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Title: Quantum-controlled synthetic materials: entangling qubits with quantum matter

Abstract: Analog quantum simulators and digital quantum computers are two distinct paradigms driving near-term applications in quantum science, from probing many-body phenomena to identifying computational advantage over classical systems. Merging the high-fidelity many-body evolution of analog simulators with the robust control and measurement of digital machines offers an opportunity to unlock new capabilities in state preparation, characterization, and dynamical control.

In this talk, I will describe a hybrid platform that embeds digital quantum control in the analog evolution of a synthetic quantum material. Our system consists of an array of capacitively coupled transmon qubits realizing a Bose-Hubbard model for strongly interacting microwave photons. Capitalizing on the precise time- and space-resolved control of the lattice potential profile has played a pivotal role in preparing quantum fluids of light [1] and investigating quantum dynamics in our synthetic platform. Going beyond the classical control of the lattice, we harness the quantum nature of our sites to entangle the lattice energy landscape with an ancilla qubit [2]. This Hamiltonian-level control couples the ancilla to the degrees of freedom generating the evolution rather than to the evolving state itself. Driving the dynamics under a superposition of lattice configurations guides the many-body system into strongly correlated states where different phases of matter coexist, ordering photons into superpositions of solid and fluid eigenstates.

Leveraging this hybrid analog-digital control, we adiabatically introduce disorder to localize the photons into an entangled cat state and enhance its coherence with a many-body echo protocol. I will also discuss how the ancilla doubles as a probe, using many-body Ramsey interferometry [3] to extract eigenstate information from the relative phase it accumulates. With a single control qubit, this work illustrates the potential for entangling quantum computers with quantum matter – synthetic and solid-state – for advantage in sensing and materials characterization.

[1] Brendan Saxberg*, Andrei Vrajitoarea*, Gabrielle Roberts*, Margaret G Panetta, Jonathan Simon, David I Schuster, *Nature* 612, 435–441 (2022)

[2] Andrei Vrajitoarea, Gabrielle Roberts, Kaden RA Hazzard, Jonathan Simon, David I Schuster, *arXiv:2602.06108* (2026)

[3] Gabrielle Roberts*, Andrei Vrajitoarea*, Brendan Saxberg, Margaret G Panetta, Jonathan Simon, David I Schuster, *Sci. Adv.* 10, eado1069 (2024)