Realization of strong coupling between deterministic atom arrays and a high finesse miniature optical cavity

Yanxin Liu, 1,2, * Zhihui Wang, 1,2, * Pengfei Yang, 1,2 Qinxia Wang, 1,2
Qing Fan, 1,2 Gang Li, 1,2, † Pengfei Zhang, 1,2, § and Tiancai Zhang 1,2, ¶

1 State Key Laboratory of Quantum Optics and Quantum Optics Devices, and Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China
2 Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan 030006, China

We experimentally demonstrate the strong coupling between one-dimensional (1D) single atom arrays and a high finesse miniature cavity. The atom array is obtained by loading single atoms into a 1D optical tweezer array with dimension 1 × 11. Therefore, deterministic number of atoms is obtained, and the atom number is determined by imaging the atom arrays on a CCD camera in real time. By precisely controlling the position and the spacing of the atom array in the high finesse Fabry-Perot cavity, all the atoms in the array are strongly coupled to the cavity simultaneously. The spectra of vacuum Rabi splitting are discriminated with deterministic number of atoms.

Strongly coupled cavity quantum electrodynamics (QED) is a basic physical system for studying the light-matter interaction [1], which not only is a test bed for studying fundamental physics but also provides powerful quantum resources for quantum information [2–6]. As a promising platform to realize the quantum network [7], optical cavity QED system has been attracting intense interest. Matured by the single atom control in the small cavity mode, the research has been mainly focused on the interaction between the single atoms and single photons. Plenty of new quantum technologies and devices, e.g., single photon sources and blockade [8–14], quantum interface [15, 16], quantum logic gates [17–20], quantum measurements [21–26], and quantum routers [27–31] etc., have been invented and investigated. Significantly, the demonstration of the elementary quantum network [32] between two nodes with individual atom in each cavity has brought a great leap for the quantum networks.

The multi-atom cavity QED system, in which individual atom can be discriminated and controlled, would be more interesting for both fundamentals of physics and application. First of all, the cavity photon mediated interactions between different atoms enriches the dynamics and complexity of the coupling graphs for research of many-body physics [33–35]. Moreover, in the context of recent progress on the programmable arrays of atoms in quantum simulations and quantum computations [36–41], the development of a multi-qubit module with optical links, which possess the abilities of processing quantum information locally and interfacing qubits between atoms and photons, brings new perspectives for the quantum networks and the distributed quantum computation [42].

However, to build such multi-atom cavity QED is very tough because the stringent requirement on the position control of every atom in order to get a steady and uniform strong coupling for each atom to a tiny cavity mode. Up to now, only two neutral atoms have been successfully controlled in the same mode of a Fabry-Perot (F-P) or nanophotonic cavity [42–45]. A cavity QED system with 1D atom arrays being transversely integrated with a high finesse F-P cavity, where the individual atom is controlled to enter the cavity mode one by one, has also been presented recently [46, 47]. A system of 5 ions couples to a F-P cavity has also been demonstrated [48], but not in the strong coupling regime. In this letter, we report the strong coupling between one dimensional (1D) atom arrays and a miniature F-P cavity. The atom arrays are engineered to couple the cavity simultaneously with uniform coupling strength. The strong coupling of up to 8 atoms out of 11-tweezer arrays has been demonstrated. The vacuum Rabi splitting can be discriminated from 1 to 8 atoms individually and the √N-scale of collective enhancement for the coupling strength on atom number N is validated with deterministic number of atoms.

The experimental setup is illustrated in Fig. 1. The core of the setup is a miniature optical F-P cavity [Fig. 1(a)] which is composed of two high-reflectively coated mirrors with curvature radius of 100 mm. The mirrors have transmittances of 4.9 and 84.9 ppm, respectively, at 852 nm. The length of the cavity is fixed as 1.27 mm to accommodate the atom arrays while keeping the strong coupling for individual atom. The waist of the TEM00 mode and finesse of the cavity are 46 µm and 5.7 × 10^6, respectively. Thus, the cavity QED parameters for individual cesium atom in our system are (g0, κ, γ) = 2π × (3.2, 1.0, 2.6) MHz, where g0 denotes the theoretical maximum coupling strength between cesium atom (for transition |g⟩ ≡ |S1/2⟩F = 4, mF = 4⟩ ↔ |e⟩ ≡ |P3/2⟩F = 5, mF = 5⟩) and the cavity TEM00 mode. κ and γ are the decay rates from the cavity and atom, respectively. The cooperative coefficient is C = g0^2 / 2kγ = 1.9, which means that our system is a strongly coupled cavity QED system for individual atom when the position can be controlled precisely at the antinode of the cavity standing-wave mode.

The whole system including the optical cavity and the mount are placed inside a high-vacuum glass cell with inner dimension of 20 mm × 25 mm on the cross section. The length of cavity is actively stabilized to the cesium transition line |g⟩ ↔ |e⟩ (the resonant wavelength is around 852.356 nm).
by an auxiliary locking laser at 820.9 nm (114 free spectral ranges off to the atomic transition), whose frequency has been locked to the cesium transition line via a transfer cavity [details can be found in the Supplemental Materials (SM)] [49]. The locking laser also forms a lattice with positive potentials along the cavity axis. Thanks to the relative long cavity length, a small magneto-optical trap (MOT) can be built directly inside the F-P cavity [Fig. 1(b)] to accumulate the atoms emitted from the first-stage two-dimensional MOT (see SM [49]). The atomic ensemble has a diameter of 150 μm and atom number around 10^5. The temperature is about 15 μK after polarization gradient cooling.

Figure 1(c) shows the brief drawing of the experimental setup. The optical tweezer arrays are generated by strongly focusing a one-dimensional laser beam array with dimension of 1 × 11 by a homemade high-numerical-aperture objective with NA=0.4 and focal length f=28.8 mm [50]. The laser beam arrays come from the diffraction of an acousto-optic deflector (AOD, DTSX, AA Opto Electronic) driven by a multi-tone radio frequency (RF) signal. Every tweezer has a waist radius of 1.81 μm, which ensures that only single atom is loaded by the light-assisted collision process [51]. The tweezer arrays are projected into the cavity transversely from the outside of the vacuum glass cell and the orientation is along the cavity axis (Z-axis). The optical tweezers load single atoms directly from the precooled cesium atom ensembles. The fluorescence of the loaded single atoms is collected by the same objective, separated from the trapping beam by a dichroic beam splitter cube, and imaged on an EMCCD camera eventually. Figure 1(d) shows an average picture of the single atoms trapped by the tweezer arrays.

Figure 2(a) gives the typical histogram of the fluorescence from one of the tweezers recorded by the EMCCD camera. The bimodal structure of the count distribution indicates that each time only one atom is loaded into one tweezer, and the loading probability is around 50%. The average lifetime for the trapped individual atom is measured around 3.1(1) s [as shown in Fig. 2(b)] when the tweezer overlaps with the intracavity lattice. The lifetime is limited by the heating due to the variance of the overlap between the optical tweezer and the intracavity lattice. Figure 2(c) shows the atom number distribution in all 11 optical tweezers. From the single atom loading probability (50%) we expect that the average atom number for all the 11 tweezers is around 5.5. However, we only get 3.6 from Fig. 2(c). The reason is that several tweezers on the edge are not exactly overlapped with the atomic ensemble in the measurement. If all the tweezers overlap well with the atomic ensemble, the average atom number could reach the prospected result.

The challenge of the experiment is to control the position of every atom to reach the maximum and steady coupling to the cavity. In order to get this condition, the position of each tweezer should be not only overlapping exactly with the antinode of the cavity standing-wave mode in the Z direction but also in the center of the mode profile in both X and Y directions. However, since the size of the optical tweezer is much bigger than the structure of the standing wave, it is impossible to confine the atom around the small region of the antinode by
FIG. 2. The loading of single atoms into the tweezer arrays. (a) Typical histogram of the electron counts of the fluorescence from the optic tweezer with No. 6 in Fig.1(d) on the EMCCD camera for 500 trials of atom loading. The blue line is the fitting with bimodal Gaussian function. (b) Atom retention versus the atom holding time. The exponential fitting gives a characteristic atom lifetime of 3.1(1) s. (c) The probability of the number of single atoms loaded into all 11 optical tweezers. The probabilities are counted for 500 trials of atom loading, which gives the average atom number of about 3.6.

the optical tweezer alone. With the aid of the blue-detuned lattices induced by the 820.9-nm locking laser the problem can be resolved.

When the blue lattice is taken into account, the atom trapped in the tweezer will be pushed to the node of the lattice. Thus, the maximum and steady coupling can be achieved as long as the tweezer is placed at spot where the node of the lattice and the antinode of the 852-nm mode coincide in space [as shown in the inset of Fig. 1(c)]. The overlap between the nodes of the lattice and the antinode of the 852-nm mode repeats every 11.07 µm in the cavity. Between the two neighbored exact-overlapping spots, the node of the lattice will gradually displace from the anti-node of 852-nm mode and totally mismatch in the middle, where the atom uncouples to the cavity mode. The solid line in Fig. 3(b) presents the theoretical prediction of the coupling strength of the atom when it is trapped in the different site of lattice along the Z direction.

To achieve the optimal condition, only one tweezer is switched on by driving the AOD with a single tone RF signal around 75 MHz for the initial optimization. The position of the trap in the Z direction can be scanned either by a motorized stage or the RF driving frequency to the AOD. Here it is scanned step by step by the motorized stage. On every scanned spatial point, a single atom is loaded into the tweezer and the atom-cavity coupling strength is checked by measuring the vacuum Rabi splitting spectrum. One of the typical spectra is shown as the red data point in Fig. 3(a). The coupling strength Ω can be obtained by fitting the data with the theoretical transmitting spectrum [49]

\[
T = \frac{\kappa^2 (\gamma^2 + \Delta_{pa}^2)}{(\Omega^2 - \Delta_{pa}^2 + \gamma \kappa)^2 + (\kappa \Delta_{pa} + \gamma \Delta_{ca} - \gamma \kappa)^2},
\]

where \(\Delta_{ca} (\Delta_{pa})\) is the frequency detuning between cavity (probe) and atom. \(\Omega\) is the coupling strength which equals to \(g\) for single atom. \(\Delta_{ca}\) can also be determined by the fitting. The relative coupling strength \(\Omega/\Omega_{\text{max}}\), where \(\Omega_{\text{max}}\) is the maximum in one scan trial, versus the position on Z axis is shown as the red points in Fig. 2(b), which agrees well with the theoretical prediction from the overlap between the blue lattice and 852-nm cavity mode. Thus, the optimum position for maximum coupling of one tweezer in the Z direction can be obtained.

Then, all the 11 tweezer arrays are switched on with the center RF frequency fixed as 75 MHz. The distance between the neighbored tweezers is set as 11.07 µm to match the overlapping pattern between the intracavity lattice and the 852-nm mode by setting the spacing of the multi-tone RF frequency as 1.50 MHz. Therefore, all the loaded atoms should be maximally coupled to the 852-nm cavity mode in the Z direction. To check this, the positions of all the 11 tweezers are scanned by the motorized stage along with the loaded atoms. The vacuum Rabi splitting is measured in the meantime, and the coupling strength is extracted with same procedures as the single tweezer case. One of the typical spectra is shown as blue data points in Fig. 3(a). The dependence of relative coupling strength \(\Omega/\Omega_{\text{max}}\) [blue points in Fig. 3(b)] on positions again agrees well with the prediction. The coupling strength of multiple atoms goes up and down at same pace, which means all the atoms couple to the cavity maximally along the Z direction.

After the Z-positions of the atomic arrays have been optimized on the maximum coupling spots, the positions in the X and Y directions are also scanned with all the eleven tweezers on. The measured coupling coefficient versus X and Y are displayed in Fig. 3(c), where the results follow well with the Gaussian mode profile. The fittings of the results by Gaussian function give the mode waist in the X and Y directions as 48.0(2.8) and 45.7(1.7) µm, respectively, which are in good agreement with one calculated from the geometry of the F-P cavity. Therefore, by setting the positions in the X and Y directions to the maximum coupling spots we can eventually optimize and realize the strong coupling between deterministic atom arrays and the F-P cavity.
In principle, our cavity QED system can realize the strongly coupling between the F-P cavity and atoms with deterministic number smaller than 11. Here, we demonstrate the coupling between the cavity and atom arrays with atom number from 1 to 8. The measured vacuum Rabi spectra on the transmission and the images of atom arrays are depicted in Fig. 4. The atom number is exactly determined by the image on EMCCD and the coupling strength $\Omega$ is extracted by fitting with Gaussian functions give the mode waist of 48.0(2.8) and 45.7(1.7) $\mu$m along with X and Y axis, respectively. The light shifts of atom in different tweezers are uneven due to the small variance of the trap shapes and intensities. The $\Delta_{\text{ca}}$ extracted from the data fitting are within the range of 0.1–0.7 MHz for all the subfigures.

The single shot images of the trapped atoms are shown as the inset picture, which are used to precisely count the atom number. The experimental data (black circles) are fitted (red lines) by Eq. (1) to determine $\Omega_N$.

The variance of the two normal splitting peaks in Fig. 4 mainly comes from the uneven $\Delta_{\text{ca}}$ in different tweezers. Since we leave all the tweezers on with a shallow trap depth ($\sim 0.18$ mK) during the measurement, the light shifts of atom in different tweezers are uneven due to the small variance of the trap shapes and intensities. The $\Delta_{\text{ca}}$ extracted from the data fitting are within the range of 0.1–0.7 MHz for all the subfigures.

The extracted vacuum Rabi splitting $\Omega_N$ versus atom number $N$ are displayed in Fig. 5. The single-atom coupling strength $g$ can be deduced from $\Omega_N$ by $g = \Omega_N / \sqrt{N}$. We got eight values of $g$ corresponding to atom number from 1 to 8. The variance of $g$ is within ±4% of the average value $2\pi \times 2.37$ MHz. The single atom coupling strength can also be obtained by fitting the data with $g' = \Omega_N / \sqrt{N}$ (red solid line), which gives $g' = 2\pi \times 2.38(2)$ MHz, and it is almost the same as the averaged value.

The collective enhancement of light-matter interaction by using multiple atoms is a basic principle in quantum physics. The dependence of the collective enhancement on atom number has been proved by large number of atoms [32] and sin-


**FIG. 5. The dependence of the collective coupling strength on atom number.** The solid red line is the fitting with $\Omega_N = g'\sqrt{N}$, which gives single atom coupling strength of $g' = 2\pi \times 2.38(2)$ MHz. The black dashed line is the theoretical result for the collective enhancement relation $\Omega_N = g\sqrt{N}$ with the measured single atom coupling strength $g = 2\pi \times 2.37$ MHz.

...single qubits in superconducting circuits [53]. Here this fundamental relation can be tested by using deterministic atom numbers with discrimination of real single atom level in our cavity QED system. As displayed in Fig. 5, the theoretical collective enhancement relation $\Omega_N = g\sqrt{N}$ is shown as the black dashed line with the single atom coupling strength $g = 2\pi \times 2.37$ MHz. We see that the experiment agrees very well with the theory, which validates the principle of collective enhancement.

In summary, we have developed a new cavity QED system in which a well-controlled 1D atom arrays strongly couples to a miniature F-P cavity. The system is flexible to realize the strong coupling between the cavity and atoms with arbitrarily deterministic number within 11 atoms. We demonstrated the strong coupling between the cavity and atoms with deterministic number from 1 to 8, and the principle of collective enhancement of light-matter interaction with multiple atoms is experimentally tested and validated for the first time with single atoms. The system can be expanded to a larger size of 1D atom arrays by increasing the number of optical tweezers. It provides a versatile platform to study the light-matter interaction, quantum networks with node containing multiple atomic qubits [54], and many-body physics with the interaction mediated by photons [33–35]. Furthermore, by introducing the sorting method to produce defect-free atom arrays and the Rydberg interaction between the neighbored atoms, the system can be harnessed to study the quantum many-body physics with the interaction mediated by photons [33–35].

This work was supported by the National Key Research and Development Program of China (Grants Nos. 2021YFA1402002 and 2017YFA0304502), the National Natural Science Foundation of China (Grant Nos. U21A6006, U21A20433, 11974223, 11974225, 12104277, and 12104278), and the Fund for Shanxi 1331 Project Key Subjects Construction.

* These authors contributed equally to this work.
† gangli@sxu.edu.cn
‡ zhangpengfei@sxu.edu.cn
§ tczhang@sxu.edu.cn
[1] S. Dutra, “Cavity quantum electrodynamics,” John Wiley and Sons, Inc. (2005).
[2] J. M. Raimond, M. Brune, and S. Haroche, “Manipulating quantum entanglement with atoms and photons in a cavity,” Rev. Mod. Phys. 73, 565 (2001).
[3] S. Haroche, “Nobel lecture: Controlling photons in a box and exploring the quantum to classical boundary,” Rev. Mod. Phys. 85, 1083 (2013).
[4] A. Reiserer and G. Rempe, “Cavity-based quantum networks with single atoms and optical photons,” Rev. Mod. Phys. 87, 1379 (2015).
[5] A. Blais, A. L. Grimsmo, S. M. Girvin, and A. Wallraff, “Circuit quantum electrodynamics,” Rev. Mod. Phys. 93, 025005 (2021).
[6] H. Ritsch, P. Domokos, F. Brennecke, and T. Esslinger, “Cold atoms in cavity-generated dynamical optical potentials,” Rev. Mod. Phys. 85, 553 (2013).
[7] H. J. Kimble, “The quantum internet,” Nature 453, 1023 (2008).
[8] J. McKeever, A. Boca, A. D. Boozer, J. R. Buck, and H. J. Kimble, “Experimental realization of a one-atom laser in the regime of strong coupling,” Nature 425, 268 (2003).
[9] J. McKeever, A. Boca, A. D. Boozer, R. Miller, J. R. Buck, A. Kuzmich, and H. J. Kimble, “Deterministic generation of single photons from one atom trapped in a cavity,” Science 303, 1992 (2004).
[10] A. Kuhn, M. Hennrich, and G. Rempe, “Deterministic single-photon source for distributed quantum networking,” Phys. Rev. Lett. 89, 067901 (2002).
[11] O. Morin, M. Körber, S. Langenfeld, and G. Rempe, “Deterministic shaping and reshaping of single-photon temporal wave functions,” Phys. Rev. Lett. 113, 133602 (2019).
[12] K. M. Birnbaum, A. Boca, R. Miller, A. D. Boozer, T. E. Northup, and H. J. Kimble, “Photon blockade in an optical cavity with one trapped atom,” Nature 436, 87 (2005).
[13] S. Rosenblum, O. Bechler, I. Shomroni, Y. Lovsky, G. Guendelman, and B. Dayan, “Extraction of a single photon from an optical pulse,” Nat. Photonics 10, 19 (2016).
[14] C. Hamsen, K. N. Tolazzi, T. Wilk, and G. Rempe, “Two-photon blockade in an atom-driven cavity qed system,” Phys. Rev. Lett. 118, 133604 (2017).
[15] T. Wilk, S. C. Webster, A. Kuhn, and G. Rempe, “Single-atom single-photon quantum interface,” Science 317, 488 (2007).
[16] J. Schupp, V. Krcmarsky, V. Krutyanskij, M. Meraner, T. Northup, and B. Lanyon, “Interface between trapped-ion qubits and traveling photons with close-to-optimal efficiency,” PRX Quantum 2, 020331 (2021).
[17] A. Reiserer, N. Kalb, G. Rempe, and S. Ritter, “A quantum gate between a flying optical photon and a single trapped atom,” Nature 508, 237 (2014).
[18] B. Hacker, S. Welte, G. Rempe, and S. Ritter, “A photon photon quantum gate based on a single atom in an optical resonator,” Nature 536, 193 (2016).
“A passive photon-atom qubit swap operation,” Nat. Phys. 14, 996 (2018).

[20] S. Daiss, S. Langenfeld, S. Welte, E. Distante, P. Thomas, L. Hartung, O. Morin, and G. Rempe, “A quantum-logic gate between distant quantum-network modules,” Science 371, 614 (2020).

[21] J. Volz, R. Gehr, G. Dubois, J. Esteve, and J. Reichel, “Measurement of the internal state of a single atom without energy exchange,” Nature 475, 210 (2011).

[22] A. Reiserer, S. Ritter, and G. Rempe, “Nondestructive detection of an optical photon,” Science 342, 1349 (2013).

[23] L. M. Duan and H. J. Kimble, “Scalable photonic quantum computation through cavity-assisted interactions,” Phys. Rev. Lett. 92, 127902 (2004).

[24] D. Niemietz, P. Farrera, S. Langenfeld, and G. Rempe, “Nondestructive detection of photonic qubits,” Nature 591, 570 (2021).

[25] S. Welte, P. Thomas, L. Hartung, S. Daiss, S. Langenfeld, O. Morin, G. Rempe, and E. Distante, “A nondestructive bell-state measurement on two distant atomic qubits,” Nat. Photonics 15, 504 (2021).

[26] E. Distante, S. Daiss, S. Langenfeld, L. Hartung, P. Thomas, O. Morin, G. Rempe, and S. Welte, “Detecting an itinerant optical photon twice without destroying it,” Phys. Rev. Lett. 126, 253603 (2021).

[27] I. Shomroni, S. Rosenblum, Y. Lovsky, O. Bechler, G. Guendelman, and B. Dayan, “All-optical routing of single photons by a one-atom switch controlled by a single photon,” Science 345, 903 (2014).

[28] M. Scheucher, A. Hilico, E. Will, J. Volz, and A. Rauschenbeutel, “Quantum optical circulator controlled by a single chirally coupled atom,” Science 354, 1577 (2016).

[29] B. Dayan, A. Parkins, T. Aoki, E. P. Ostby, K. J. Vahala, and H. J. Kimble, “A photon turnstile dynamically regulated by one atom,” Science 319, 1062 (2008).

[30] A. Kubanek, A. Ourjoumtsev, I. Schuster, M. Koch, P. W. H. Pinkse, K. Murr, and G. Rempe, “Two-photon gateway in one-atom cavity quantum electrodynamics,” Phys. Rev. Lett. 101, 203602 (2008).

[31] T. Aoki, A. S. Parkins, D. J. Alton, C. A. Regal, B. Dayan, E. Ostby, K. J. Vahala, and H. J. Kimble, “Efficient routing of single photons by one atom and a microtoroidal cavity,” Phys. Rev. Lett. 102, 083601 (2009).

[32] S. Ritter, C. Nölleke, C. Hahn, A. Reiserer, A. Neuzner, M. Uphoff, M. Mücke, E. Figueroa, J. Bochmann, and G. Rempe, “An elementary quantum network of single atoms in optical cavities,” Nature 484, 195 (2012).

[33] E. J. Davis, G. Bentisen, L. Homeier, T. Li, and M. H. Schleier-Smith, “Photon-mediated spin-exchange dynamics of spin-1 atoms,” Phys. Rev. Lett. 122, 010405 (2019).

[34] J. Muniz, D. Barberena, R. J. Lewis-Swan, D. J. Young, J. R. K. Cline, A. M. Rey, and J. K. Thompson, “Exploring dynamical phase transitions with cold atoms in an optical cavity,” Nature 580, 602 (2020).

[35] A. Perival, E. S. Cooper, P. Kunkel, J. F. Wienand, E. J. Davis, and M. Schleier-Smith, “Programmable interactions and emergent geometry in an array of atom clouds,” Nature 600, 630 (2021).

[36] M. Saffman, T. G. Walker, and K. Mølmer, “Quantum information with Rydberg atoms,” Rev. Mod. Phys. 82, 2313 (2010).

[37] S. Ebadi, T. T. Wang, H. Levine, A. Keesling, 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, “Quantum phases of matter on a 256-atom programmable quantum simulator,” Nature 595, 227 (2021).

[38] P. Scholl, M. Schuler, H. J. Williams, A. A. Eberharder, D. Barredo, K. N. Schymik, V. Lienhard, L. P. Henry, T. C. Lang, T. Lahaye, A. M. Läuchli, and A. Browaeys, “Quantum simulation of 2d antiferromagnets with hundreds of rydberg atoms,” Nature 595, 233 (2021).

[39] 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, “High-fidelity entanglement and detection of alkaline-earth rydberg atoms,” Nat. Phys. 16, 857 (2020).

[40] T. M. Graham, Y. Song, J. A. Scott, C. Poole, L. Phuttitan, K. Jooya, P. Eichler, X. Jiang, A. A. Marra, B. Grinkemeyer, M. Kwon, M. Ebert, J. Cherek, M. Lichtman, M. Gillette, J. P. Gilbert, D. N. Bowman, T. Ballance, C. Campbell, E. D. Dahl, O. Crawford, N. Blunt, B. R. T. W. Noel, and M. Saffman, “Multi-qubit entanglement and algorithms on a neutral-atom quantum computer,” Nature 604, 457 (2022).

[41] D. Bluvstein, H. Levine, G. Semeghini, T. T. Wang, S. Ebadi, M. Kalinowski, A. Keesling, N. Maskara, H. Pichler, M. Greiner, V. Vuletić, and M. D. Lukin, “A quantum processor based on coherent transport of entangled atom arrays,” Nature 604, 451 (2022).

[42] T. Dordević, P. Samutpraphoot, P. L. Ocola, H. Bernien, B. Grinkemeyer, I. Dimitrova, V. Vuletić, and M. D. Lukin, “Entanglement transport and a nanophotonic interface for atoms in optical tweezers,” Science 373, 1511 (2021).

[43] B. Casabone, A. Slute, K. Friebe, B. Brandstätter, K. Schüppert, R. Blatt, and T. E. Northup, “Heralded entanglement of two ions in an optical cavity,” Phys. Rev. Lett. 111, 100505 (2013).

[44] S. Welte, B. Hacker, S. Daiss, S. Ritter, and G. Rempe, “Cavity carving of atomic bell states,” Phys. Rev. Lett. 118, 210503 (2017).

[45] R. Reimann, W. Alt, T. Kampschulte, T. Macha, L. Ratschbacher, N. Thau, S. Yoon, and D. Meschede, “Cavity-modified collective rayleigh scattering of two atoms,” Phys. Rev. Lett. 114, 023601 (2015).

[46] E. Deist, J. A. Gerber, Y.-H. Lu, J. Zeiher, and D. M. Stamper-Kurn, “Superresolution microscopy of optical fields using tweezer-trapped single atoms,” Phys. Rev. Lett. 128, 083201 (2022).

[47] E. Deist, Y. H. Lu, J. Ho, M. K. Pasha, J. Zeiher, Z. Yan, and D. M. Stamper-Kurn, “Fast non-destructive cavity readout of single atoms within a coherent atom array,” arXiv:220514138 (2022).

[48] S. Begley, M. Vogt, G. K. Gulati, H. Takahashi, and M. Keller, “Optimized multi-ion cavity coupling,” Phys. Rev. Lett. 116, 223001 (2016).

[49] See Supplemental Material at [URL will be inserted by publisher], for the details of the theory of the vacuum Rabi spectra of multi-atom cavity QED, the double MOT system, the scheme of the cavity locking, analysis of the consistency of the optical tweezers, and the experimental sequences.

[50] S. Li, G. Li, W. Wu, Q. Fan, P. Yang, P. Zhang, and T. Zhang, “High-numerical-aperture and long-working-distance objective for single-atom experiments,” Rev. Sci. Instrum. 91, 043104 (2020).

[51] N. Schlosser, G. Reymond, and P. Grangier, “Collisional blockade in microscopic optical dipole traps,” Phys. Rev. Lett. 89, 023005 (2002).

[52] Y. O. Dudin, L. Li, F. Bariani, and A. Kuzmich, “Observation of coherent many-body rabi oscillations,” Nat. Phys. 8, 790 (2012).

[53] Z. Wang, H. Li, W. Feng, X. Song, C. Song, W. Liu, Q. Guo, X. Zhang, H. Dong, D. Zheng, H. Wang, and D.-W. Wang, “Controllable switching between superradiant and subradiant states in
a 10-qubit superconducting circuit,” Phys. Rev. Lett. 124, 013601 (2020).
[54] A. A. Kaufman, “Photons and qubits get a better connection,” Science 373, 1436 (2021).
[55] X. F. Zhang, Q. Sun, Y. C. Wen, W. M. Liu, S. Eggert, and A. C. Ji, “Rydberg polaritons in a cavity: A superradiant solid,” Phys. Rev. Lett. 110, 090402 (2013).
SUPPLEMENTARY MATERIAL
for “Realization of strong coupling between deterministic atom arrays and a high finesse miniature optical cavity”

The supplementary material presents the theory of the vacuum Rabi spectra of multi-atom cavity QED, the double MOT system, the scheme of the cavity locking, analysis of the consistency of the optical tweezers, and the experimental sequences.

1. THEORY OF THE VACUUM RABI SPECTRA OF MULTI-ATOM CAVITY QED

Considering a dissipated cavity QED system and using a near-resonance coherent laser to excite cavity mode with a frequency of $\omega_p$, the total Hamiltonian of the multi-atom cavity QED system can be expressed as [1]:

$$H_{total} = H_{TC} + H_P.$$  \hfill (S1)

The first term $H_{TC}$ represent Tavis-Cummings Hamiltonian for a system of multiple atoms interacting with a single mode cavity

$$H_{TC} = \hbar \omega_c a^+ a + \hbar \sum_{k=1}^{N} \omega_k \left( \sigma_k^z + \frac{1}{2} \right) + \hbar \sum_{k=1}^{N} g_k (a^+ \sigma_k^- + \sigma_k^+ a),$$  \hfill (S2)

and the second term is the pump term with the form

$$H_P = \hbar \eta \left( a e^{i\omega pt} - a^+ e^{-i\omega pt} \right).$$  \hfill (S3)

Here, $\omega_c$ is the resonance frequency of the cavity mode. $\omega_k$ is the transition frequency of the $k^{th}$ atom between the excited energy level $|e\rangle$ and the ground energy level $|g\rangle$. $a^+$ and $a$ are the creation and annihilation operators of the photon. The atomic spin operator of $\sigma_k^+ = |e\rangle \langle g|$ and $\sigma_k^- = |g\rangle \langle e|$ are ladder operators of the $k^{th}$ atom. $\sigma_k^z = \frac{1}{2} (|e\rangle \langle e| - |g\rangle \langle g|)$ is the Pauli $z$-operator of the $k^{th}$ atom and $\sigma_k^+ a + \sigma_k^- a^+$ represents the interaction of the cavity mode and the $k^{th}$ atom. $\eta$ denotes the strength of the probe beam. $g_k$ is the coupling strength of the $k^{th}$ atom to the cavity mode and $N$ is the number of effective atoms coupled to the cavity.

We change to the reference frame associated with the probe beam and rewrite the Hamiltonians in terms of collective spin operators as

$$H_{TC} = \hbar \Delta_{pc} a^+ a + \hbar \Delta_{pa} F + \hbar \sqrt{N} g \left( J^+ a + a^+ J^- \right)$$  \hfill (S4)

and

$$H_P = \hbar \eta \left( a - a^+ \right),$$  \hfill (S5)

where

$$F = \sum_{k=1}^{N} \sigma_k^z$$  \hfill (S6)

and

$$J^\pm = \sum_{k=1}^{N} \frac{g_k}{\sqrt{\sum_{k=1}^{N} |g_k|^2}} \sigma_k^\pm = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} \sigma_k^\pm$$  \hfill (S7)

are the atomic collective spin operators. The detuning between probe laser and atom is $\Delta_{pa} = \omega_p - \omega_a$ and the detuning between probe laser and cavity is $\Delta_{pc} = \omega_p - \omega_c$. The $\omega_k$ and $g_k$ for different atoms are assumed the same, respectively, as $\omega_k = \omega$ and $g_k = g$.

The dynamics of the coupled system can be theoretically obtained by solving the Lindblad master equation

$$\dot{\rho} = -\frac{i}{\hbar} [H_{TC} + H_P, \rho] + \mathcal{L} [\rho].$$  \hfill (S8)
\[ \mathcal{L}[\rho] = \kappa \left( 2a \rho a^\dagger - a^\dagger a \rho - \rho a a^\dagger \right) + \gamma \sum_{k=1}^{N} \left( 2\sigma_k^- \rho \sigma_k^+ - \sigma_k^+ \rho \sigma_k^- - \rho \sigma_k^+ \sigma_k^- \right). \]  

(S9)

The time evolution of the expectation value of any operators \( \hat{\sigma} \) can be calculated by [2, 3]

\[ \langle \dot{\hat{\sigma}} \rangle = Tr \{ \hat{\sigma} \dot{\rho} \} \]  

(S10)

Then, the time evolution \( \langle a \rangle \), \( \langle J^- \rangle \) and \( \langle J^z \rangle \) can be derived as

\[ \langle \dot{a} \rangle = i (\Delta_{pc} + i\kappa) \langle a \rangle - ig\sqrt{N} \langle J^- \rangle - i\eta, \]  

(S11)

\[ \langle J^- \rangle = i (\Delta_{pa} + i\eta) \langle J^- \rangle + \frac{i2g}{\sqrt{N}} \langle J^a \rangle \]  

(S12)

and

\[ \langle \dot{J}^z \rangle = -2g \left( \frac{N}{2} + \langle J^z \rangle \right) + 2i\sqrt{N}g (a^+ J^- - J^+ a), \]  

(S13)

respectively.

When the probe laser is very weak, it can be assumed that all the atoms are staying on the ground state. Thus, the system evolves within the Hilbert space spanned by states \( \{|gg\ldots gg,0\}, |gg\ldots gg,1\} \), \( \frac{1}{\sqrt{N}} (|eg\ldots gg,0\rangle + |ge\ldots gg,0\rangle + \cdots + |gg\ldots ge,0\rangle) \). We then have \( \langle J^z \rangle = -\frac{N}{2} \) and \( \langle J^a \rangle = -\frac{N}{2} \langle a \rangle \). Therefore, Eqs (S11) and (S12) can be simplified to

\[ \langle \dot{a} \rangle = i (\Delta_{pc} + i\kappa) \langle a \rangle - i\Omega_{eff} \langle J^- \rangle - i\eta \]  

(S14)

and

\[ \langle \dot{J}^- \rangle = i (\Delta_{pa} + i\eta) \langle J^- \rangle - i\Omega_{eff} \langle a \rangle, \]  

(S15)

where \( \Omega_{eff} = \sqrt{N}g \). The steady state of the system can be obtained by setting \( \langle a \rangle = 0, \langle J^- \rangle = 0 \). Then the transmission spectrum of the coupled system is:

\[ T = \frac{\kappa^2 \left( \gamma^2 + \Delta_{pa}^2 \right)}{\left( \Omega_{eff}^2 - \Delta_{pa}^2 + \Delta_{ca} \Delta_{pa} + \gamma \kappa \right)^2 + \left( \kappa \Delta_{pa} + \gamma \Delta_{pa} - \gamma \Delta_{ca} \right)^2}, \]  

(S16)

in which \( \Delta_{ca} = \omega_c - \omega_a \) is the detuning between cavity and atom.

II. THE DOUBLE MOT SYSTEM

The whole vacuum system is shown in Fig. S6, which includes two-stage Magnetically Optical Trap (MOT) system. The first stage is a two-dimensional (2D) MOT, and the second stage is a three-dimensional MOT. The two parts are separated by a differential tube with an inner diameter of 1 mm and length of 10 mm. The light beams of the 2D-MOT are shaped as ellipse with size about 6 mm\( \times \)12 mm. The optical power of each cooling beam and the repumping beam is 20 mW and 2 mW, respectively. The cesium atoms from the dispenser are precooled by 2D-MOT and pushed to the 3D-MOT with the aid of a pushing beam. The 3D-MOT resides in the center of the miniature Fabry-Perot (F-P) cavity with length of 1.27 mm and captures the atoms from the 2D-MOT. To accommodate the 3D MOT within the cavity, the MOT beams are also converted to ellipse with size about 0.8 mm \( \times \) 1.6 mm. The angle of the transverse beams for the MOT is also squeezed to 20\(^\circ\). The power of each cooling and repumping beam is 400 \( \mu \)W and 60 \( \mu \)W, respectively. Eventually, we get about 10\(^5\) atoms in the 3D MOT. The MOT coils and the optical holders are fixed together on single mount, thus the position of the 3D MOT can be moved freely and finely by a 3D positioner.
III. THE SCHEME OF THE CAVITY LOCKING

The miniature F-P cavity is locked by an 821-nm locking laser which is resonant to the F-P cavity. The frequency is blue detuned to the 852-nm mode by 13.46 THz, which is 114 free spectra ranges of the cavity away from 852-nm. The frequency of the locking laser is stabilized to a transfer cavity (TC) which has been locked to cesium transition lines via the 852 nm probe laser. The scheme of the locking system is shown Fig. S7.

The probe laser, which is an external cavity diode laser, is firstly locked to the TC with linewidth of 1 MHz by Pound-Drever-Hall (PDH) method [4] to suppress the linewidth. The long-time frequency drift is then suppressed by locking the laser and TC system to the cesium transition line. The transition line is obtained by polarization spectroscopy. After these two steps a narrow linewidth and stable probe laser and a frequency-stabilized TC cavity is obtained. The frequency of the 821-nm locking laser is then stabilized to the TC by another PDH locking loop. The locking laser is finally feed to the miniature F-P cavity via a fiber phase modulator and locked to one of the sidebands to maintain the frequency of 852-nm mode. By changing the frequency of the sideband, the resonance frequency of the miniature cavity can be tuned freely. The standing-wave field of the locking laser inside of the miniature cavity also forms a blue detuned lattice for the intracavity cesium atoms control.

IV. ANALYSIS OF THE CONSISTENCY OF THE OPTICAL TWEEZERS

As we presented in the main text, the optical tweezer array is generated by focus 11 optical beam arrays at 1018 nm from diffraction of an acousto-optic deflector (AOD) with a homemade objective. The consistency of the trap size and trap depth depends on the performance of the AOD diffraction. However, the intermodulation between different RF tones and nonlinearity of the diffraction will cause the inhomogeneity. The inhomogeneity can be suppressed by adjusting the phases and amplitude of the different RF tones [5]. In order to characterize the consistency of the optical tweezers, the intensity and size of the tweezers are measured and the results are shown in Fig. S8. Figure S8a shows the distribution of intensity for dipole trap array and the fluctuation is within 2.2%. The measurement of the beam waist is obtained by capturing the enlarging image of the final dipole trap array by an imaging system with magnification of 8.27 and fitting its gray scale map with Gaussian function. The uniformity of beam waist is 3.6%, as shown in Fig. S8b. The magnification is delicately calibrated by a resolution test target (R1DS1N, Thorlabs). The distance between the adjacent traps is also accurately calibrated in the experiment to be 11.06(2) µm when the RF frequency interval is 1.50 MHz, as shown in Fig. S8c.
The time sequence of experimental process is shown in Fig. S9. At the beginning of the experiment, the cold atomic beam precooled by a 2D-MOT is pushed through the differential tube with a diameter of 1 mm to the center of the cavity. Then a small cold atomic cloud is captured in the center of the microcavity by the 3D-MOT. At the end of the MOT loading period, the tweezer array is turned on and overlaps with the atomic cloud spatially for 400 ms to load the atoms. During the loading phase, the barrier of intracavity lattice is setting as about 3 µK. Afterward, the 3D-MOT laser beams and the anti-Helmholtz magnetic field are turned off to allow the background atoms to dissipate freely for 50 ms. An extra 2-ms light assisted collision phase associated with 455-nm light (6S1/2|F = 4 ⟷ 7P3/2|F = 5) is followed to ensure that single atom is loaded. Two polarization gradient cooling (PGC) phases with red detuning 30 MHz and 50 MHz, respectively, are applied for cooling down the atomic temperature to about 15 µk. After a cesium atom is successfully loaded, the depth of tweezer is decreased to 0.18 mK and the barrier of intracavity lattice is increased to 0.27 mK. The atom is then initialized into the state of 6S1/2|F = 4, mF = 4⟩ by optical pumping process. Finally, a weak probe light with σ+ polarization is applied to scan the vacuum Rabi splitting spectrum of the atom-cavity system.

The number of atoms coupling with the cavity is determined by fluorescence imaging of the single-atom array, which is excited by weak MOT beams. During this process the depth of the red detuned dipole trap is increased to about 0.45 mK, and the depth of the standing wave trap is decreased to 3 µK. In order to enhance the atomic radiation rate along the direction of the cavity side, the miniature cavity is tuned with −10-MHz detuned to the atomic transition by quickly dragging the frequency of the cavity locking laser before the atom imaging.

* These authors contributed equally to this work.
† gangli@sxu.edu.cn
‡ zhangpengfei@sxu.edu.cn
§ tczhang@sxu.edu.cn

[1] S. Dutra, “Cavity quantum electrodynamics,” John Wiley and Sons, Inc. (2005).
[2] A. Dombi, A. Vukics, and P. Domokos, “Optical bistability in strong-coupling cavity qed with a few atoms,” J. Phys. B: At. Mol. Opt. Phys. 46, 224010 (2013).
[3] H. Carmichael, “An open systems approach to quantum optics,” Springer-Verlag (1991).
[4] E. D. Black, “An introduction to Pound-Drever-Hall laser frequency stabilization,” Am. J. Phys. 69, 79 (2001).
[5] M. Endres, H. Bernien, A. Keesling, H. Levine, E. Anschuetz, K. A., C. Senko, V. Vuletic, M. Greiner, and M. Lukin, “Supplementary information: atom-by-atom assembly of defect-free one-dimensional cold atom arrays,” Science 354, 1024 (2016).
FIG. S8. **The characterization of dipole trap array.** a is the intensity distribution of the dipole trap array and b is the beam waist distribution. The error bar in b is the fitting error. c is the image of the final dipole trap array magnified by 8.27 times. The size of each pixel is 3.45μm.

FIG. S9. **Time sequence of experimental process.**