Merging and alignment of Dirac points in a shaken honeycomb optical lattice

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Inspired by the recent creation of the honeycomb optical lattice [1] and the realization of the Mott insulating state in a square lattice by shaking [2], we theoretically study a system of ultacold fermionic atoms loaded into a honeycomb optical lattice, which is shaken linearly in a harmonic fashion (Figure 1). Because the shaking is periodic in time, Floquet theory can be used to derive a time-independent description. In the effective time-independent Hamiltonian, the hopping matrix elements become renormalized by a zeroth-order Bessel function of the first kind. This result is in accordance with previously found results for square lattices [2]. The renormalization depends on the shaking direction, frequency, and amplitude. Since the Bessel function goes through zero, the hopping matrix elements can vanish, depending on the shaking parameters. Therefore, we include both nearest-neighbor and next-nearest-neighbor hopping.

Because of the different renormalizations of the nearest-neighbor and next-nearest-neighbor hopping parameters, the system exhibits several intriguing features (Figure 2), such as the merging of Dirac points. The merging of Dirac points is a topological phase transition between a state where the two energy bands touch at the band contact points and a state where the spectrum is gapped [3]. Furthermore, when the lattice is shaken parallel to one of the nearest neighbor vectors, an alignment of Dirac points can be induced. In this case, the Dirac points align in lines while simultaneously the saddle points between the aligned Dirac points are lowered. In absence of next-nearest-neighbor hopping, a complete alignment corresponds to a set of one-dimensional systems, in which the Dirac points become trivial. If the next-nearest-neighbor hopping terms are zero, it is also possible to reach the zero-dimensional limit, since the atoms are confined to dimers if two of the three nearest-neighbor hopping parameters are rendered zero. In the presence of next-nearest-neighbor hopping terms, the two energy bands will start to overlap for sufficiently large shaking amplitudes, which would correspond to a metallic phase in a solid state system.

Lastly, we study density profiles and momentum-resolved Raman spectroscopy as possible detection methods. By using mean field theory, we derive a recursive equation for the density in the presence of interactions, which is exact in the case without interactions present. We use the result to determine the dependence of the density on the chemical potential, in order to find which chemical potential is required to have half filling, which is one particle per lattice site when 2 species of fermions are present. Within the local density approximation similar calculations yield the density profile of the system in an overall trapping potential. Although the density profile is important regarding experiments, the quite different conditions may lead to very similar density profiles. Hence, the density profile can only give limited information about the band structure.

Momentum-resolved Raman spectroscopy [4] may be used to determine the band structure of the system. There are some considerations of time and length scales that need to be taken into account. If this technique may be applied to the shaken honeycomb optical lattice, it could be a powerful tool in determining the band structure of the system, even in the presence of a trapping potential and interactions.

References

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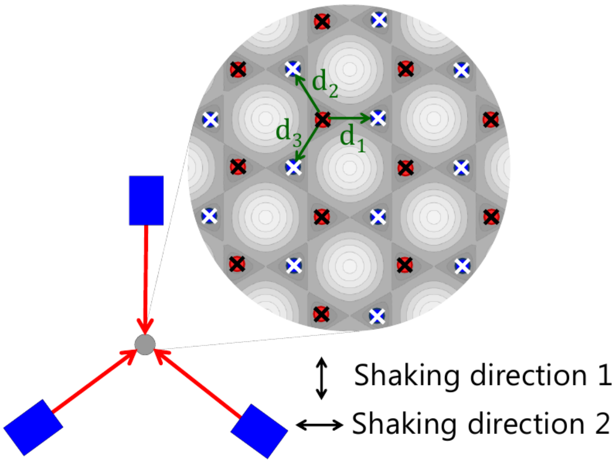
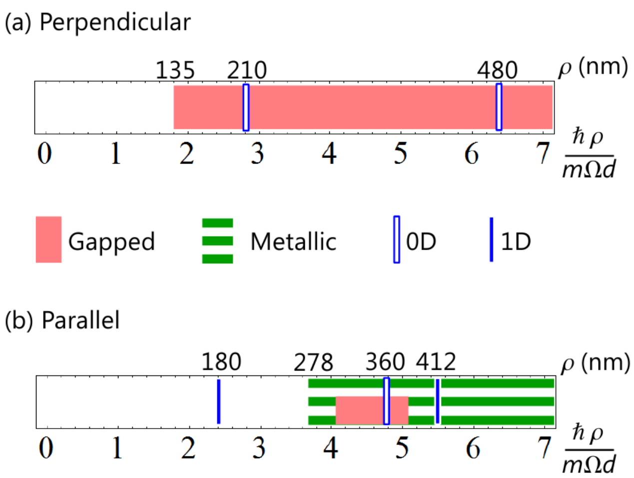
Figure 1



The honeycomb optical lattice is created by three lasers. The two sublattices are indicated by black and white crosses. The vectors joining nearest-neighbor lattice sited and the two studied shaking directions are shown.

Figure 2



State of shaking on the system as a function of the shaking amplitude ρ or the dimensionless argument of the Bessel function, where m is the mass of the atoms, $2\pi\ \Omega$ is the shaking frequency, and d is the distance between nearest-neighbor lattice sites.