| 69 | 3     | 2.753 751 90      |    | 6     | 2.734 955 80      |
|    | 4     | 2.750 236 53      |    | 7     | 2.728 140 55      |
|    | 5     | 2.749 379 75      |    | 8     | 2.713 174 28      |
|    | 6     | 2.719 565 11      |    | 1     | 2.760 353 76      |
|    | 7     | 2.729 107 78      |    | 2     | 2.758 213 71      |
|    | 8     | 2.713 083 52      |    | 3     | 2.754 547 05      |
| 70 | 3     | 2.753 698 45      |    | 4     | 2.751 787 62      |
|    | 4     | 2.750 364 04      |    | 5     | 2.749 265 15      |
|    | 5     | 2.749 266 63      |    | 6     | 2.736 433 65      |
|    | 6     | 2.722 625 17      |    | 7     | 2.728 692 66      |
|    | 7     | 2.728 931 74      |    | 8     | 2.713 606 30      |
|    | 8     | 2.713 374 54      |    | 1     | 2.762 192 34      |
| 71 | 3     | 2.753 606 97      |    | 2     | 2.760 144 54      |
|    | 4     | 2.750 438 77      |    | 3     | 2.754 872 56      |
|    | 5     | 2.749 153 25      |    | 4     | 2.751 981 88      |
|    | 6     | 2.725 552 12      |    | 5     | 2.749 430 08      |
|    | 7     | 2.728 750 50      |    | 6     | 2.737 113 54      |
|    | 8     | 2.712 551 98      |    | 7     | 2.728 904 26      |
|    | 1     | 2.762 192 34      |    | 2     | 2.760 144 54      |
| 72 | 3     | 2.753 973 35      |    | 3     | 2.754 872 56      |
|    | 4     | 2.750 944 03      |    | 4     | 2.751 981 88      |
|    | 5     | 2.749 409 48      |    | 5     | 2.749 430 08      |
|    | 6     | 2.726 897 38      |    | 6     | 2.737 113 54      |
|    | 7     | 2.728 880 20      |    | 7     | 2.728 904 26      |
|    | 8     | 2.712 551 98      |    | 8     | 2.713 498 64      |
| 73 | 3     | 2.754 176 31      |    | 1     | 2.764 389 69      |
|    | 4     | 2.751 246 56      |    | 2     | 2.763 960 40      |
|    | 5     | 2.749 532 47      |    | 3     | 2.755 316 70      |
|    | 6     | 2.730 954 96      |    | 4     | 2.752 270 80      |
|    | 7     | 2.728 037 71      |    | 5     | 2.749 658 77      |
|    | 8     | 2.713 052 18      |    | 6     | 2.737 673 32      |
| 74 | 1     | 2.756 543 85      |    | 7     | 2.728 778 71      |
|    | 2     | 2.754 300 03      |    | 8     | 2.714 288 47      |
|    | 3     | 2.751 552 23      |    | 1     | 2.756 103 81      |
|    | 4     | 2.751 552 23      |    | 2     | 2.763 960 40      |
|    | 5     | 2.749 510 64      |    | 3     | 2.755 277 19      |
|    | 6     | 2.751 552 23      |    | 4     | 2.752 128 81      |
|    | 7     | 2.728 632 77      |    | 5     | 2.749 345 23      |
|    | 8     | 2.713 481 34      |    | 6     | 2.737 524 41      |

TABLE I. Energy and quantum defect values of the observed resonances for $n = 65$–80. Index numbers indicate the number assigned to each peak in Fig. 9(c). Typical uncertainty of the resonance frequency is about 10 MHz coming from the uncertainty of the wavemeter.

[20] N. Schine, A. W. Young, W. J. Eckner, M. J. Martin, and A. M. Kaufman, arXiv (2021), 2111.14653.

[21] M. A. Norcia, A. W. Young, W. J. Eckner, E. Oelker, J. Ye, and A. M. Kaufman, arXiv 10.1126/science.aay0644 (2019), 1904.10934.

[22] I. S. Madjarov, A. Cooper, A. L. Shaw, J. P. Covey, V. Schkolnik, T. H. Yoon, J. R. Williams, and M. Endres, Physical Review X 9, 041052 (2019) 1908.05619.

[23] A. W. Young, W. J. Eckner, W. R. Milner, D. Ketlar, M. A. Norcia, E. Oelker, N. Schine, J. Ye, and A. M. Kaufman, Nature 588, 408 (2020).

[24] A. Yamaguchi, S. Uetake, S. Kato, H. Ito, and Y. Takahashi, New Journal of Physics 12, 103001 (2010).
[25] S. Kato, K. Shibata, R. Yamamoto, Y. Yoshikawa, and Y. Takahashi, Applied Physics B 108, 31 (2012).

[26] V. A. Dzuba, V. V. Flambaum, and S. Schiller, Physical Review A 98, 022501 (2018), 1803.02452.

[27] H. Kitayoshi, S. Sumiea, K. Siirakawa, and S. Takeshita, in Digest of Papers-International Test Conference (IEEE, 1985) pp. 825–834.

[28] A. Fuhrmanek, R. Bourgain, Y. R. P. Sortais, and A. Browaeys, Physical Review A 85, 062708 (2012), 1107.5781.

[29] C. Tuchendler, A. M. Lance, A. Browaeys, Y. R. P. Sortais, and P. Grangier, Physical Review A 78, 033425 (2008), 0805.3510.

[30] M. Endres, H. Bernien, A. Keesling, H. Levine, E. R. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletic, M. Greiner, and M. D. Lukin, Science 354, 1024 (2016).

[31] D. Barredo, S. d. Léseleuc, V. Lienhard, T. Lahaye, and A. Browaeys, Science 354, 1021 (2016), 1607.03042.

[32] T. Tomita, S. Nakajima, Y. Takasu, and Y. Takahashi, Physical Review A 99, 031601 (2019), 1809.09989.

[33] J. W. Cho, H.-g. Lee, S. Lee, J. Ahn, W.-k. Lee, D.-h. Yu, S. K. Lee, and C. Y. Park, Physical Review A 85, 035401 (2012).

[34] D. Leibfried, R. Blatt, C. Monroe, and D. Wineland, Reviews of Modern Physics 75, 281 (2003).

[35] S. Saskin, Building Quantum Systems with Ytterbium Rydberg Arrays, Ph.D. thesis, Princeton University (2021).

[36] H. Lehec, A. Zuliani, W. Maineult, E. Luc-Koenig, P. Pillet, P. Cheinet, F. Niyaz, and T. F. Gallagher, Physical Review A 98, 062506 (2018), 1805.02712.

[37] J. F. Wyart and P. Camus, Physica Scripta 20, 43 (1979).