Analog Quantum Simulation and Digital Quantum Computation with Ultracold Atoms in Optical Lattices

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In our quantum gas microscope experiment, we load fermionic ^{6}Li atoms into optical superlattices, and image the local density and spin by performing site-resolved projective measurements [1]. I will present how the exceptional control of optical superlattices and local measurements enables us to perform analog quantum simulation [2] and realize building blocks for digital quantum computation [3, 4].

We conduct systematic experimental quantum simulations of the Fermi-Hubbard model, a key model frequently used to study the physics of high-temperature superconductivity. Using multi-point spin and charge correlators, we perform thermometry, study magnetic polarons and their interactions, and directly observe traces of moving dopants, which are signatures of the strongly correlated states. Furthermore, we identify a universal scaling behavior in magnetic and spin-charge correlations, governed by a doping-dependent energy scale consistent with the pseudogap temperature T^*. Comparison with state-of-the-art numerical simulations confirms the quantitative accuracy of our analog quantum simulation [2].

In the digital approach, we implement high-fidelity collisional entangling gates with fermionic atoms in an optical superlattice, achieving Bell state lifetimes beyond 10 s and gate fidelities up to 99.75(6)%. We realize robust pair-exchange gates, enabling local characterization of spin-exchange and pair-tunneling dynamics [4]. These results demonstrate key building blocks for scalable, symmetry-preserving analog-digital hybrid quantum simulators [5, 6, 7].

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