Arrays of individually controlled ions suitable for two-dimensional quantum simulations

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A precisely controlled quantum system may reveal a fundamental understanding of another, less accessible system of interest. A universal quantum computer is currently out of reach, but an analogue quantum simulator that makes relevant observables, interactions and states of a quantum model accessible could permit insight into complex dynamics. Several platforms have been suggested and proof-of-principle experiments have been conducted. Here, we operate two-dimensional arrays of three trapped ions in individually controlled harmonic wells forming equilateral triangles with side lengths 40 and 80 μm. In our approach, which is scalable to arbitrary two-dimensional lattices, we demonstrate individual control of the electronic and motional degrees of freedom, preparation of a fiducial initial state with ion motion close to the ground state, as well as a tuning of couplings between ions within experimental sequences. Our work paves the way towards a quantum simulator of two-dimensional systems designed at will.
Richard Feynman was one of the first to recognize that quantum systems of sufficient complexity cannot be simulated on a conventional computer. He proposed to use a quantum mechanical system instead. A universal quantum computer would be suitable, but practical implementations are a decade away at best. However, universality is not required to simulate specific quantum models. It is possible to custom-build an analogue quantum simulator (AQS) that allows for preparation of fiducial input states, faithful implementation of the model-specific dynamics and for access to the crucial observables. Simulations on such AQSs could impact a vast variety of research fields, that is, physics, chemistry and biology, when studying dynamics that is out of reach for numerical simulation on conventional computers.

Many experimental platforms have been suggested to implement AQSs. Different experimental systems provide certain advantages in addressing different physics. Results that are not conventionally tractable may be validated by comparing results of different AQSs simulating the same problem. Over the last two decades, many promising proof-of-principle demonstrations have been made using photons, superconductors, atoms and trapped atomic ions. Trapped ions in particular have seen steady progress from demonstrations with one or two ions to arrays containing more than 100 ions. Ions are well suited to further propel the research since they provide long-range interaction and individual, fast controllability with high precision.

Two-dimensional trap-arrays may offer advantages over trapping in a common potential, because they are naturally suited to implement tuneable couplings in more than one spatial dimension. Such couplings are, in most cases, at the heart of problems that are currently intractable by conventional numerics. Our approach is based on surface-electrode structures originally developed for moving ion qubits through miniaturized and interconnected, linear traps as proposed in refs 25,26. This approach is pursued successfully as a scalable architecture for quantum computer, see, for example, ref. 27. For AQSs, it is beneficial to have the trapped ion ensembles coupled all-to-all so they evolve as a whole. This is enabled by our array architecture with full control over each ion. Individual control allows us to maintain all advantages of single trapped ions while scaling the array in size and dimension.

Optimized surface electrode geometries can be found for any periodic wallpaper group as well as quasi-periodic arrangements, as, for example, Penrose-tilings. A first step, trapping of ions in two-dimensional arrays of surface traps, has been proposed and demonstrated. Boosting the strength of interaction to a level comparable to current decoherence rates requires inter-ion distances \( d \) of a few tens of micrometres. Such distances have been realized in complementary work, where two ions have been trapped in individually controlled sites of a linear surface-electrode trap at \( d \) between 30 and 40 µm. The exchange of a single quantum of motion, as well as entangling spin–spin interactions have been demonstrated in this system. The increase in coupling strength was achieved with a reduction of the ion-surface separation to order \( d \) and the concomitant increase in motional heating due to electrical noise. Recently, methods for reducing this heating by more than two orders of magnitude with either surface treatments or cold electrode surfaces have been devised.

Here, we demonstrate the precise tuning of all relevant parameters of a two-dimensional array of three ions trapped in individually controlled harmonic wells on the vertices of equilateral triangles with side lengths 80 and 40 µm. In the latter, Coulomb coupling rates approach current rates of decoherence. Dynamic control permits to reconfigure Coulomb and laser couplings at will within single experiments. We initialize fiducial quantum states by optical pumping, Doppler and resolved sideband cooling to near the motional ground state. Our results demonstrate important prerequisites for experimental quantum simulations of engineered two-dimensional systems.

Results

Trap arrays and control potentials. Our surface ion trap chip is fabricated in similar manner to that described in ref. 40 and consists of two equilateral triangular trap arrays with side length of \( \approx 40 \) and \( \approx 80 \) µm, respectively (Fig. 1a,b), both with a distance of \( \approx 40 \) µm between the ions and the nearest electrode surface. The shapes of radio-frequency (RF) electrodes of the arrays are optimized by a linear-programming algorithm that yields electrode shapes with low fragmentation, and requires only a single RF-voltage source for operation. To design different and even non-periodic arrays for dedicated trap distances, we can apply the same algorithm to yield globally optimal electrode shapes. Resulting electrode shapes may look significantly different, but will have comparable complexity, spatial extent and the same number of control electrodes per trap site. Therefore, we expect that different arrays will not require different fabrication techniques (Methods). The two arrays are spaced by \( \approx 5 \) mm on the chip, and only one of them is operated at a given time. Although we achieve similar results in both arrays, the following discussion is focussed on the 80 µm array.

Three-dimensional confinement of \( ^{25}\text{Mg}^+ \) ions is provided by a potential \( \phi_{RF} \) oscillating at \( \Omega_{RF} \) from a single RF electrode driven at \( \Omega_{RF}/(2\pi) = 48.3 \) MHz with an approximate peak voltage \( U_{RF} = 20 \) V. Setting the origin of the coordinate system at the centre of the array and in the surface plane of the chip, the RF potential features three distinct trap sites at \( T_0 \approx (-46,0,37) \) µm, \( T_1 \approx (23, -23, \sqrt{3}, 37) \) µm, and \( T_2 \approx (23, 23, 37) \) µm. Owing to the electrode symmetry under rotations of \( \pm 2\pi/3 \) around the \( z \)-axis, it is often sufficient to consider \( T_0 \) only, as all our findings apply to \( T_1 \) and \( T_2 \) after an appropriate rotation. Further, the RF potential exhibits another trap site at \( (0,0,81) \) µm (above the centre of the array); this 'ancillary' trap is used for loading as well as for re-capturing ions that escaped from the other trap sites. We approximate the RF confinement at position \( r \) by a pseudopotential \( \phi_{ps}(r) = Q/(4m\Omega_{RF})E_{RF}(r) \), cp. ref. 41, where \( Q \) denotes the charge and \( m \) the mass of the ion, and \( E_{RF}(r) \) is the field amplitude produced by the electrode. Calculations of trapping potentials are based on ref. 42 and utilizing the software package. Equipotential lines of \( \phi_{ps} \) are shown in Fig. 1c–e.

Near \( T_0 \) we can approximate \( \phi_{ps} \) up to second order and diagonalize the local curvature matrix to find normal modes of motion described by their mode vectors \( u_i, u_j, u_k \), which coincide (for the pure pseudopotential) with \( x, y, z \); we use \( u_i \) with \( j = [1,2,3] \), and throughout our manuscript to describe the mode vectors of a single ion near \( T_0 \). We find corresponding potential curvatures at \( \kappa_{ps,1} \approx 3.0 \times 10^{18} \text{ V m}^{-2}, \kappa_{ps,2} \approx 5.9 \times 10^{17} \text{ V m}^{-2} \), and \( \kappa_{ps,3} \approx 9.2 \times 10^{17} \text{ V m}^{-2} \), whereas mode frequencies can be inferred from these curvatures as \( \omega_i \approx \sqrt{(Q/m)\kappa_{ps,j}} \), with \( j = [1,2,3] \); \( \omega_1/(2\pi) \approx 5.4 \text{ MHz}, \omega_2/(2\pi) \approx 2.4 \text{ MHz}, \text{ and } \omega_3/(2\pi) \approx 3.0 \text{ MHz} \). Further, the Mathieu parameters \( q_i = 2(Q/m)U_{RF}/\Omega_{RF}^2\kappa_{ps,j}(r) \), where \( \kappa_{ps,j}(r) \) denotes the curvature of \( \phi_{ps} \) along direction \( i = [x,y,z] \), are at \( T_0 \): \( q_1 \approx 0.32, q_2 \approx 0.14, \text{ and } q_3 \approx 0.18 \).

To gain individual control of the trapping potential at each site, it is required to independently tune local potentials near \( T_0 \), \( T_1 \) and \( T_2 \) (Methods), that is, to make use of designed local electric
fields and curvatures. To achieve this, we apply sets of control voltages to 30 designated control electrodes (see Fig. 1 for details). In the following, a control voltage set is described by a unit vector $v \equiv (v_1, \ldots, v_{30})$, with corresponding dimensionless entries $\hat{v}_c$ with $n = \{1, \ldots, 30\}$, and result in a dimensionless control potential

$$\hat{\phi}_c = \sum_{n=1}^{30} \hat{v}_c \phi_n(r),$$

where $\phi_n(r)$ is the potential resulting when applying 1 V to the $n$-th electrode following a basis function method. We scale $\phi_c$ by varying a control voltage $U_c$ and yielding a combined trapping potential

$$\phi(r) = \phi_0(r) + U_c \hat{\phi}_c(r).$$

To design a specific $\hat{\phi}_c$, we consider the second order Taylor expansion for a point $r_0$ and small displacements $\Delta r$:

$$\hat{\phi}_c(r_0 + \Delta r) \simeq \hat{\phi}_c(r_0) + \langle \partial_k T \hat{\phi}_c(r) \rangle_{r=r_0} \cdot \Delta r + \frac{1}{2} \langle \partial_k \partial_l T \hat{\phi}_c(r) \rangle_{r=r_0} \Delta r,$$

where $\langle \partial_k T \hat{\phi}_c(r) \rangle_{r=r_0}$ is the local gradient and $\langle \partial_k \partial_l T \hat{\phi}_c(r) \rangle_{r=r_0}$ is the traceless and symmetric matrix with indices $k$ and $l = \{x, y, z\}$ that describes the local curvature; square brackets denote vectors/matrices, $\partial$ partial derivatives and the superscript $T$ the transpose of a vector. We constrain local gradients in their three degrees of freedom (DoF) and local curvatures in their five DoF at $T_0$, $T_1$ and $T_2$, and solve the corresponding system of 24 linear equations to yield $\hat{v}_c$. In principle, it would be sufficient to use 24 control electrodes, however, we consider all electrodes and use the extra DoF to minimize the modulus of the voltages we need to apply for a given effect.

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**Figure 1** | Surface-electrode ion trap featuring three individual traps. (a) Scanning electron microscope (SEM) image of a cleaved copy of our chip; white scale bar, 20 μm. It provides a cross-sectional view vertically through the trap chip (bottom half of image) and a top view of the horizontal, planar trap electrode surface (top half of image) of the 40 μm array. Buried electrode interconnects as well as the overhangs of electrodes that shield trapped ions from insulating surfaces are exposed in this view. A loading channel, vertically traversing the chip, collimates a neutral atom beam from an oven on the backside of the chip. (b) SEM top-view of the 80 μm array, dark lines indicate gaps between individual electrodes and dashed circles highlight the three trap sites at $T_0$, $T_1$ and $T_2$ that lie 40 μm above the electrode plane (white scale bar, 80 μm); corresponding loading holes appear as dark spots. A vertical plane connecting $T_0$ and $T_2$ is shown as a dotted line and labelled with $\delta_0$. The single RF electrode extends beyond the image area and encloses 30 control electrodes grouped into four islands depicted in the central part of the image, enabling the control of individual trap sites. Laser beams (coloured arrows) are parallel to the chip surface and wave vectors $k_{ps}$ of preparation and detection beams are parallel to the magnetic quantization field $B_0$ (white arrow). (c-e) The pseudopotential $\phi_{ps}(x,y,z)$ of the 80 μm array in different planes is shown, trap sites marked by red dots, motional mode vectors $u_j$ with $j = \{1,2,3\}$ at $T_0$ are represented by white arrows, and saddle points are illustrated by white crosses. In e, the heights of $T_0$, $T_2$ and the ancillary trap are indicated by red and blue lines, respectively.
In particular, we distinguish two categories of control potentials, denoted by $\hat{e}$ and $\kappa$, respectively: the first category is designed to provide finite gradients and zero curvatures at $T_0$, with zero gradients and curvatures at $T_1$ and $T_2$; for example, $\phi_e = \kappa$ provides a gradient along $\hat{x}$ at $T_0$. Control potentials of the second category are designed to provide zero gradients and only curvatures at $T_0$, whereas we require related gradients and curvatures to be zero at $T_1$ and $T_2$. For example, we design $\phi_e = \kappa_{\text{tune}}$, with the following non-zero constraints $\partial_{\hat{x}} \partial_{\hat{k}} \kappa_{\text{tune}}(\hat{r}) |_{r=T_0} = - \partial_{\hat{z}} \partial_{\hat{k}} \kappa_{\text{tune}}(\hat{r}) |_{r=T_0} = 0.937 \times 10^{-3}$ m$^{-2}$ with corresponding $U_e = U_{\text{tune}}$. Linear combination of multiple control potentials enable us, for example, to locally compensate stray potentials up to second order, to independently control mode frequencies and orientations at each trap site, and, when implementing time-dependent control potentials, to apply directed and phase-controlled mode-frequency modulations or mode excitations.

Initially, we calibrate three (static) control potentials $\hat{e}_{\text{1}}, \hat{e}_{\text{2}}$ and $\hat{e}_{\text{3}}$ to compensate local stray fields$^{50}$ with a single ion near $T_0$, whereas we observe negligible effects on the local potentials near $T_1$ and $T_2$ (Methods). Rotated versions of these control potentials are used to compensate local stray fields near $T_1$ and $T_2$. Near each site, we achieve residual stray field amplitudes $\lesssim 3$ $\text{V m}^{-1}$ in the $xy$ plane and $\lesssim 900$ $\text{V m}^{-1}$ along $z$, currently limited by our methods for detection of micromotion.

With the stray fields approximately compensated, we characterize the trap near $T_0$ with a single ion (Methods). We find mode frequencies of $\omega_{\text{1}}(2\pi) \approx 5.3$ MHz, $\omega_{\text{2}}(2\pi) \approx 2.6$ MHz and $\omega_{\text{3}}(2\pi) \approx 4.1$ MHz with frequency drifts of about $2 \pi \times 0.07$ kHz ($60 $s$^{-1}$); mode frequencies and orientations are altered by local stray curvatures on our chip, in particular, $u_z$ and $u_y$ are rotated in the $xz$ plane, while $u_x$ remains predominantly aligned along $y$. We obtain heating rates for the modes $u_z$ of $0.9(1)$ quanta ms$^{-1}$, $u_y$ of $2.2(1)$ quanta ms$^{-1}$ and $u_x$ of $4.0(3)$ quanta ms$^{-1}$.

Control of mode configurations at individual trap sites. The ability to control mode frequencies and orientations at each site with minimal effect on local trapping potentials at neighbouring sites is essential for the static and dynamical tuning of inter-ion Coulomb couplings. We experimentally demonstrate individual mode-frequency control using $\kappa_{\text{tune}}$. To this end we measure local mode frequencies with a single ion near $T_0$ or $T_2$ (Methods). Tuning of about $2 \pi \times 80$ kHz of $u_x$ near $T_0$ is shown in Fig. 2 as blue data points, accompanied by residual changes of about $2 \pi \times 1$ kHz in the corresponding mode frequency near the neighbouring site $T_2$, depicted by red data points. To infer local curvature patterns, we describe the expected detuning $\Delta \omega_2$ due to $\kappa_{\text{tune}}$ at $T_0$ (analogously at $T_2$) by

$$\Delta \omega_2 = \sqrt{\omega_2^2 + U_{\text{tune}} \left( \frac{Q}{m} \partial_{\hat{z}} \partial_{\hat{k}} \kappa_{\text{tune}}(\hat{r}) \right) |_{r=T_0} - \omega_2},$$

where we neglect a small misalignment of $u_y$ from $y$. The prediction of equation (4) is shown as a blue/dashed line in Fig. 2. The blue/solid line results from a fit with a function of the form of equation (4) to the data yielding a control curvature of $1.164(3) \times 10^{-7}$ m$^{-2}$. The inset magnifies the residual change in frequency near $T_2$. Here, a fit (red/solid line) reveals a curvature of $0.012(2) \times 10^{-7}$ m$^{-2}$. Residual ion displacements of $\Delta z = -2.95(3)$ $\mu$m from $T_0$ and $\Delta z = -2.9(4)$ $\mu$m from $T_2$, respectively, suffice to explain deviations between experimentally determined and designed curvature values and are below our current limit of precision locating the ions in that direction. In future experiments, curvature measurements may be used to further reduce stray fields.

We also implement a dynamic $U_{\text{tune}}(t)$, to adiabatically tune $\omega_2$ near $T_0$ within single experiments: we prepare our initial state by Doppler cooling, followed by resolved sideband cooling of mode $u_2$ to an average occupation number $\langle n_2 \rangle \approx 0.1$ and optical pumping to $|\uparrow\rangle$. In a next step, we apply a first adiabatic ramp from $U_{\text{tune},A} = 0 \text{ V}$ to $U_{\text{tune},B}$ between 0 and 2.3 $\text{V}$ (corresponding to a measured frequency difference $\Delta \omega_2(2\pi) \approx 430$ kHz) within $t_{\text{ramp}} = 7.5$ to 120 $\mu$s and, subsequently, couple $|\uparrow\rangle$ and $|\downarrow\rangle$ to mode $u_2$ with pulses of BR + RR tuned to sideband transitions that either add or subtract a single quantum of motion. If the ion is in the motional ground state, no quantum can be subtracted and the spin state remains unchanged when applying the motion subtracting sideband pulse. The motion-adding sideband can always be driven, and comparing the spin-flip probability of the two sidebands allows us to determine the average occupation of the dynamically tuned mode$^{48}$. We find that the average occupation numbers are independent of the duration of the ramp and equal to those obtained by remaining in a static
potential for \( t_{\text{samp}} \), that is, the motion is unaffected by the dynamic tuning.

We rotate mode orientations near \( T_0 \) in the xy plane with a control-potential \( \kappa_{\text{rot}} \), while setting additional constraints to keep gradients and curvatures of the local trapping potential constant at \( T_1 \) and \( T_2 \) (Methods). We determine the rotation of mode orientations from electron-multiplying charge-coupled device images of two ions near \( T_0 \) that align along \( u_z \) (axis of weakest confinement). Simultaneously, we trap one or two ions near \( T_1 \) and \( T_2 \) to monitor residual changes in ion positions and mode orientations (and frequencies) because of unwanted local gradients and curvatures of \( \kappa_{\text{rot}} \). We take 14 images for five different \( \kappa_{\text{rot}} \) values, while constantly Doppler cooling all ions and exciting fluorescence. Figure 3a shows two images for \( U_{\text{rot}} = 0 \) V (left) and \( U_{\text{rot}} = 2.45 \) V (right). Schematics of control electrodes are overlaid to the images and coloured to indicate their bias voltages \( U_{\text{rot}} \). Ion pairs align along \( u_z \), the lowest-frequency mode. The left image captures ion positions for \( U_{\text{rot}} = 0 \) V and, here, \( \omega_2/(2\pi) = 1.9(2) \) MHz near \( T_0 \). The right image illustrates the rotation effect for \( U_{\text{rot}} = 2.45 \) V: Mode \( u_z \) near \( T_0 \) with \( \omega_2/(2\pi) = 1.8(2) \) MHz is rotated by \( \varphi_{2,y} = 31(5) \)°, whereas ion positions near \( T_1 \) and \( T_2 \) remain unchanged; white circles indicate initial ion positions (for \( U_{\text{rot}} = 0 \)). (b) Mode \( u_y \) orientation in the \( xy \) plane for \( T_0 \) (blue dots) and \( T_1 \) (red squares), described by \( \varphi_{2,y} \) derived from a total of 14 images as a function of \( U_{\text{rot}} \); error bars denote our systematic uncertainty. The data are in good agreement with our predictions of the effect of \( \kappa_{\text{rot}} \) (solid lines).

A single ion is prepared in its motional ground state, the ratio of Rabi frequencies of carrier and sideband couplings is given by the Lamb-Dicke parameter, which is for \( u_1 \) and \( \Delta k_2 \):

\[ \eta_{1,x} = \Delta k_x \cdot u_1 \sqrt{\frac{\hbar}{2m_0 u_1}} = |\Delta k_x| \sqrt{\frac{\hbar}{2m_0 u_1}} \cos(\varphi_{1,x}), \]

where \( \varphi_{1,x} \) is the angle between \( u_1 \) and \( \Delta k_x \). The differences of carrier and sideband transition frequencies reveal the mode frequencies, whereas ratios of sideband and carrier Rabi-frequencies determine Lamb-Dicke parameters and allow for finding the orientation of modes.

We use a single ion near \( T_0 \) to determine the orientations and frequencies of two modes relative to \( \Delta k_2 \). We apply another control potential \( \kappa_{\text{rot}2} \), designed to rotate \( u_1 \) and \( u_y \) in the \( xz \) plane.
plane near T0, and implement carrier and sideband couplings to both modes with \( \Delta k \rangle \) after resolved sideband cooling and initializing \( [\dagger] \). In Fig. 4, the probability of \( [\dagger] \) is shown for different pulse durations of carrier couplings (top) and sideband couplings to mode \( \mathbf{u}_1 \) (middle) and \( \mathbf{u}_3 \) (bottom). Data points for \( U_{rot2} = -1.62 \) V are shown as blue rectangles and for \( -2.43 \) V as grey rectangles. We fit each data set to a theoretical model (blue and grey lines) to extract the angles \( \phi_{1x} \) and \( \phi_{1y} \) and distributions of Fock-state populations of each mode (shown as histograms): we find \( \phi_{1x} = 24.7(2)^\circ \) for \( U_{rot2} = -1.62 \) V and \( \phi_{1y} = 36.1(2)^\circ \) for \( U_{rot2} = -2.43 \) V, whereas average occupation numbers range between \( \pm 0.05 \) and \( \pm 0.6 \). Each data point is the average of 250 experiments and error bars (for some data smaller than symbols) denote the s.e.m. Residual variations of experimental parameters, for example, changes of stray potentials, can result in day-to-day variations of measurement outcomes that require recalibration to remain within our stated statistical uncertainties.

**Discussion**

We characterized two trap arrays that confine ions on the vertices of equilateral triangles with side lengths 80 and 40 \( \mu \)m. We developed systematic approaches to individually tune and calibrate control potentials in the vicinity of each trap site of the 80-\( \mu \)m array, by applying bias potentials to 30 control electrodes. With suitably designed control potentials, we demonstrated precise individual control of mode frequencies and orientations. By utilizing a multi-channel arbitrary waveform generator, we also dynamically changed control potentials within single experimental sequences without adverse effects on spin or motional states. Further, we devised a method to fully determine all mode orientations (and frequencies) based on the analysis of carrier and sideband couplings. Measured heating rates are currently comparable to the expected inter-ion Coulomb coupling rate of \( \Omega_{ex}/(2\pi) \approx 1 \) kHz for \( ^{25}\text{Mg}^+ \) ions in the 40-\( \mu \)m array at mode frequencies of \( \approx 2\pi \times 2 \) MHz (ref. 32). This coupling rate sets a fundamental time scale for effective spin–spin couplings. To observe coherent spin–spin couplings, ambient heating needs to be reduced. Decreases in heating rates of up to two orders of magnitude would leave \( \Omega_{ex} \) considerably higher than competing decoherence rates and allow for coherent implementation of fairly complex spin–spin couplings. Such heating rate reductions have been achieved in other surface traps by treatments of the electrodes, structure54–56 and/or cryogenic cooling of the electrodes. The couplings in question have been observed in one dimension in a cryogenic system.

Currently, we can compensate stray fields, set up normal mode frequencies and directions for all three ions and initialize them for a two-dimensional AQFS, that is, prepare a fiducial initial quantum state for ions at each trap site. A complete AQFS may use the sequence presented in Fig. 5. A dynamic ramp adiabatically transforms the system between two control sets, labelled as A and B, that realize specific mode frequencies and orientations at each site. Set A may serve to globally initialize spin-motional states of ions, potentially with more than one ion at each site, that could be the ground state of a simple initial Hamiltonian. At all sites, mode frequencies and orientations need to be suitable (bottom left of Fig. 5) to enable global resolved sideband cooling, ideally preparing ground states for all motional modes. A first ramp to set B combined with appropriate laser fields may be used to adiabatically or diabatically realize a different Hamiltonian, for example, by turning on complex spin–spin couplings. Mode frequencies and orientations are tuned such that the Coulomb interactions between ions can mediate effective spin–spin couplings, for example, all mode vectors \( \mathbf{u}_i \) are rotated to point to the centre of the triangle (bottom right of Fig. 5). During the application of such interactions, the ground state of the uncoupled system can evolve into the highly entangled ground state of a complex coupled system. In contrast, diabatic ramping to set B will quench the original ground state and the coupled system will evolve into an excited state that is not an eigenstate. After a final adiabatic or diabatic ramp back to set A, we can use global (or local) laser beams to read out the final spin states at each site.

In this way, our arrays may become an arbitrarily configurable and dynamically reprogrammable simulator for complex quantum dynamics. It may enable, for example, the observation of photon-assisted tunnelling, as required for experimental simulations of synthetic gauge fields52,53 or other interesting properties of finite quantum systems, such as thermalization, when including the motional DoF54. Concentrating on spin–spin interactions, the complex entangled ground states of spin frustration can be studied in the versatile testbed provided by arrays of individually trapped and controlled ions. Arrays with a larger number of trap sites could realize a level of complexity impossible to simulate on conventional computers.

**Methods**

**Design of arrays used in the experiments.** The design of arrays used in the experiments is based on the methods described in ref. 29. In particular, we use the Mathematica package for surface atom and ion traps43 to globally optimize the RF

**Figure 4 | Measuring mode orientations via laser couplings.** Probability of \( [\dagger] \) after applying carrier and sideband couplings via \( \Delta k \), with a single ion near T0. Mode orientations are set with static \( \kappa_{rot} \) (rotations in the \( xz \) plane) for \( U_{rot2} = 1.62 \) V (blue dots) and \( -2.43 \) V (grey squares). (a) Shows the carrier transitions, \( [\dagger, m, n_1] \leftrightarrow [\dagger, n_1, n_2] \), whereas \( b \) represents the \( u_1 \)-sideband transitions, \( [\dagger, m, n_1] \leftrightarrow [\dagger, n_1 + 1, n_2] \), and the \( u_3 \)-sideband transitions, \( [\dagger, m, n_3] \leftrightarrow [\dagger, n_3 + 1, n_1] \). From combined model fits to all transitions (for each \( \kappa_{rot} \)), we find angles \( \phi_{1x} = 24.7(2)^\circ \) for \( U_{rot2} = -1.62 \) V (blue lines) and \( 36.1(2)^\circ \) for \( U_{rot2} = -2.43 \) V (grey lines) of mode \( \mathbf{u}_1 \) relative to \( \Delta k \). Histograms in \( b \) display derived Fock-state populations with thermal average occupation numbers between \( \pm 0.05 \) and \( \pm 0.6 \). Each data point is the average of 250 experiments and error bars (for some data smaller than symbols) denote the s.e.m. Residual variations of experimental parameters, for example, changes of stray potentials, can result in day-to-day variations of measurement outcomes that require recalibration to remain within our stated statistical uncertainties.
electrode shape for maximal curvature with a given amplitude of the RF drive, whereas producing smooth continuous electrode shapes that require a single RF drive to operate the array. We specify the desired trap site positions as well as the ratio and orientation of normal-mode frequencies as a fixed input to the optimization algorithm for the pseudopotential, that is, we define that the high-frequency mode (for all three sites) lies within the xy plane and points towards the virtual centre of the array. Resulting electrode regions held to ground are subdivided into separate control electrodes that provide complete and independent control over the eight DoF at each site.

**Array scaling for future realizations.** To ensure that our approach can be scaled to more than three trapping sites, we compare designs of arrays containing different numbers of sites, $N_{\text{sites}}$, that are optimized by the algorithm described in ref. 29. Here, we assume a fixed ratio of $h/d = 1/2$, where $h$ denotes the distance of the sites to the nearest electrode surface and $d$ is the inter-site distance. Further, we specify for all arrays that the high-frequency mode is aligned orthogonally to the $xy$ plane at each site, in contrast to our demonstrated arrays (see Fig. 1 for details). This unique mode configuration permits a fair comparison of geometries with increasing $N_{\text{sites}}$. To illustrate the optimal electrode shapes, we present four examples of triangular arrays with $N_{\text{sites}} = \{3, 6, 18, 69\}$ in Fig. 6a–d. To enable the same level of individual control as demonstrated for both of our three-site arrays, we would have to subdivide the optimized ground electrodes into $\geq 8 \times N_{\text{sites}}$ control electrodes. We find that the inner areas converge to fairly regular electrode shapes for larger $N_{\text{sites}}$, whereas electrodes closer to the border are deformed to compensate for edge effects (see Fig. 6d for details). However, the spatial extent and complexity of all electrodes remains comparable to the arrays used in our experiments and, thus, fabrication of these larger arrays can be accomplished by scaling the applied techniques (see below).

To quantify the geometric strength of individual trap sites independently of $m$, $U_{\text{RF}}$, $\Omega_{\text{RF}}$, and $h$, we consider the dimensionless curvature $k$ of the pseudopotential that we normalize to the highest possible curvature for a single site$^{29}$. We show optimized $k$ for arrays with $N_{\text{sites}}$ between 1 and 102, as well as, the value for $N_{\text{sites}} = \infty$ in Fig. 6e; a fully controlled array with $N_{\text{sites}} = 102$ should be sufficient to study quantum many-body dynamics that are virtually impossible to simulate on a conventional computer. We find that $k$ for $N_{\text{sites}} = 102$ is reduced by about a factor of two compared with $k \geq 0.87$ for $N_{\text{sites}} = 3$, whereas $k \geq 0.07$ for $N_{\text{sites}} = \infty$; see ref. 29 for a detailed discussion of infinite arrays. The decrease in trap curvature can be compensated in experiments by adjusting $U_{\text{RF}}$ and $\Omega_{\text{RF}}$, correspondingly, or by reducing $h$. Further, we estimate that trapping depths remain on the same order of magnitude for increasing $N_{\text{sites}}$ compared with our demonstrated arrays (cp. Fig. 1d). For an infinite array it has been shown that depths of a few mV are achievable$^{30}$. Note, that in surface-electrode traps the trapping potential is less deep along $z$ than in the $xy$ plane, and ion-escape points (closest and lowest saddle point of the pseudopotential) typically lie above each site. In experiments, we may apply a constant bias potential to the control electrodes, surrounding ground planes, and the mesh (cover plane) to increase the depth along $z$ to a level where trapping is
routinely achieved, while reducing the depth in the xy plane. With such measures in place, we are fairly confident that ions created by photoionization from a hot atomic beam can be loaded and cooled into the local minima of larger arrays.

**Architecture of our trap chip.** The 10 × 10 mm² Si substrate of our trap chip is bonded onto a 33 × 33 mm² ceramic pin grid array (CPGA); the electrodes of the trap arrays are wire-bonded with aluminum wires to the pins of the CPGA, with independent pins for the RF electrodes of the two arrays. The trap chip contains four aluminum–12% copper metallayers, that are electrically connected by tungsten vertical interconnects thereby allowing ‘islanded’ control electrodes in the top electrode layer (Fig. 1). The buried electrical leads are isolated by intermediate SiO₂ layers, nominally 2 µm thick, while the surface layer is spaced by 10 µm from the buried layers. All electrodes are mutually separated by nominally 1.2–1.4 µm gaps and a 50-nm gold layer is evaporated on the top surfaces in a final fabrication step. The trap chip fabrication is substantially the same as that described in the Supplement to ref 40. Each control electrode is connected to ground by 820 P F capacitors located on the CPGA to minimize potential changes due to capacitive coupling to the RF electrodes.

**Compensation of stray potentials at each site.** For compensation of local stray fields in the xy plane, we vary the strength of individual control potentials \( \delta_k \) and \( \delta \) and find corresponding coefficient settings where we obtain a maximal Rabi rate of 8 GHz. This is the case for pure RF tuning along z, and the curvature along y and the curvature as a function of \( \delta_{k} \) (along this axis) is described by: \( \delta_k \delta \delta_{k} (U_{\text{rot}}) |_{z,T_k} = \delta_k \delta \delta_{k} (U_{\text{rot}}) |_{z,T_k} = \Upsilon U_{\text{rot}} \delta_{k} U_{\text{rot}} |_{z,T_k} \). Finally, we insert this into \( \omega_2 = \sqrt{2} \delta_2 \delta_{k} \delta_{k} |_{z,T_k} \) to find equation (4).

**Data availability.** The data that support the findings of this study are available from the corresponding author upon request.

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Author contributions
M.M., H.K. and U.W. participated in the design of the experiment and built the experimental apparatus. M.M., H.K., M.W., F.H. and U.W. collected data and analysed results. M.M., U.W., D.L. and T.S. participated in the design of the trap arrays and the experiment. M.R., P.M. and D.L.M. participated in the design and fabricated the trap chips. T.S. participated in the design and analysis of the experiment. M.M. and H.K. contributed equally to this work and all authors discussed the results and the text of the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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