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Progress in Trapped-Ion Quantum Simulation

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Abstract

Trapped ions offer long coherence times and high fidelity, programmable quantum operations, making them a promising platform for quantum simulation of condensed matter systems, quantum dynamics, and problems related to high-energy physics. We review selected developments in trapped-ion qubits and architectures and discuss quantum simulation applications that utilize these emerging capabilities. This review emphasizes developments in digital (gate-based) quantum simulations that exploit trapped-ion hardware capabilities, such as flexible qubit connectivity, selective mid-circuit measurement, and classical feedback, to simulate models with long-range interactions, explore non-unitary dynamics, compress simulations of states with limited entanglement, and reduce the circuit depths required to prepare or simulate long-range entangled states.

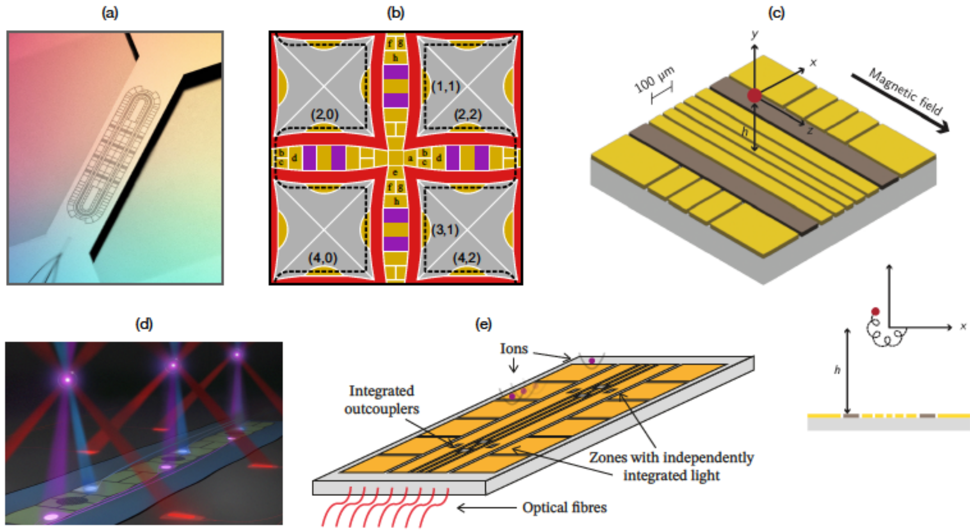


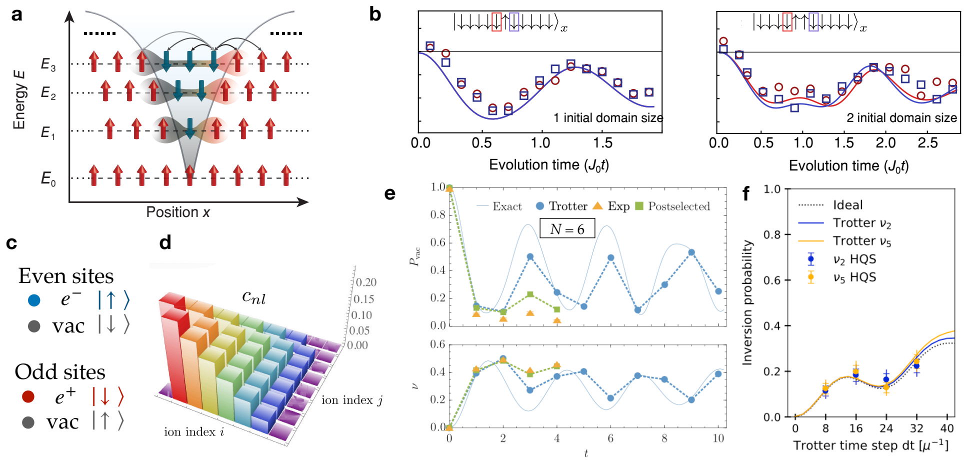
Figure 1

Recent progress in scaling the QCCD architecture: a) In recent years, the QCCD architecture has been pushed to unprecedented scales, though the largest demonstrations remain fundamentally 1D. Shown above is the surface trap at the center of the H2 quantum computer (built by Quantinuum and Honeywell). **b)** Significant progress towards large-scale 2D architectures has been made, including the rearrangement of ions in a 2D grid trap using broadcast electrode signals. **c)** An exciting alternative to grid-like RF traps is the creation of micro-fabricated Penning traps in which ions are confined to (and movable within) a 2D plane. **d,e)** Scaling of the QCCD architecture benefits from the integration of light into the trap itself, routed through waveguides underneath the electrodes and focused out through the surface using grating couplers. Multiple groups have now demonstrated on-chip integration of optics and even the sequential generation of coherent operations on ions transported between multiple trap zones (51). Panel (a) adapted from Ref. (43). Panel (b) adapted from Ref. (46). Panel (c) adapted from Ref. (52). Panel (d) adapted from Ref. (50). Panel (e) adapted from Ref. (51).

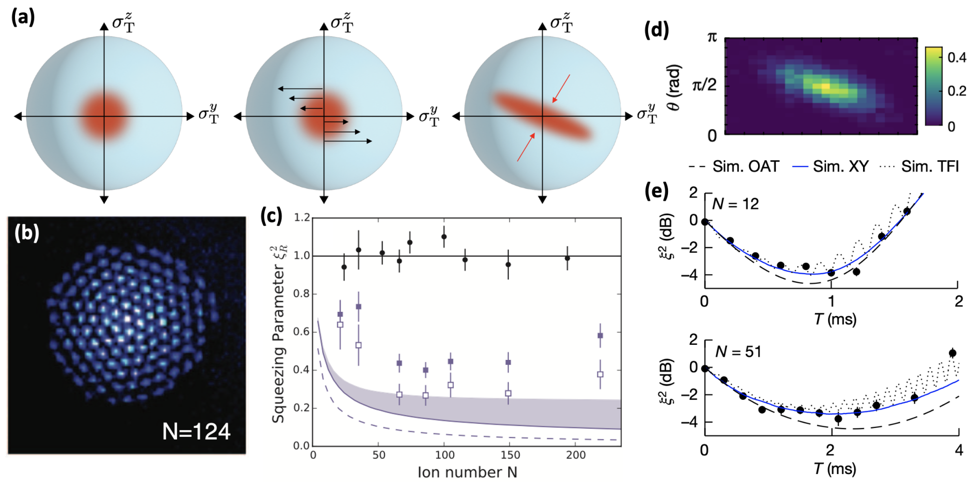
Recently, a promising alternate path to achieving 2D arrays of qubits above microfabricated chips has emerged based on arrays of Penning traps (53). By combining static electric quadrupole potentials above the chip surface with large magnetic fields, 2D arrays of ions can, in principle, be trapped without any RF signals. In this approach, there is no need to dissipate any power in the trap, alleviating one of the known challenges of scaling the QCCD architecture. Furthermore, as shown recently in Reference (52), heating rates in this architecture can be ~ 1 quanta/s or even lower, and transport can be performed in the whole 2D plane, relaxing another challenge of the QCCD architecture based on RF fields.

2.1.3. Optical Interconnects A third approach to scaling trapped-ion quantum computers is to fabricate individual, relatively small-scale traps containing tens of qubits and link them together using optical interconnects (54, 55). In this approach, two distant modules have ions that emit two identical photons, each entangled with their respective qubit, which then interfere on a beam-splitter, creating a heralded remote entangled state among the qubits. The entangling rate can be broken down into the product (56, 57) $R_{\mathrm{ent}} = \frac{1}{2}\left(P_{\mathrm{gen}}P_{\mathrm{coll}}\right)^2 R$, where P_{gen} and P_{coll} are the photon generation and collection probabilities and R is the

$\hbar$



Trapped-ion simulations of nuclear and high-energy physics: a) **b)** $p \sim$. **c)** **d)** **e)** ν P t $|\langle\psi| e$ $|\psi\rangle|$ $|\psi\rangle$ N **f)** N $|\ \rangle$ $|\ \rangle$ $\nu \leftrightarrow \nu$



Spin squeezing in 1D and 2D trapped ion quantum simulators. a)

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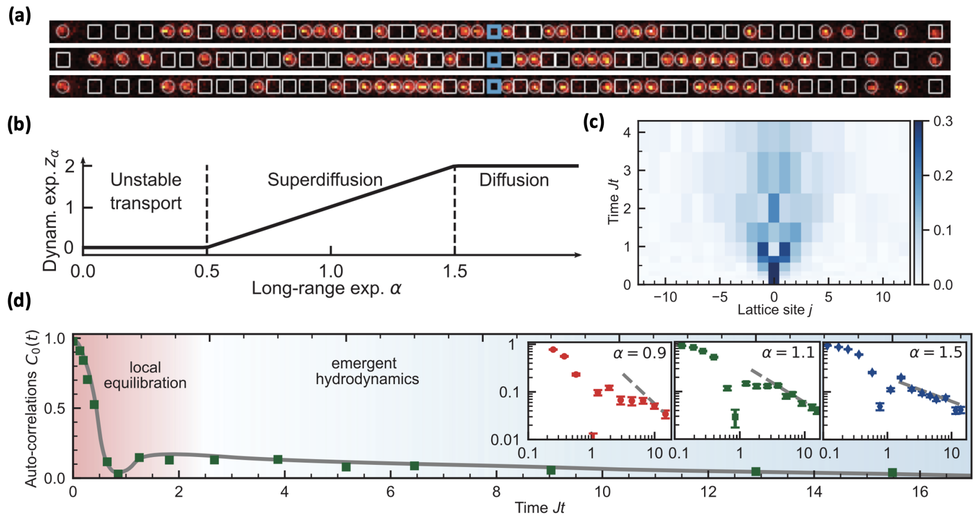

Emergence of hydrodynamics in a 1D ion chain. a)

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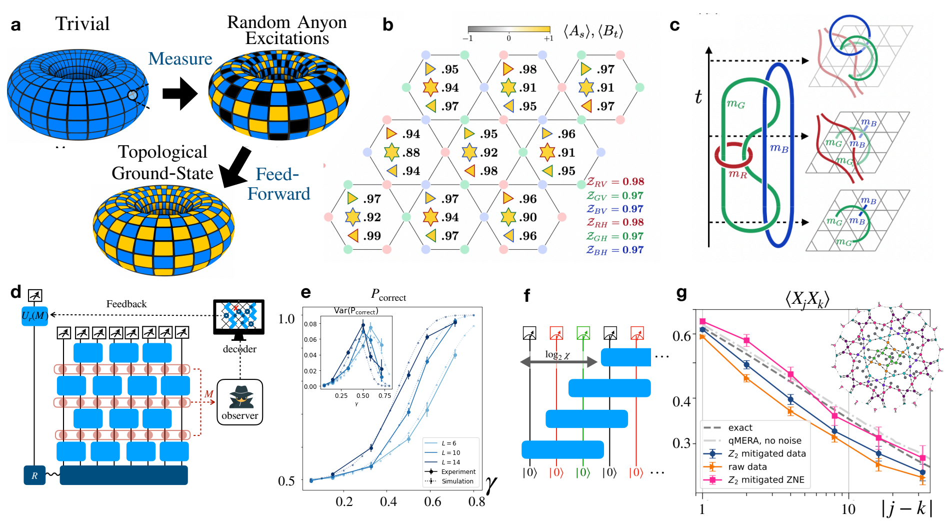

Creating and simulating highly entangled states and criticality with measurements and feed-forward. a)

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