

Plane-selective manipulations of nuclear spin qubits in a three-dimensional optical tweezer array

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One of the central challenges for a practical fault-tolerant quantum computer is scalability. A three-dimensional structure of optical tweezer arrays offers the potential for scaling up neutral atom processors. However, coherent *local* operations, essential for quantum error correction, have yet to be explored for this platform. Here, we demonstrate plane-by-plane initialization of nuclear spin qubits of ^{171}Yb atoms in a three-dimensional atom array and plane-dependent coherent temporal evolution of qubits, as well as plane-selective qubit manipulation by exploiting the plane-selective excitation of the atoms from the $^1S_0$ to the $^3P_2$ state. This plane-selective manipulation technique paves the way for quantum computing and quantum simulation in three-dimensional multilayer architectures.

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Neutral atoms in optical tweezer arrays, which allow individual atom control and Rydberg-mediated entanglement generation, have the potential to make a significant contribution to quantum science and technology [1–3]. Recent developments in this platform have enabled a wide range of research in precision measurement, quantum simulation, and quantum computing [4–10]. The scalability of the system is one of the central issues in quantum science for, e.g., the study of quantum many-body physics, quantum-projection-noise-limited precision measurement, and the implementation of fault-tolerant quantum computation (FTQC) [11–15]. The neutral atom system offers scalability advantages of minimal couplings between multiple qubits and inherent uniformity of qubit quality. This enables efficient controllability for a large number of atoms, facilitating the development of state-of-the-art programmable large-scale platforms [16–26].

Extending the atom tweezer array platform from a commonly adopted two-dimensional (2D) array configuration to a 3D structure is expected to enhance the scalability in quantum processing. The pioneering works that saw the successful generation of 3D optical tweezer arrays [27–34] demonstrated important protocols of 3D atom-by-atom assembly [32–36] and flexible controls of Rydberg interaction in 3D directions [33,37–39]. However, the ability to perform plane-selective coherent manipulations, which is one important ingredient in a 3D atom tweezer array quantum processor, remains to be explored. This will provide full 3D controllability when combined with the already established local qubit manipulations and measurements for a 2D array system, such as direct local

manipulations by individual Raman beams [40], local off-resonant addressing beams combined with globally irradiated resonant beams [41–56], and more recent movement-induced shifts using shuttling techniques [57,58].

The 3D structure is also beneficial for implementing efficient quantum error-correcting codes such as 3D topological codes [59–62], which have favorable features such as the implementation of transversal non-Clifford logical gates [40,61,63–65] and single-shot decoding [66–70]. To realize these codes, one promising approach entails shuttling techniques in a real two-dimensional plane [40,71]. Another promising approach is to trap qubits in a real 3D space. In the latter approach, 3D connectivity is achievable by nearest-neighbor interactions, which could generate the entanglement within an order of microseconds, as recently demonstrated in experiments of high-fidelity two-qubit gate operations [72–76]. Moreover, the realization of 3D structure and 3D controllability could be a milestone in the development of four-dimensional codes [59,77], which possess self-correcting properties with coherence times that scale indefinitely with system size [78,79]. This could be accomplished by incorporating an extra dimension, such as a synthetic dimension [80] or a moving tweezer array [40,71], into the existing 3D system. Note that an optical lattice system is one of the 3D quantum systems with high controllability in which local controls have been reported, including coherent manipulations with individual atom addressing beams [44,45] and plane-selective state preparation and imaging using magnetic and electric field gradients [81–87].

In this work, we report the demonstration of plane-selective manipulations of single ytterbium atoms in a holographically generated $4 \times 4 \times 3$ cuboid atom tweezer array. We successfully implement local operations in the 3D atom tweezer array using global controls applied to the entire atomic array. Specifically, by working with the ground-state nuclear spin qubit of ^{171}Yb defined as $|0\rangle = |^1S_0, m_F = +1/2\rangle$ and $|1\rangle = |^1S_0, m_F = -1/2\rangle$ as well as the magnetic field

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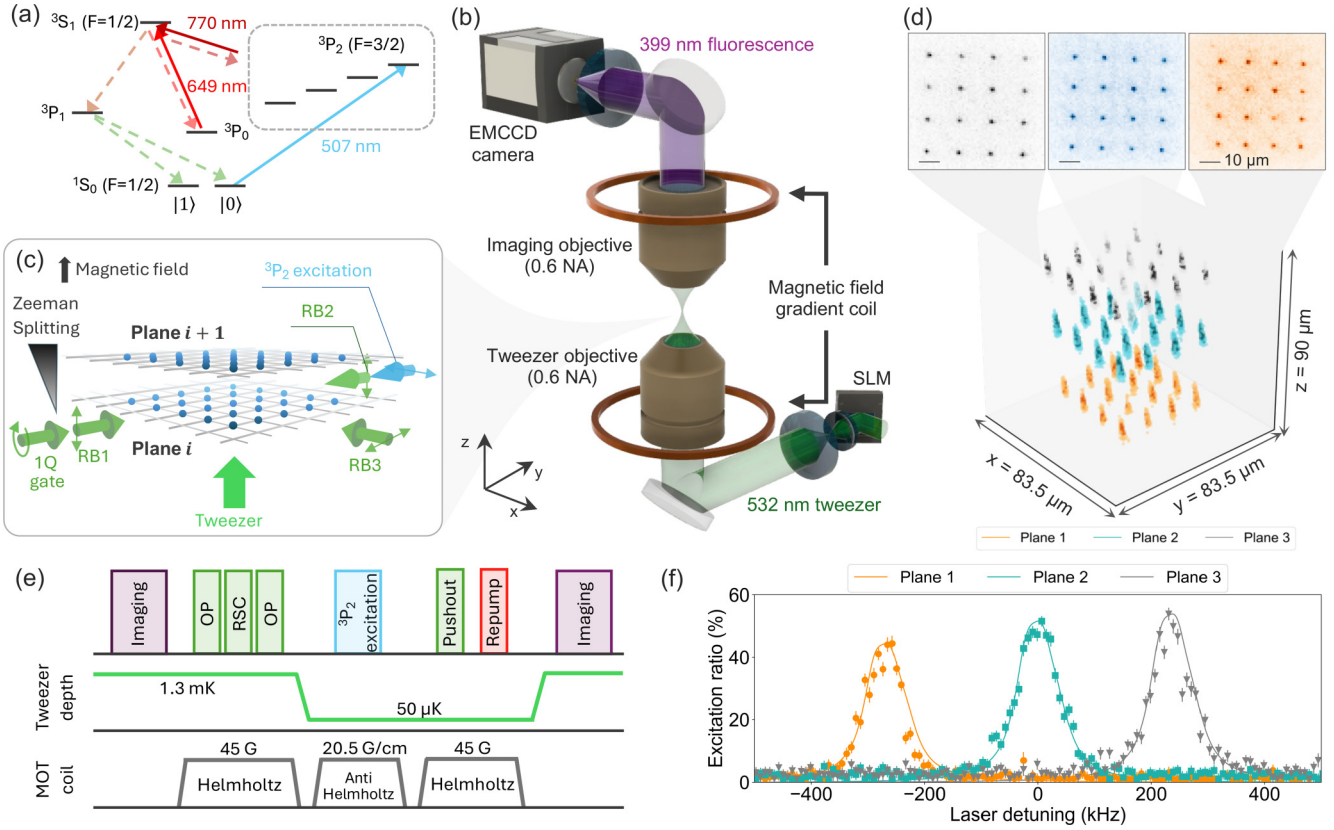


FIG. 1. Overview of the 3D ytterbium optical tweezer array. (a) Relevant energy diagram of ^{171}Yb atom showing the transitions used to plane-selective controls. (b) Tweezer beam path and imaging system. 3D optical tweezer arrays are generated by combining a quadratic and grating phase hologram displayed on a SLM. The imaging objective is dynamically moved in the z -direction using a piezostage to capture the fluorescence of atoms located in different planes. (c) Schematic illustration of the control beams geometry. All control beams are irradiated globally over the entire array. We use $^1S_0 - ^3P_1$ transition lasers (556 nm) for Raman sideband cooling with three Raman beams (RBs) and a single-qubit gate for nuclear spin qubits in the ground state. For plane-selective operation, we apply a 507 nm beam to shelve the atoms in the target plane in the presence of a magnetic field gradient to create a different $^3P_2$ resonance for a different plane. (d) Reconstructed average fluorescence image of single ^{171}Yb atoms in a $4 \times 4 \times 3$ cuboid array, where the site spacing setpoint is $(x, y, z) = (10, 10, 30) \mu\text{m}$. For clarity, the fluorescence image for each plane was colored after the data acquisition. (e) Experimental sequence for plane-selective $^3P_2$ excitation. OP represents optical pumping. (f) Excitation spectrum of the 3D array. Solid lines show the simulated spectrum taking into account a residual differential light shift with inhomogeneity of the trap depth and magnetic field fluctuations. The error bars represent the standard error of the mean.

sensitive metastable state $^3P_2$ under a magnetic field gradient [Fig. 1(a)], we simultaneously realize both coherent manipulation of the qubit and the plane-selectivity in the initialization and shelving. The demonstrated plane or space-selective excitation to the metastable state under a magnetic field gradient represents a scalable approach, as the addressing spectrum depends solely on the distance between atoms and is independent of the number of qubits. Our ability to perform plane-selective manipulations is highlighted by the successful demonstration of local coherent qubit rotations $R_X(\theta)$ on specific planes, while on the other selected plane the operations of $R_X(\theta = 0) = I$ are performed. These results underscore the usefulness of an optical-metastable-ground (omg) architecture of ^{171}Yb atoms [57,88] in 3D tweezer arrays, leading to the feasibility of the midcircuit operations [89–91], a significant step towards FTQC in 3D tweezer arrays.

3D Optical Tweezer Array. Our 3D optical tweezer array system utilizes a spatial light modulator (SLM) to generate

holograms that include Fresnel lens phases to shift tweezer positions in the z -direction [Fig. 1(b)] [32,33]. While our experimental setup is basically the same as that in our previous work [92], we have incorporated a piezostage (P-528.ZCD, PI) to dynamically move the imaging objective lens, enabling the imaging of the atoms on the individual planes [Figs. 1(b) and 1(c)]. This imaging system can typically focus on each plane within approximately 20 ms, which is sufficiently fast for the experiments described in this paper. Each plane is then imaged with a 60 ms exposure time. The $4 \times 4 \times 3$ cuboid array structure is successfully imaged in this way, as shown in Fig. 1(d). All control laser beams are irradiated globally across the entire array [Fig. 1(c)]. The magnetic field gradients required for local manipulation experiments are generated by the anti-Helmholtz coil, which also serves as the coil used for magneto-optical trapping (MOT). The details of the experiments, such as the Fresnel lens phase implementation, Raman sideband cooling (RSC), and tweezer

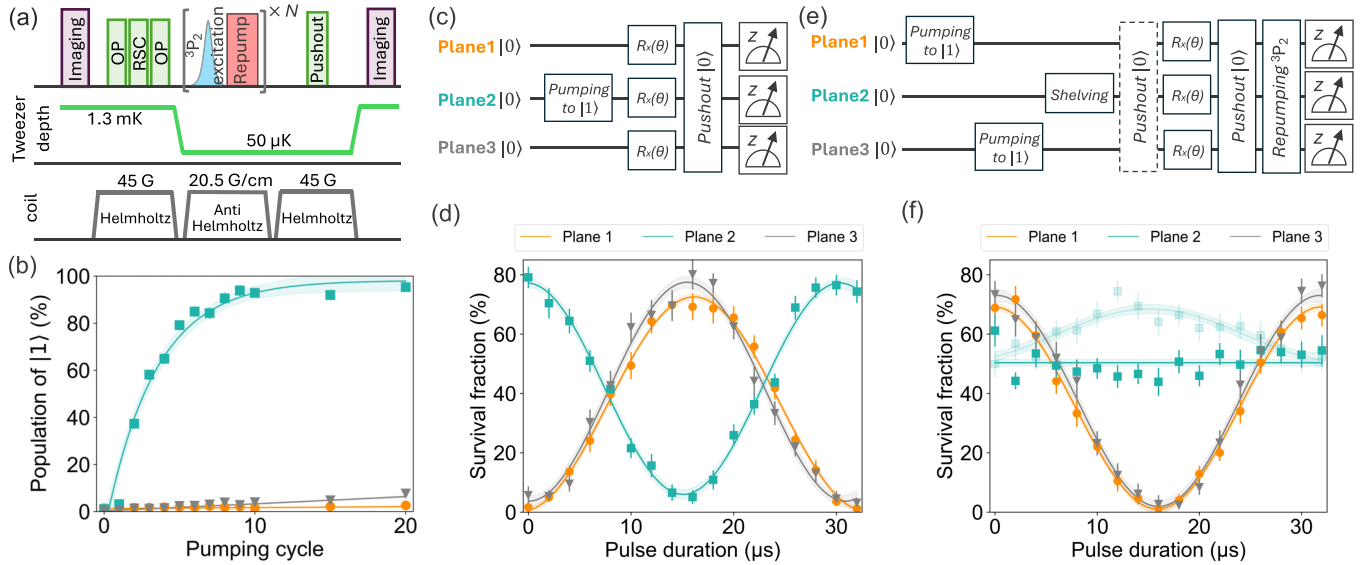


FIG. 2. Plane-selective controls. (a) Experimental sequence for plane-selective initialization. After first imaging, we perform optical pumping to $|0\rangle$ and then RSC in 1.3 mK deep tweezer, followed by irradiating the N pulse trains of the $^3P_2$ excitation and repumping beams under a magnetic field gradient. (b) Population of $|1\rangle$ after several pumping cycles. The atoms in Plane 2 are selectively pumped to $|1\rangle$ with a fidelity of 95.3(2.0)% (survival probability corrected). (c)–(f) Plane-selective manipulations. (c),(e) Quantum circuit representations of experimental sequences for the plane-selective Rabi oscillation after (c) selective initialization and (e) selective shelving. (d),(f) Rabi oscillation between $|0\rangle$ and $|1\rangle$ states. (d) We observe the coherent Rabi oscillations of the qubits in Planes 1 and 3, while the qubits in Plane 2 exhibit the bit-flipped behavior after running the (c) circuit. (f) The qubits in Planes 1 and 3 show coherent Rabi oscillations starting from the initially prepared $|1\rangle$ state, after running the (e) circuit. In contrast to (d), the flat line of Plane 2 (blue) indicates noncoupling to the ground-state manipulation, while the limited shelving fidelity results in a residual oscillation (light blue). The circuit for obtaining blue (light blue) data includes (does not include) the pushout pulse before the nuclear spin control [dashed box in (e)]. In (b), (d), and (f), error bars and shaded regions represent the standard error of the mean and 1σ -confidence intervals of the fit, respectively.

homogenization, are described in Sec. S1 of the Supplemental Material (SM) [98].

Plane-selective Control. The most essential ingredient for plane-selective control of the 3D array in this work is the spectral addressing using the magnetic-field-sensitive metastable $^3P_2$ state under a magnetic field gradient. The hyperfine manifold $F = 3/2$ in the $^3P_2$ state has a Zeeman splitting of 2.5 MHz/G $\times m_F$, resulting in frequency shifts of 7.7 kHz/ μ m for $m_F = 3/2$ when applying a magnetic field gradient of 20.5 G/cm in our system.

As is shown in Fig. 1(e), when performing the $^3P_2$ excitation, we decrease the tweezer depth to 50 μ K to reduce the line-broadening effect due to differential light shift (DLS) between the $^1S_0$ and $^3P_2$ states. This allows for well-resolved plane-selective excitation to the $^3P_2$ state at the current tweezer array spacing, as shown in Fig. 1(f). The observed spectral separation of 7.76(2) kHz/ μ m is close to the designed value of 7.7 kHz/ μ m. The solid line in Fig. 1(f) represents the simulated spectrum. To simulate the spectrum of the carrier component, we analyze the systematic effects arising from the residual DLS and the Zeeman shift of the $|^3P_2, F = 3/2, m_F = 3/2\rangle$ state. The dominant source of noise in our system is the ripple in the current of the power supply for the magnetic field gradient coil (relative standard deviation of 0.3%). Based on our analysis, the simulated carrier spectrum linewidth is 53.1 kHz [full width at half-maximum (FWHM)]. This broad linewidth obscures the sideband structure of ± 28 kHz, resulting in a total linewidth

of 77 kHz, which reproduces the experimental data well, as shown in Fig. 1(f).

Regarding the $^3P_2$ excitation fidelity, with a square pulse irradiation for 5 ms, we observe the excitation fidelity of 44.9(1.8)%, 53.2(1.7)%, and 51.4(1.8)% for Planes 1, 2, and 3, respectively. The limited excitation fraction is attributed to shot-to-shot detuning errors arising from the broad spectral linewidth. To improve the excitation fidelity in subsequent plane-selective control experiments, a hyperbolic secant (HS1) pulse is employed [93–96] with a typical frequency scan range of ± 30 kHz. As a result, the excitation ratios for Planes 1, 2, and 3 are improved to 77.7(1.7)%, 83.2(2.1)%, and 82.4(2.0)%, respectively. Further improvements of the fidelity can be achieved by reducing the current noise and by employing composite pulses [89,97].

The achieved plane-selectivity in the spectroscopy is utilized to demonstrate a plane-selective state initialization via the repumping process of the $^3P_2$ state [Fig. 1(a)]. The pulse sequence is shown in Fig. 2(a). First, all atoms in the array are initialized to the $|0\rangle$ state by optical pumping via the $|1\rangle \leftrightarrow |^3P_1, F = 3/2, m_F = 1/2\rangle$ transition. Subsequently, the atoms trapped in a particular plane are selectively excited to the $|^3P_2, F = 3/2, m_F = 3/2\rangle$ state. The repumping of the atoms in the $^3P_2$ state via the $^3S_1, F = 1/2$ state eventually results in a random spontaneous decay from the $^3P_1$ state to either $|0\rangle$ or $|1\rangle$ in the ground state. The result of successful plane-selective pumping is shown in Fig. 2(b). After 20 pumping cycles, the atoms on Plane 2 are initialized to $|1\rangle$ with a

fidelity of 95.3(2.0)% (survival probability corrected). The finite population of $|1\rangle$ in Planes 1 and 3 is due to the small but nonzero excitation probability to the $^3P_2$ state. This crosstalk could be suppressed by narrowing the excitation linewidth or increasing a magnetic field gradient. Note that, in the current setup, we change the magnetic field from a plane-selective pumping condition where a magnetic field gradient is applied, to a state-selective measurement condition using a pushout beam where a 45 G z -biased magnetic field is applied. This change can cause bit-flips if the magnetic field control is not sufficiently slow, leading to the remaining initialization error. Unlike experiments with alkali-metal atoms with large magnetic moments, adiabaticity in magnetic controls of nuclear spin qubits should be more careful. This error can be reduced by performing a state-selective readout, which does not require a strong bias magnetic field for the pushout process [89].

The demonstrated plane-selective initialization is then utilized to further perform plane-dependent coherent temporal evolution of qubits in a 3D tweezer array. As described in the quantum circuit of Fig. 2(c), we initialize the atoms in Plane 2 to $|1\rangle$ selectively, and then apply a nuclear spin control beam to the atoms globally in the direction of the horizontal plane [Fig. 1(c)]. After the circuit operation, we observe a Rabi oscillation in Plane 2 that is phase-shifted by π from other planes [Fig. 2(d)].

For the feasibility of midcircuit operations in 3D tweezer arrays, we demonstrate that the atoms in a particular plane can be protected from the ground-state nuclear spin manipulation by the $^3P_2$ shelving technique. The quantum circuit is illustrated in Fig. 2(e). To suppress the influence of the pushout beam [dashed box in Fig. 2(e)] prior to the nuclear spin control, Planes 1 and 3 are initialized to the $|1\rangle$ state with 10 pumping cycles at the beginning of the circuit. Subsequently, we shelve atoms in Plane 2 with the HS1 pulse, followed by pushing out the $|0\rangle$ state before applying the nuclear spin manipulation pulse to the entire array. Figure 2(f) shows the measurement results after this quantum circuit. While atoms in Planes 1 and 3 exhibit Rabi oscillations (orange and gray), shelved atoms in Plane 2 are independent of the pulse width (blue), indicating that the atoms in Plane 2 are selectively decoupled from the ground-state manipulation. The light blue data in Fig. 2(f) show the measurement result by a sequence without the pushout beam [dashed box in Fig. 2(e)], and a residual oscillation of the ground-state nuclear spin qubit is observed. To quantify the residual oscillation, we fit the data by a function $P_s P_{3P_2} P_r + P_s (1 - P_{3P_2}) (1 + \sin(\Omega t + \phi)) / 2$ with the $^3P_2$ excitation fidelity P_{3P_2} , the Rabi frequency Ω , and phase ϕ as free parameters. Here, the survival probability P_s is determined from the maximum value of the data 74.4(3.5)%, and the repumping fidelity P_r is 98.2(4.2)%, which is obtained as described in Sec. S3 in the SM [98]. From the fitting, the $^3P_2$ excitation fraction is determined to be 72.0(2.5)%, which is lower than 83.2(2.1)% obtained in the plane-selective excitation experiment. We attribute this decreased fidelity to the instability of the excitation laser frequency after switching the laser frequency to the resonance of each plane, where the $^3P_2$ excitation laser frequency is currently tuned by switching the locking frequency to an ultra-low-expansion (ULE) cavity used for the laser frequency

stabilization. This can be solved by switching the frequency using a conventional double-path acousto-optic modulator.

Discussion. A shorter interplane distance is desirable for achieving sufficiently strong Rydberg interactions in a 3D structure. In our current experiment, the spacing smaller than 30 μm does not provide sufficient spectral resolution to address different layers. This limitation arises from the broadened linewidth of the $|0\rangle \leftrightarrow |^3P_2, F = 3/2, m_F = 3/2\rangle$ transition of ^{171}Yb atoms due to the magnetic field fluctuation induced by the gradient coils. The effect of the coil current noise is actually quantitatively evaluated from the difference in the measurement of the excitation linewidth of 2.6(4) kHz (FWHM) for $|^1S_0, m_F = 1/2\rangle \leftrightarrow |^3P_2, F = 3/2, m_F = 3/2\rangle$ in 2D arrays without the application of a magnetic field gradient. We expect that a straightforward solution of working with a larger magnetic field gradient of 300 G/cm as well as suppressing the magnetic field fluctuation by a factor of 50 will enable the experiment to be carried out at a shorter interplane distance (see Sec. S3 in the SM [98] for details).

A key challenge for quantum computation in 3D tweezer arrays is a plane-selective midcircuit measurement. While the $^1S_0 \leftrightarrow ^1P_1$ probe light illuminates the entire array during imaging, only the atomic fluorescence from a single plane is focused onto the camera. Thus, atoms in other planes that are out of focus experience excess scattering. To address this, one promising strategy is to shelve all the atoms that are in nontarget planes into a metastable state, isolating them from the lasers for imaging and cooling. In our current experiment, an optical tweezer at a 532 nm wavelength and 1.3 mK depth is utilized during imaging, causing a severe decrease in survival probability of atoms in the $^3P_2$ state, due to the atomic loss by the ionization of the $^3P_2$ state (see Sec. S3 in the SM [98]). Improving the cooling performance during imaging, such as by cooling atoms in tweezers at a magic condition [89,90], will allow us to image the atoms in shallower depth of the tweezers [92], facilitating plane-selective midcircuit measurements with sufficiently high imaging fidelity.

Summary. We have successfully developed a programmable 3D atom tweezer array of ^{171}Yb with the capability of plane-selective manipulation. We demonstrate plane-by-plane initialization of the nuclear spin qubits and plane-dependent coherent temporal evolution of qubits, as well as plane-selective qubit manipulation by exploiting the plane-selective excitation of the atoms from the $^1S_0$ to the $^3P_2$ state under a magnetic field gradient. While plane-selective imaging is widely used in optical lattice platforms, our work represents the first realization of plane-selective initialization and plane-selective manipulations in an optical tweezer array within a magnetic field gradient. Furthermore, our plane-selective manipulation technique utilizing the metastable $^3P_2$ manifolds enables local control of even magnetically insensitive qubits, showing a sensitivity of 7.7 kHz/ μm in a 20.5 G/cm gradient. This contrasts with the inherent sensitivity of 1.5 Hz/ μm for ^{171}Yb nuclear spin qubits in the same magnetic field gradient magnitude.

In addition to quantum computing, a system of 3D atom tweezer arrays with plane-selective coherent controllability also opens up new horizons for quantum simulations. The pyrochlore lattice, a natural platform for quantum spin ice,

can be realized by trapping atoms in arbitrary geometries and tuning the parameters of the transverse Ising-like Hamiltonian [33,99,100]. Additionally, a recent proposal suggests utilizing interspecies (interisotopes) interactions in a 3D tweezer system to generate the ground state of the X-cube model, highlighting the potential of 3D dual-species (dual-isotope) arrays for observing Fracton order [101].

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Data Availability. The data supporting this study's findings are available within the article.

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