Ultracold gases are remarkably versatile and controllable systems with untapped potential to emulate a variety of quantum phenomena [1]. Atoms are, however, electrically neutral and therefore it is highly desirable to make them behave as charged particles. This capability has recently been demonstrated in a series of recent experiments [2–4]. Although many challenges remain ahead, atoms exposed to synthetic gauge field offer great opportunities for the realization of new classes of quantum materials with custom-designed properties, and with unforeseen applications.

The first implementation of an effective magnetic field was accomplished by rotating an atomic cloud [5]. In the rotating frame of reference, an atom experiences the Coriolis force that emulates the Lorentz force experienced by a charged particle in a uniform magnetic field. Large vortex lattices have been created in this way, however, so far the strength of the effective magnetic field achieved by rotation is too weak to lead to new physics.

An alternative approach invokes the vector potential, A, that induces a geometric phase as a charged particle moves around a closed loop. This notion of geometric phase can be adapted to a neutral atom that slowly moves in the presence of laser fields. If the lasers are chosen to ‘dress’ the internal atomic levels, so that the dressed eigenstates become position dependent, the center of mass adiabatically evolves according the operator \( \mathbf{p} - \mathbf{A} \) instead of just \( \mathbf{p} = -i\hbar \nabla \). The atom thus effectively moves as a charged particle in a magnetic field \( \mathbf{B} = \nabla \times \mathbf{A} \) (see Fig. 1a).

Exploiting this idea series of experiments have implemented artificial magnetic and electric fields [2–4]. The idea has also been implemented in the presence of a superimposed periodic optical lattice potential (see Fig. 1b). In this case, the length scale imposed by the lattice competes with the one associated with the magnetic field and can lead to frustration, manifested as an energy spectrum with fractal characteristics [2,3].

Generalizations to emulate non-Abelian gauge potentials, associated in many cases to spin-orbit coupling can emerge when the geometric phase is replaced by a matrix acting on the internal Hilbert space [2–5]. This happens if there is a manifold of degenerate dressed states, such that even for arbitrarily slow motion, after traveling around a contour the particle ends up in a different internal state. Although various proposals for generating non-Abelian potentials exist, they remain to be implemented. On the other hand, Abelian spin-orbit coupling, arising from the momentum kicks imparted on the atom by the laser photons that drive internal transitions, has been realized in several laboratories using...
different laser configurations in alkali-metal (one outer electron) and alkaline-earth (two outer electrons) atoms \(^2\text{–}_5\).

There is a great vista ahead. For example, the inclusion of collisions or dipolar interactions will open a window to engineer fractional Hall liquids, unconventional superfluids and interacting topological phases. The creation of dynamical gauge fields important in many areas of physics such as quantum chromodynamics is also an open direction. The time is just ripe for investigating rich and unexplored physics with synthetic gauge fields for ultracold matter.

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