Quantum Simulation: Platforms, Challenges and Applications

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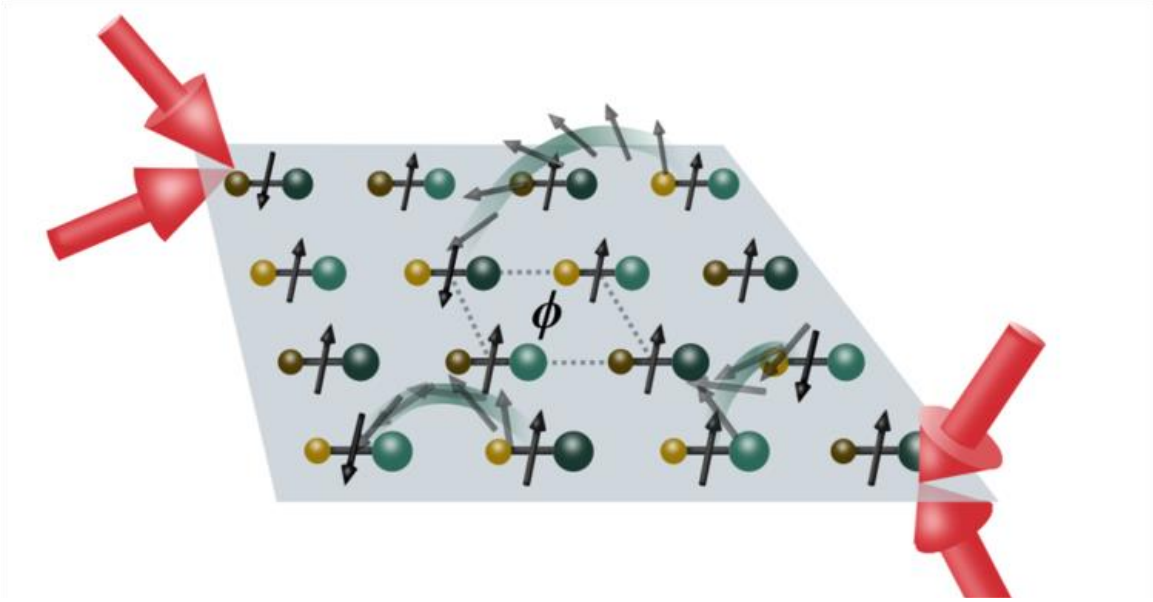
Nearly four decades ago, Richard Feynman gave a visionary lecture titled: "Simulating physics with computers". There, he emphasized the impossible complexity of simulating a quantum mechanical system using a classical computer [1,2]. Indeed, even describing the full quantum state of ~60 electron spins is well beyond current computational capabilities. To overcome this challenge, Feynman proposed the notion of a "quantum simulator". The intuition is strikingly simple: Make use of fully controllable quantum building blocks to mimic the interactions that underlie a less accessible quantum system [3,4]. Experimental progress along this direction has been truly extraordinary in the past decades, enabling us to isolate single microscopic particles (at the nanoscale), to manipulate and control their internal quantum states, and to detect them with almost perfect fidelity [5,6]. This paper is organized to highlight three of the major experimental platforms associated with quantum simulation (ultracold atomic systems [7], polar molecules [8], and superconducting qubits [9]), to give examples of the phenomena they can simulate, and to provide an overview of the key challenges facing the field.

Many-body phases in ultracold atomic systems

Ultracold quantum gases provide a number of unique opportunities when it comes to simulating nature. They offer a tremendous amount of control, can be imaged with single atom resolution and can mimic the underlying structure of solid-state materials [5,7]. In addition to all of these features, perhaps the most crucial aspect underlying their broad scientific impact is the existence of a flexible array of cooling techniques that can effectively quench the kinetic energy of atomic systems. Indeed, ultracold atomic systems have reached the extraordinary realm of sub-nanokelvin temperatures, revealing, along the way, phenomena ranging from Bose-Einstein condensation and Cooper-paired superfluidity to Mott insulators and localization.

Despite these successes, the temperature of atomic quantum simulations are still too high to simulate a number of more exotic- and delicate- quantum mechanical phases including antiferromagnetic spin liquids, fractional Chern insulators and high-temperature superconductivity. The figure of merit for observing such physics is not

Figure 1: Polar Molecule Quantum Simulation -- Schematic representation of the two-dimensional array of polar molecules dressed by optical beams (red arrows). Each polar molecules is characterized as an effective pseudo-spin-flip, which can hop and interact mediated by the long-range dipolar interaction [11].



the absolute temperature, but rather the dimensionless entropy density. To this end, reaching ultra-low entropy densities remains a major challenge for many-body quantum simulations despite the multitude of kinetic cooling techniques. This challenge is particularly acute for gases in deep optical lattice potentials, for which transport, and thus evaporative cooling, is slowed. Moreover, in lattice systems representing models of quantum magnetism, the entropy resides primarily in spin, rather than motional, degrees of freedom. Expelling such entropy through evaporative cooling requires the conversion of spin excitations to kinetic excitations, a process that is typically inefficient.

Two broad approaches have been proposed toward overcoming this challenge. The first is adiabatic preparation, where one initializes a low entropy state and changes the Hamiltonian gradually until the desired many-body state is reached. However, the final entropy density is bounded from below by the initial entropy density, and experimental constraints or phase transitions may preclude a suitable adiabat.
The second approach is to 'shift entropy elsewhere' [10], using the system's own degrees of freedom as a bath. Indeed, this approach helps to stabilize the Mott-insulating phase of the Bose-Hubbard model, where the low-density wings of the system serve as an entropy sink allowing for in-situ evaporative cooling.

On the applications front, ultra-cold atomic simulations have raised the possibility of studying topological phases in out-of-equilibrium spin systems. Unlike traditional condensed matter systems, one cannot simply "cool" into a desired topological ground state by decreasing the temperature of a surrounding bath. Rather, preparation must proceed coherently. This necessitates a detailed knowledge of the phase transitions separating topological states from their short-range-entangled neighbors and requires understanding the interplay between topology, lattice symmetries and out-of-equilibrium dynamics.

One particular context where lattice and topology meet is in the notion of fractional Chern insulators - exotic phases, which arise when strongly interacting particles inhabit a flat topological bandstructure. Particles injected into these exotic states of matter fractionalize into multiple independently propagating pieces, each of which carries a fraction of the original particle's quantum numbers. While similar effects underpin the fractional quantum Hall effect observed in continuum two dimensional electron gases, fractional Chern insulators, by contrast, are lattice dominated. They have an extremely high density of correlated particles whose collective excitations can transform non-trivially under lattice symmetries. Since the FCI state generally competes with superfluid and crystalline orders, the resulting phase diagram exhibits both conventional and topological phases.

Spin liquids in polar molecules

Recently, polar molecules trapped in optical lattices have emerged as a powerful new platform for quantum simulation [8]. This platform exhibits many advantages, including local spatial addressing, stable long-lived spins, and intrinsic long-range dipolar interactions. Typically, the molecules are subject to a static electric field and their motion is pinned by a strong laser field. This implies that the degree of freedom, which (often) participates in the quantum simulation is an effective rotational excitation.

These rotational excitations have been shown to be able to simulate a large number of interesting many-body quantum phases. In particular, by varying the DC electric field strength as well as the tilt of the electric field vector, one can sharply modify the geometry of the dipoles and introduce additional dispersion into their single-particle bandstructures. On the other hand, increasing the electric field strength enhances the long-range interactions. These qualitative differences in the microscopics of polar molecules yield a rich phase diagram exhibiting both conventional and topological phases, including crystalline ordering, superfluids and chiral spin liquids. The nature of these phases can be characterized using a number of diagnostics, including the ground-state degeneracy and the real-space structure factor.

Of particular interest in the context of polar molecular simulations is the realization of quantum spin liquids. Such spin liquids are characterized by entanglement over macroscopic scales and can exhibit a panoply of exotic properties, ranging from emergent gauge fields and fractionalized excitations to robust chiral edge modes. In this context, recent work has demonstrated that polar molecule simulations naturally realize the so-called dipolar Heisenberg antiferromagnet. This simulation requires only a judicious choice of two molecular rotational states (to represent a pseudo-spin) and a constant electric field. The simplicity of this system stems from using rotational states with no angular momentum about the electric field axis and contrasts with previous works where non-zero matrix elements appear for the transverse electric dipole operator, unavoidably generating ferromagnetic spin-spin interactions. Motivated by this physical construction, large-scale numerical studies of the dipolar Heisenberg model find evidence for quantum spin liquid ground states on both triangular and kagome lattices.

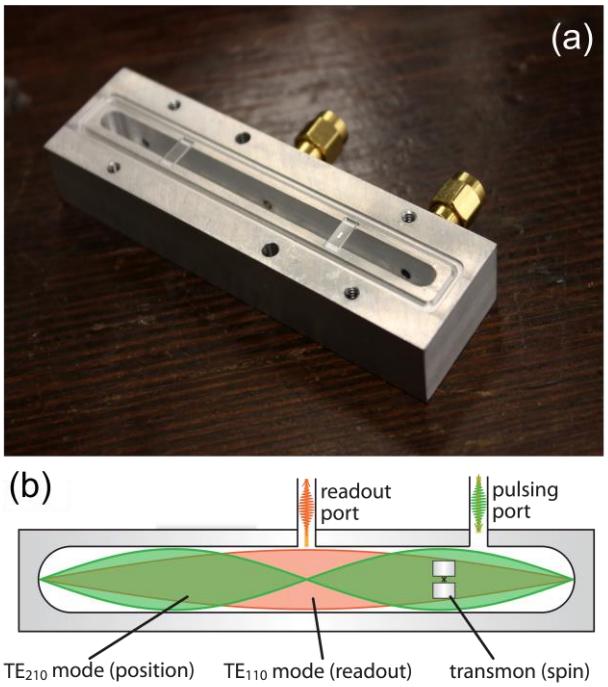


Figure 2: (a) Cavity resonator and a coupled superconducting transmon qubit. (b) Schematic of the simulation platform for quantum walks. The fundamental (TE110, orange) mode is used to measure the qubit state. The transmon qubit is dispersively coupled to both cavity modes [12].

Quantum walks in superconducting qubits

Much like their classical stochastic counterparts, discrete-time quantum walks have stimulated activity across a broad range of disciplines. In the context of computation, they provide exponential speedup for certain oracular problems and represent a universal platform for quantum information processing. Quantum walks also exhibit features characteristic of a diverse set of physical phenomena, and thus represent an ideal platform for quantum simulation.

Recently, it has been demonstrated that quantum walks can be directly realized using superconducting transmon qubits coupled to a high-quality-factor electromagnetic cavity. In this platform, the quantum walk takes place in the phase

space of the cavity mode and each lattice site corresponds to a particular coherent state of the cavity, while the two logical states of the superconducting qubit form the internal spin of the walker. Coherent spin rotations can be performed using microwave driving, while spin-dependent translations arise naturally from the dispersive coupling between the qubit and the cavity.

A unique application of this particular quantum simulation platform is in the direct measurement of so-called topological invariants. In these protocols, a geometric signature of the topological invariant is imprinted as a Berry phase on the quantum state of the particle. This phase can then be extracted and disentangled from other contributions via a simple interferometric protocol.

Conclusion

Over the last decade, the quantum simulation community has made remarkable progress in the controlled manipulation of individual quanta. These advances have opened the door for the engineering of quantum many-body systems as well as the development of quantum technologies. Looking forward, the continued dialogue between AMO physics, condensed matter, and quantum information science promises to be fruitful for both the fundamental and applied sciences, enabling the simulation of macroscopic quantum behavior and providing detailed microscopic intuition [13-17].

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