Atomic Landau-Zener tunneling in Fourier-synthesized optical lattices

Tobias Salger, Carsten Geckeler, Sebastian Kling, and Martin Weitz
Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, 53115 Bonn
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We report on an experimental study of quantum transport of atoms in variable periodic optical potentials. The band structure of both ratchet-type asymmetric and symmetric lattice potentials is explored. The variable atom potential is realized by superimposing a conventional standing wave potential of \( \lambda/2 \) spatial periodicity with a fourth-order multiphoton potential of \( \lambda/4 \) periodicity. We find that the Landau-Zener tunneling rate between the first and the second excited Bloch band depends critically on the relative phase between the two spatial lattice harmonics.

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Transport properties of quantum objects subject to a periodic potential are determined by the particle’s band structure. The energy spectrum here splits into continuous energy bands separated by bandgaps. For example, the more than 20 orders of magnitude difference in electrical conductivity between an isolator and a good conductor thus finds a natural physical explanation [1]. In recent years, atoms confined in periodic optical potentials, so-called optical lattices, have developed a powerful tool for the observation of effects known or predicted in solid state physics [2]. So far, the band structure has been exploited only for sinusoidal lattice potentials, as can be realized with the ac Stark shift of optical standing waves. In remarkable experiments with such standing wave lattices, Bloch oscillations and Landau-Zener transitions have been observed [2,4,5].

Here we report on experiments studying the band structure of optical lattices with variable inversion symmetry and shape, as a step towards simulating the variety of potential forms that nature provides us in the system of electrons in natural crystals. The used potentials are realized by superimposing a conventional standing wave lattice of \( \lambda/2 \) spatial periodicity with a \( \lambda/4 \) periodicity lattice realized using the dispersion of higher order Raman transitions. By varying the phase between the two spatial harmonics, symmetric and ratchet-type asymmetric lattice potentials are realized, which exhibit a different band structure. We experimentally demonstrate that the strength of interband transitions for an atomic Bose-Einstein condensate depends on the shape of the lattice potential.

Before proceeding, let us point out that in semiconductor heterostructures effects of the inversion symmetry of quantum wells have been studied using magnetotransport [6]. In the area of atomic physics, directed transport has been achieved in driven ratchet systems with the temporal symmetry broken by dissipative processes [7]. Further, in theoretical works, atom transport has been studied in periodic double well systems [8]. Let us begin by describing our calculations of the band structure in a Fourier-synthesized atom potential realized by superimposing two lattice potentials of spatial periodicities \( \lambda/2 \) and \( \lambda/4 \):

\[
V(z) = \frac{V_1}{2} \cos(2kz) + \frac{V_2}{2} \cos(4kz + \varphi)
\]

where \( V_1 \) and \( V_2 \) denote the potential depths of the two lattice harmonics respectively and \( \varphi \) the relative phase. According to Bloch’s theory [9], the band structure of the periodic potential can be derived by solving the eigenvalue equation \( Mc_q^l = E_q^l c_q^l \), where the quasimomentum \( q \) conventionally is restricted to the first Brillouin zone: \( -\hbar k < q < \hbar k \). Here we search for the Eigenenergies \( E_q^l \) of the Eigenstates \( |n,q\rangle = \sum_l c_q^l e^{i\phi^l} \) using the coupling matrix \( M \) with elements \( M_{jj} = (2\hbar k + q)^2/2m, M_{j,j+1} = M_{j+1,j} = V_1/4, \) and \( M_{j,j+2} = M_{j+2,j} = V_2/4 \cdot e^{i\phi} \), where the index \( n \) denotes the band number. The matrix can be readily diagonalized. For the lattice potential of eq. (1), Fig. 1 shows a spatial lattice potential (left) and the corresponding band structure (right) for different values of the relative phase \( \varphi \) of the two spatial lattice harmonics. It is clearly visible that the gap between the first and second excited band is strongly dependent on the value of the relative phase, while no such significant modification of the splitting between the other shown bands is visible. Physically, the variation of this splitting on the relative phase of the lattice harmonics can be understood by the interference of the second order Bragg scattering amplitude of the standing wave potential of periodicity \( \lambda/2 \) with the first order Bragg scattering amplitude of the \( \lambda/4 \) periodicity multiphoton lattice potential, which both contribute to this bandgap. In the limit of a very shallow lattice with the four-photon contribution being a small perturbation, i.e. \( V_2 \ll V_1 \ll E_r \) (where \( E_r = \hbar^2 k^2/2m \) denotes the atomic recoil energy), the size of this bandgap is determined by the simple analytical expression \( |V_1^2/8E_r + e^{i\phi} \cdot V_2| \), which directly shows the two interfering contributions of coupling Rabi frequencies arising from different lattice harmonics. For larger potential values, higher order corrections come into play, but by numerical diagonalization of the coupling matrix \( M \), the band structure for arbitrary potential values is readily determined. The bandgap reaches a maximum.
value for $\varphi = 0^\circ$ in which case the lattice potential resembles a periodic sequence of hills (Fig. 1a). On the other hand, the bandgap reaches its minimum value for $\varphi = 180^\circ$, corresponding to an array of potential dimples in the spatial lattice structure (Fig. 1c). For a suitable choice of potential values, the bandgap between first and second excited bands can even disappear. The situation of spatial lattice potentials with broken spatial symmetry, as, e.g. the saw-tooth like structures shown in Fig. 1b for $\varphi = \pm 90^\circ$, yields an intermediate value of the bandgap. We experimentally exploit the band structure of the Fourier-synthesized lattice by means of quantum transport experiments. Specifically, the size of the gap between first and second excited Bloch bands is measured by means of Landau-Zener tunneling of atoms in an accelerated lattice potential. The acceleration provides an inertial force in the moving lattice frame, emulating a 1-D potential. The acceleration provides an effective potential with periodicity $\lambda/4$, which is based on a three-level configuration with two stable ground states $|g_0\rangle$ and $|g_1\rangle$ and one spontaneously decaying excited state $|e\rangle$ [11, 12]. Compared to the four-photon ladder scheme, in this improved approach one absorption (stimulated emission) process has been replaced by a stimulated emission (absorption) process of a counterpropagating photon respectively. A minimum of three laser frequencies is required to suppress standing wave effects, and the atoms are irradiated with two optical beams of frequencies $\omega + \Delta \omega$ and $\omega - \Delta \omega$ from one side and a further beam of frequency $\omega$ from the counterpropagating direction. The high frequency resolution of Raman spectroscopy here allows to clearly separate in frequency space the desired four-photon process from lower order contributions. The described scheme can be extended to higher lattice periodicities, where in general an effective potential with periodicity $\lambda/2n$ can be achieved by a 2n-th order process [12]. By combining lattice potentials of different spatial periodicities, arbitrarily shaped periodic potentials can be synthesized.

Our experimental setup has been described in [10, 13]. Briefly, light for generation of variable atomic lattice potentials is produced by a tapered diode laser tuned some...
2 nm to the red of the rubidium D2-line. The emitted radiation is split into two, and each of the partial beams pass an acoustooptic modulator. The modulators are used for beam switching and to superimpose several optical frequencies onto a single beam path, as is required to generate superpositions of a standing wave potential and a four-photon lattice potential by realizing the scheme of Fig. 2b. After passing the modulators, the two beams are directed through optical fibers and send in a counterpropagating geometry onto a rubidium (\(^{87}\)Rb) Bose-Einstein condensate.

Our Bose-Einstein condensate is produced all-optically by evaporative cooling of \(^{87}\)Rb atoms in a CO\(_2\)-laser dipole trap. During the evaporation, a magnetic field gradient is activated, resulting in a spin-polarized condensate with \(1.6 \times 10^4\) atoms in the \(|F = 1, m_F = -1\rangle\) ground state. A magnetic bias field generates a frequency splitting of \(\omega_D \approx 2\pi \cdot 805 kHz\) between neighboring Zeeman ground states. The direction of the magnetic field forms an angle respectively to the optical beam, so that atoms experience \(\sigma^+, \sigma^-\) and \(\pi\)-polarized light simultaneously.

For generation of a multiphoton lattice potential with the scheme of Fig. 2b, the \(F = 1\) ground state components \(m_F = -1\) and 0 are used as states \(|g_0\rangle\) and \(|g_1\rangle\), while the \(5P_3/2\)-manifold serves as the excited state \(|e\rangle\). The Raman detuning \(\delta\) is \(2\pi \cdot 50kHz\). The used potential depths are \(V_1 \approx 3E_r\) and \(V_2 \approx 2E_r\) for the lattice contributions with periodicities \(\lambda/2\) and \(\lambda/4\) respectively, and different values of the phase \(\varphi\) between the two spatial harmonics were used in the course of the experiments. Experimentally, the potential values of both lattice harmonics and the phase \(\varphi\) can be monitored by a series of Raman-Nath diffraction experiments on pulsed optical potentials and Rabi-oscillations \([10, 14]\), so that all parameters of the Fourier synthesized lattice potential of eq. 1 are known. One of the lattice beams with frequency \(\omega\) is used for both the standing wave and the four-photon lattice potential. When this beam is acoustooptically detuned by a small amount \(\delta_{\text{Dopp}}\), the reference frame in which the optical potential is stationary moves with a velocity \(v_{rel} = \delta_{\text{Dopp}}/2\pi \cdot \lambda/2\), where \(\lambda\) denotes the laser wavelength. We adiabatically load the atomic Bose-Einstein condensate into the first band by transferring the atoms into a lattice potential moving with \(v_{rel} \equiv q_0/m \approx 1.5 hh/m\).

The lattice beams form an angle of \(41^\circ\) relatively to the axis of gravity, and the ballistic free atomic fall accelerates the atoms over the bandgap between the first and second excited Bloch band. Fig. 3 shows the result of a measurement monitoring for different final values of the atomic quasimomentum. Here, two different lattice forms were investigated. For a phase shift \(\varphi \approx 0^\circ\) (dots), corresponding to a potential form with a sequence of hills, atoms are Bragg-diffracted at the bandgap towards higher velocities. In contrast, for a phase shift \(\varphi \approx 180^\circ\) (crosses), corresponding to a lattice consisting of a periodic sequence of dimples, the ballistic free atom flight is hardly modified by a bandgap between the first two excited bands. We attribute this striking modification of transport properties on the potential shape to the strong dependence of the size of the bandgap between the first two excited Bloch bands on the relative phase \(\varphi\) between lattice harmonics. For a phase shift \(\varphi = 180^\circ\), almost all atoms undergo Landau-Zener transitions over the bandgap near \(q = 2\pi\) (corresponding to the second gap at \(q = 0\) in the reduced zone scheme), while adiabaticity is better achieved with \(\varphi = 0^\circ\), giving evidence for an increased splitting of the bandgap. At the bandgap, Bragg diffractions changes the atomic momentum in units of \(4\pi h\). For a more detailed investigation of the bandgap we have recorded the Landau-Zener tunneling rate as a function of the phase between the lattice harmonics. For this measurement we have increased the beam detuning \(\delta_{\text{Dopp}}\) with a constant rate, so that the lattice potential is accelerated relatively to the atomic frame with an acceleration of \(6.44 m/s^2\), somewhat exceeding the projection of the earth’s gravitational field onto the beam axis. Fig. 4 shows experimental data for the fraction of tunneled atoms as a function of phase \(\varphi\) between the two lattice harmonics. The data fits well to a sinusoidal curve, as shown by the solid line. Notably, asymmetrically shaped ratchet-like potentials result in an intermediate value of the Landau-Zener tunneling rate, while smallest (largest) values are achieved for hill-type (dimple-type) periodic arrays. It is interesting to note that this characteristics is in contrast to the behaviour in dissipative lattices, where maxima and minima of the particle transport are achieved for ratchet-like potentials of different symmetry. Experimentally, a related obser-
periodicity of the optical potential. The four-photon contribution with depth of the optical standing wave contribution to the variation of the Landau-Zener tunneling rate on the potentials [7]. In subsequent experiments, we have studied the variation has been made in pulsed, driven ratchet potentials [2]. In subsequent experiments, we have studied the variation of the Landau-Zener tunneling rate on the depth of the optical standing wave contribution to the total optical potential. The four-photon contribution with periodicity of $\lambda/4$ here was left constant (see eq. 1). Fig. 5 shows experimental data for the interband tunneling for a phase shift $\varphi = 0^\circ$ (dots) and $\varphi = 180^\circ$ (crosses). For the former phase shift value, the tunneling rate decreases with the standing wave contribution $V_1$ for all parts of the curve, as is consistent with a monotonically increasing energy gap between the bands. On the other hand, for a phase shift $\varphi = 180^\circ$ between lattice harmonics a local maximum of the tunneling rate is observed for an intermediate value of $V_1$. This is attributed to the width of the band gap between the lowest two excited bands reaching a minimum for certain value of $V_1$, as is expected when considering that the bandgap for this phase shift value is diminished by destructive interference of the amplitudes of second order Bragg scattering of the standing wave potential and first order Bragg scattering of the potential with periodicity $\lambda/4$. The inset of Fig. 5 is to indicate the dependence of the theoretical value of the bandgap as a function of $V_1$. We interpret the experimental data of Fig. 5 as clear evidence for the destructive (constructive) interference of scattering amplitudes contributing to the size of the bandgap at a phase shift of $\varphi = 180^\circ$ ($\varphi = 0^\circ$) respectively between lattice harmonics. To conclude, we have studied the band structure of optical lattices with variable spatial symmetry and shape by means of quantum transport of an atomic Bose-Einstein condensate. We find that the Landau-Zener tunneling rate between the first and second excited Bloch band depends critically on the phase between spatial Fourier components of the lattice, which is attributed to interference effects within the band spectrum.

For the future, we expect that optical lattices of non-standard shape allow for novel quantum gas phases, and model solid state physics problems such as quantum magnetism and frustrated lattices [13, 16, 17]. A different perspective includes quantum ratches with atomic Bose-Einstein condensates [13]. An exploration of the Hamiltonian ratchet regime is expected to allow for novel quantum dynamical phenomena.

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