ULTRACOLD ATOMS

Engaged in gauge theory

Two independent cold-atom experiments have demonstrated the building blocks for the quantum simulation of dynamical gauge fields — an advance that holds promise for our understanding of computationally intractable problems in high-energy physics.

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Interactions between light and matter explain how we see things in daily life. But how atoms in a material transfer their presence to light is non-trivial: the same carbon atoms that make diamond shiny can make graphite appear pitch black. The reason involves the fundamental coupling between photons and atoms, which quantum electrodynamics addresses by treating photons as gauge fields. In practice, however, this formulation quickly becomes computationally intractable as both the matter and photons are many-body quantum fields, and their coupling generally leads to complex correlations and entanglement. Writing in *Nature Physics*, Frederik Görg and colleagues[1] and Christian Schweizer and colleagues[2] have now pushed us closer to realizing experimental simulations of these systems.

Researchers working with cold atoms have long attempted to mimic the physics of gauge fields, which generalize the concept of electromagnetic fields and carry forces between fundamental particles[3]. An important milestone was achieved in 2009 with an apparatus in which neutral atoms feel forces identical to those experienced by charged particles in electric and magnetic fields[4]. Despite these advances, the task of constructing a quantum system whose dynamics can be interpreted as a coupled matter–gauge field[5] remained elusive, as did the ability to use cold atoms to simulate the physics of dynamical gauge fields.

So what is a dynamical gauge field? The term gauge field refers to an important but technical property of the theory of elementary particles: as the force carriers, the gauge fields always interact with particles through their geometrical derivatives. For example, electromagnetism can be formulated in terms of the vector and scalar potentials (the gauge fields), but forces all arise from their derivatives: electric and magnetic fields. There are an infinite number of vector potentials that give rise to the same electric and magnetic fields, a feature described as 'gauge freedom'.

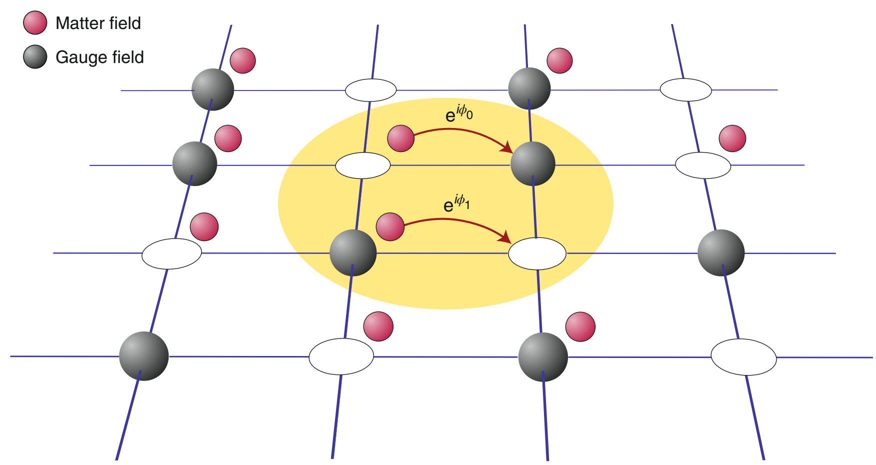

Fig. 1 | Experimental scheme to generate a dynamical lattice gauge field. Atoms in two spin states — one (red) representing the matter field and the other (black) representing the gauge field — are loaded into optical lattices. Open circles are empty sites. The lattice gauge theory reported in the experiments (shown in the yellow region) is characterized by different Peierls phases ϕ_0 and ϕ_1 of the tunnelling of the matter field depending on the site occupancies of the gauge field.

The ability to manipulate different vector potentials without changing the physics is a property of the theory that is known as 'gauge symmetry'.

The term dynamical gauge fields highlights the key difference between the experiments reported here and earlier ones. Previously realized artificial electromagnetic fields were either static or had their dynamics completely constrained by external controls. Such static or slaved gauge fields cannot support gauge bosons, analogues of photons in electromagnetism. Thus, the experiments reported here represent a notable improvement of the state of the art, where two key ingredients — gauge–matter coupling and gauge symmetry — are incorporated simultaneously.

The synthesis of dynamical gauge fields in ultracold experiments requires overcoming several challenges. Firstly, new degrees of freedom need to be introduced to the cold atoms to allow them to represent the matter and gauge fields separately, as well as making one depend on the other. Secondly, the gauge symmetry requires a fine control of the form and the strength of their coupling. Finally, experiments frequently suffer from fast atom loss and heating because of the inelastic photon scattering, calling for new approaches to improve the stability of the set-ups.

Substantial progress was made recently by harnessing the Floquet engineering technique[6]. In a Floquet scheme, modulation at frequency ω can couple two quantum states with energy difference $\hbar\omega$, where $\hbar$ is the reduced Planck constant, and one can superimpose multiple frequency components to the modulation waveform to couple more states. Within this framework, a constant vector potential proportional to the atomic density was introduced to a Bose–Einstein condensate through simultaneous modulations of the lattice potential and atomic interactions[7].

The experiments conducted by Görg and colleagues and Schweizer and colleagues have brought the synthesis of gauge fields to the next level. The ultimate goal is to simulate lattice gauge theories (Fig. 1). Researchers realized that in a setting based on two atoms in a double-well potential, the presence of an atom in one lattice site — left or right — affects the quantum-mechanical phase of the second atom as it tunnels between the two sites. This quantum phase, called the Peierls phase, is analogous to the Aharanov–Bohm phase that a charged particle acquires in moving through a magnetic field, and is also what characterizes the lattice gauge field[8]. A density-dependent gauge field thus requires the Peierls phases to be different for different atomic lattice site occupancy.

Görg and colleagues controlled the tunnelling of fermionic particles between two sites by modulating the lattice at the frequency that matched the energy difference between the states before and after the tunnelling. To imprint different Peierls phases for different occupancies, the researchers employed a two-frequency modulation with the frequencies specifically tuned to assist different tunnelling processes. Measurements from Ramsey interferometry confirmed that the Peierls phases, or equivalently the gauge fields, that were synthesized indeed depended on the site occupancy.

Schweizer and colleagues simulated a $\mathbb{Z}_2$ lattice gauge theory[9] with bosonic particles in their version of the double-well experiment. Here, $\mathbb{Z}_2$ symmetry refers to the gauge symmetry where the product of the charge and its surrounding electric fields is a constant of motion[2]. To control the Peierls phases, a clever trick was implemented: by offsetting the two wells precisely by the atomic interaction energy, tunnelling processes for different occupancies can be induced by the same frequency component in the modulation[2]. The density dependence and the gauge symmetry of the field were confirmed from the dynamics of the coupled matter–gauge system.

The experiments carried out by Görg and colleagues and Schweizer and colleagues, while so far limited in sample size, demonstrated the power of Floquet engineering in the bottom-up construction of the lattice gauge models with cold atoms in optical lattices. Future experiments will continue to add features that are important for the simulation of models of particle and high-energy physics. We expect a steady progression towards larger systems and more exotic gauge symmetries. One can imagine a future where cold-atom experiments play a role in helping to understand lattice quantum chromodynamics models, and in enabling ab initio calculations of physical quantities of fundamental interest. ❐

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