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Realization of the Harper Hamiltonian with Ultracold Atoms in Optical Lattices

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Abstract: We experimentally realized the Harper Hamiltonian with charge neutral, ultracold atoms in optical lattices using laser-assisted tunneling and a potential energy gradient. The energy spectrum of this Hamiltonian is the fractal Hofstadter butterfly.

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Systems of charged particles in magnetic fields have led to many discoveries in science such as the integer [1] and fractional quantum Hall effects [2] and have become important paradigms of quantum many-body physics. Generalizations have led to the study of topological insulators, initially in condensed matter [3] but also more recently in photonic systems [4, 5]. We have proposed and implemented a scheme which realizes the Harper Hamiltonian [6], a lattice model for charged particles in magnetic fields, whose energy spectrum is the fractal Hofstadter butterfly [7].

We experimentally realize this Hamiltonian with ultracold, charge neutral bosonic atoms of $^{87}$Rb in a two-dimensional optical lattice by creating an artificial gauge field using laser-assisted tunneling and a potential energy gradient provided by gravity [8]. A schematic of our setup is shown in Fig. 1 (a),(b) and (c). The laser-assisted tunneling process is characterized by studying the expansion of the atoms in the lattice as shown in Fig. 1 (d).

In a uniform lattice, atoms are free to tunnel. However, in the presence of a uniform energy offset between neighboring lattice sites, tunneling along the offset direction is suppressed. Applying a pair of laser beams that are frequency
detuned to the offset induces Raman transitions which re-establish tunneling and create the Harper Hamiltonian,

$$H = -\sum_{m,n} (K e^{-i\Phi_{m,n}} \hat{a}_{m+1,n}^\dagger \hat{a}_{m,n} + J \hat{a}_{m,n}^\dagger \hat{a}_{m+1,n} + H.c.),$$

where $\hat{a}_{m,n}$ ($\hat{a}_{m,n}^\dagger$) is the creation (annihilation) operator of a particle at lattice site $(m,n)$ and $\Phi_{m,n} = \delta \mathbf{k} \cdot \mathbf{R}_{m,n} = m\phi_x + n\phi_y$ is a spatially varying phase, where the energy offset is in the $x$-direction. For our particular experimental setup, the magnitude of the tunneling amplitudes in terms of the bare tunneling amplitudes $J_{x,y}$, the energy offset $\Delta$, and the two-photon Rabi frequency in energy units $\Omega$ can be written $K = J_{x}J_{1}(2\Omega/\Delta)$ and $J = J_{x}J_{0}(2\Omega/\Delta)$, where $J_{n}(x)$ are Bessel functions of the first kind of order $n$. The experimentally determined atomic cloud width qualitatively agrees with the Bessel function behavior as shown in Fig. 2 (a). We can also suppress nearest-neighbor tunneling while inducing next-nearest-neighbor tunneling with the appropriate laser detuning as shown in Fig. 2 (b).

![Fig. 2. (a) In situ cloud width expansion as a function of resonant Raman laser intensity shows the laser-assisted tunneling rate $K$ along the tilt direction (blue circles) and the tunneling rate $J$ along the transverse direction (red squares). Data taken at lattice depths of 9 $E_r$ and hold time of 1500 ms. Inset: Theoretical prediction for the tunneling rates $K$ and $J$ in terms of Bessel functions. (b) Next-nearest-neighbor tunneling induced and observed. The center is at 2$\Delta$ (compare to Fig. 1 (d)).](image)

Furthermore, this scheme can be extended to realize spin-orbit coupling and the spin Hall effect for neutral atoms in optical lattices by modifying the motion of atoms in a spin-dependent way by laser recoil and Zeeman shifts due to magnetic field gradients [9]. One major advantage of our scheme is that it does not rely on near-resonant laser light to couple different spin states. Our work is a step towards studying novel topological phenomena with ultracold atoms.

References