Observation of Atomic Wannier-Stark Ladders in an Accelerating Optical Potential

S. R. Wilkinson, C. F. Bharucha, K. W. Madison, Qian Niu, and M. G. Raizen
Department of Physics, The University of Texas at Austin, Austin, Texas 78712-1081
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We report observation of Wannier-Stark ladders with ultracold sodium atoms in an accelerating one-dimensional standing wave of light. Atoms are trapped in a far-detuned standing wave that is accelerated for a controlled duration. A small oscillatory component is added to the acceleration, and the fraction of trapped atoms is measured as a function of the oscillation frequency. Resonances are observed where the number of trapped atoms drops dramatically. The separation between resonant peaks is found to be proportional to the acceleration. We show that this resonant structure can also be understood as a temporal quantum interference effect. [S0031-9007(96)00369-9]

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Motion of ultracold atoms in optical lattices formed by interfering beams of light has become an active area of research in recent years. Most work so far has concentrated on near-resonant optical lattices, where the internal atomic structure plays an important role, and a wide range of phenomena have been observed [1,2]. In the limit of large detuning from resonance, spontaneous scattering can be neglected, and the optical lattice creates a dipole potential for the atoms. An interesting direction is to utilize optical dipole forces due to an accelerating standing wave of light to launch laser-cooled atoms, creating a cold atomic beam that could be used for atomic interferometry and atom optics [3,4]. This method has the advantage of negligible transverse heating which is a problem for the case of resonant radiation pressure. Ultimately, by using longer-period standing waves and weak potentials, this approach may enable launching of sub-recoil atoms. For sufficiently weak potentials it is clear that quantum effects in atomic motion can dominate, and a detailed study of quantum transport in optical lattices is important.

Following this direction, we report the first observation of atomic Wannier-Stark ladders in a potential formed by an accelerating standing wave of light. This is a fundamental effect of quantum transport in optical lattices. Wannier-Stark ladder resonances were predicted to occur in the band structure of an electron moving in a periodic lattice with a dc electric field [5], and have been the topic of extensive study in condensed-matter physics. Although this phenomenon was controversial for many years [6], it was recently observed in superlattices [7]. Our work is the first spectroscopic study of Wannier-Stark ladders free from complications such as the impurities, lattice vibrations, and multiparticle interactions present in solids.

We consider the motion of ultracold atoms in an accelerating potential of the form $V_0 \cos[2k_L x - k_L a t^2 + \lambda \cos(2\pi \nu_p t)]$, where a is the acceleration, ν_p is the modulation frequency, and λ is the dimensionless modulation amplitude. In the reference frame of the standing wave, this potential becomes

$$V_0 \cos(2k_L x) + Max + \frac{(2\pi \nu_p)^2 M \lambda}{2k_L} x \cos(2\pi \nu_p t), \tag{1}$$

where M is the mass of the atom. This equation is analogous to the condensed-matter problem, where the first term is the periodic potential, the second term acts like a dc electric field, and the third term is the ac probe. In our experiments the periodic potential is created by a standing wave of light. An atom in a far-detuned standing wave of light experiences a potential of the ground state given by $V_0 \cos(2k_L x)$ where V_0 is known as the optical dipole potential [8]. In the large detuning regime, spontaneous scattering can be neglected.

The quantized energy band structure for $V = V_0 \cos(2k_L x)$ is displayed in Fig. 1. It shows the energy–wave number dispersion relation in the first Brillouin zone [9]. Figure 2 displays the energy band structure in space. It shows that the lowest energy band is the only band completely contained in the wells, which clearly illustrates that this regime is deep in the

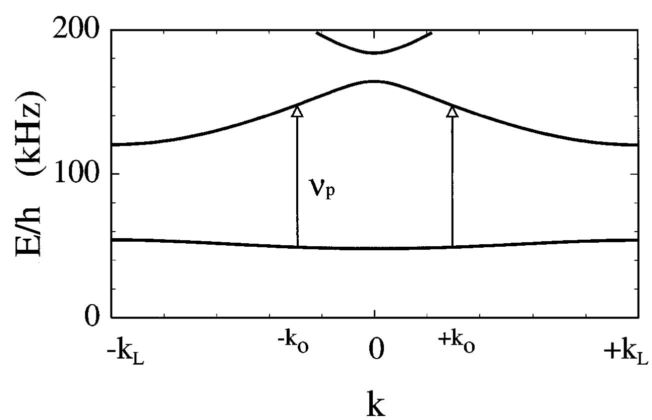

FIG. 1. Band structure of an optical lattice, with $V_0/h = 68$ kHz. This is shown for the reciprocal lattice in the reduced zone scheme, limited to the first Brillouin zone, $[-k_L, +k_L]$. In the experiment, a phase modulation at frequency ν_p drives transitions between the two lowest bands. This modulation is resonant for two wave numbers, $\pm k_0$.

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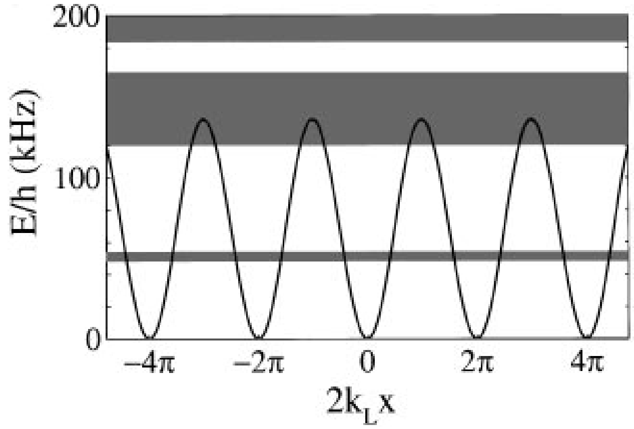

FIG. 2. Band structure of an optical lattice, with $V_0/h = 68$ kHz. The curved line is the periodic potential plotted as a function of position, x. The allowed energy bands are the shaded regions, while the energy gaps are blank.

quantum limit. When the standing wave is accelerated, the atomic wave number (k) changes in time and the atoms move periodically across the first Brillouin zone, a phenomenon known as Bloch oscillations. The Bloch period, T_B, is given by $T_B = 2\hbar k_L/Ma$, and the Wannier-Stark ladder splitting is the inverse Bloch period. The periodic Bloch oscillations within each band can be interrupted by Landau-Zener (nonadiabatic) tunneling between bands [10].

In order to observe the Wannier-Stark ladder, we add a phase modulation at ν_p to the accelerating optical potential. The ac field can drive resonant transitions between the first two bands as indicated by the arrows in Fig. 1. For appropriate values of the acceleration, the Landau-Zener tunneling rate from the lowest band is negligible, while the tunneling rate from higher bands is large [11]. Therefore only the atoms in the lowest band are accelerated, while atoms in the higher bands are left behind. By applying a weak phase modulation and measuring the number of atoms that are accelerated, the probability of excitation can be studied. A theoretical analysis of this problem finds that the transition probability as a function of modulation frequency displays several equally spaced resonances, which are identified as an atomic Wannier-Stark ladder [11].

The experimental study of this system relies on cooling and trapping of atoms to prepare the initial conditions. A magneto-optic trap (MOT) in the $\sigma^+ - \sigma^-$ configuration is used to trap and cool sodium atoms [8]. A single-mode dye laser is servolocked 20MHz to the red of the $(3S_{1/2}, F = 2) \rightarrow (3P_{3/2}, F = 3)$ transition at 589 nm. Optical pumping to the $F = 1$ ground state is prevented by a sideband at 1.712 GHz. A cloud of approximately 10^5 atoms forms a spatial Gaussian distribution with $\sigma_x = 0.12$ mm. The Gaussian momentum distribution has a width of $\sigma_p = 5\hbar k_L$ centered at $p = 0$. This sample is sufficiently dilute that atom-atom interactions are negligible. After the cooling and trapping stage, the MOT laser beams and magnetic field gradient are turned off.

The accelerating standing wave is provided by a second stabilized single-mode dye laser tuned far (up to 20 GHz) from atomic resonance. The output beam from this laser is split. One beam is aligned through a 40 MHz acousto-optic modulator (AOM) in a double-pass configuration, and the twice-diffracted spot is used (nominally offset by 80 MHz), enabling the tuning of the beam frequency over a range of 4 MHz without significant misalignment. This beam is then aligned through an electro-optic phase modulator to enable periodic phase modulation of the standing wave. The other beam is aligned through an 80 MHz AOM using the first-order diffracted spot. The beams are linearly polarized, spatially filtered, and aligned on the trapped atoms in a counterpropagating configuration, with a beam waist of 2.4 mm in the center of the trap. The beams are turned on simultaneously (in less than 150 ns) and a subset of atoms are trapped and accelerated. Prior to the interaction, the atoms are optically pumped into the $3S_{1/2}, F = 2$ hyperfine ground state but are not optically pumped into a particular Zeeman sublevel. This is not a problem in the experiment since the optical dipole potential created by far-detuned, linearly polarized light is the same for the different sublevels [12]. The frequency stability between the two beams was measured by an optical heterodyne to be better than 2 kHz. The standing wave is accelerated by varying the frequency difference of its two beams linearly in time. A linear ramp of 4 MHz in 800 μs (in one beam) creates an accelerating potential of 1500 $\mathrm{m/s^2}$. In the experiments described here, accelerations of up to 1800 $\mathrm{m/s^2}$ were used, with interaction times of up to 1 ms. For these parameters, the Landau-Zener tunneling rate from the lowest band is negligible, as described earlier. The tunneling rates are determined from a theoretical analysis [11], and the numerical results are in agreement with simple estimates in the adiabatic regime. We have also studied experimentally the tunneling rates from the lowest band in the regime of larger acceleration, and find good agreement with the theoretical analysis. The final velocity of the standing wave was chosen to be 1.2 m/s (momentum of $40\hbar k_L$). As shown in Fig. 3(a), this velocity is sufficient to distinguish the trapped atoms from the rest of the distribution.

After interacting with the accelerating standing wave the atoms drift in the dark for 3 ms, then the $\sigma^+ - \sigma^-$ beams are turned back on without the magnetic field gradient, forming optical molasses [8]. The motion of the atoms in the molasses is effectively frozen for short times during which the fluorescence is recorded on a charge coupled device camera [13]. Intensity fluctuations in the trapping laser are stabilized to approximately 1% to enable good background subtraction of scattered light. The resulting

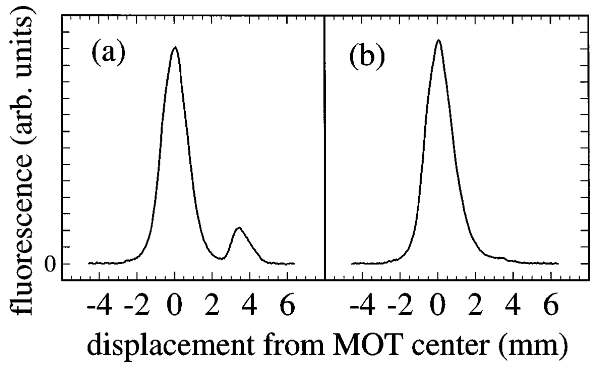

FIG. 3. Distribution of atoms after exposure to an accelerating standing wave. The displacement is the distance from the atoms' initial location in the magneto-optic trap. The fluorescence is proportional to the number of atoms at a given displacement. In (a) a fraction of the atoms was trapped by the standing wave and accelerated for 650 μs to a final velocity of 1.2 m/s. The atoms then drifted ballistically for 3 ms, allowing them to separate spatially from the main distribution. Here $V_0/h = 68$ kHz. In (b) the fraction of trapped atoms was dramatically reduced by adding a modulation $\lambda = 0.13$ to the standing wave at a frequency of $\nu_p = 87$ kHz. At this frequency, atoms are driven to the second band and lost by Landau-Zener tunneling, leading to a flat shoulder in the distribution.

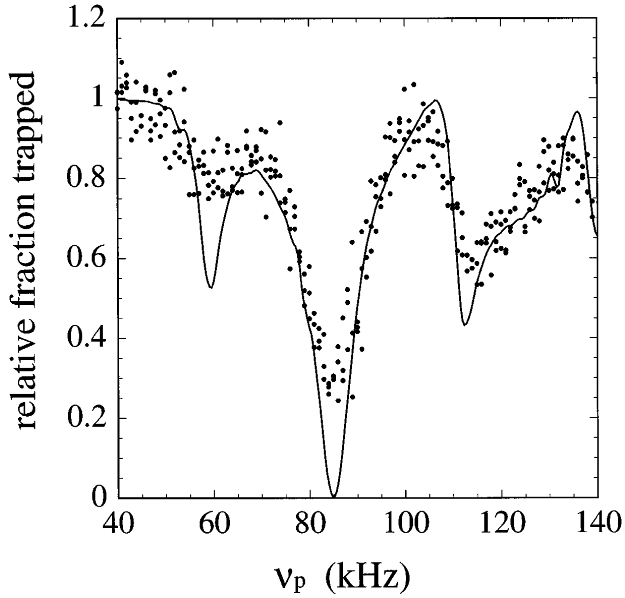

FIG. 4. Wannier-Stark ladder resonances. Each point represents an experimental run as shown in Fig. 3(b). The fraction of trapped atoms is normalized to the number that is trapped when no modulation is applied [Fig. 3(a)]. For this spectrum, the experimental parameters are $V_0/h = 75 \pm 7$ kHz, $a = 1570 \pm 10$ m/s^2, and $\lambda = 0.096 \pm 0.002$. The final velocity was 1.2 m/s. The solid line is a quantum numerical simulation, which uses the experimental parameters.

2D images are integrated to give the 1D distribution along the standing-wave axis. The final distributions are characterized by two peaks: the larger one centered around $x = 0$ corresponds to atoms that are not trapped by the standing wave. The smaller peak is from the atoms that were trapped and is centered around $x = 3.5$ mm. Examples of these distributions are shown in Fig. 3. The distribution in Fig. 3(a) was made with the phase modulation off and was used to normalize the distributions with the phase modulation on. In Fig. 3(b), the modulation frequency was set at a Wannier-Stark resonance, and the accelerated peak is nearly gone. In this case, there is a flat shoulder corresponding to atoms that are driven out of the well during the acceleration. Because the final velocity is fixed, we change the linear ramp time of the frequency offset to obtain different accelerations. The ramp times were varied in the range from 650 to 1000 μs, corresponding to accelerations that range from 1200 to 1800 m/s^2. A spectrum is measured by scanning ν_p in 1 kHz steps over a range of (typically) 100 kHz, and each frequency step is repeated several times. The amplitude of phase modulation was adjusted to optimize the visibility of the resonances. We found that the optimum was $\lambda = 0.096$ where a 50% increase in the amplitude caused noticeable broadening. The laser intensity and detuning were adjusted to give $V_0/h = 68$ kHz; this value gave the desired band structure that is shown in Fig. 2.

An example of a measured spectrum is shown in Fig. 4; it has two clear resonances which are necessary to determine the Wannier-Stark splitting. The theoretical curve is the result of a numerical integration of the time-dependent Schrödinger equation that used the experimental conditions [11]. In our first measurements of the spectra the resonances were resolved but broader than predicted by the numerical simulations. We found that this was due to the small Gaussian variation of the well depth for atoms that move transversely with respect to the standing wave. The absolute locations of the resonances are sensitive to the well depth, and as atoms move transversely across the spatial Gaussian profile of the standing wave their resonances shift. The resonant frequencies are in the range of 100 kHz while the splittings are 3 to 4 times smaller, therefore even a 5% variation of the resonant frequency is significant. To verify this picture, we limited the binning window on the 2D images so that in one transverse direction we restricted our measurement to a subset of colder atoms. We found that this procedure gave narrower resonances, and it was used in all the data that are shown.

The Wannier-Stark splitting as a function of acceleration was determined from a range of spectra, and the results are shown in Fig. 5. These results are consistent with the predicted linear scaling, within the experimental uncertainty. The range of possible accelerations was limited in the experiment: for smaller acceleration, the resonances are not cleanly resolved, while for larger acceleration the splitting becomes comparable to the width of the second band.

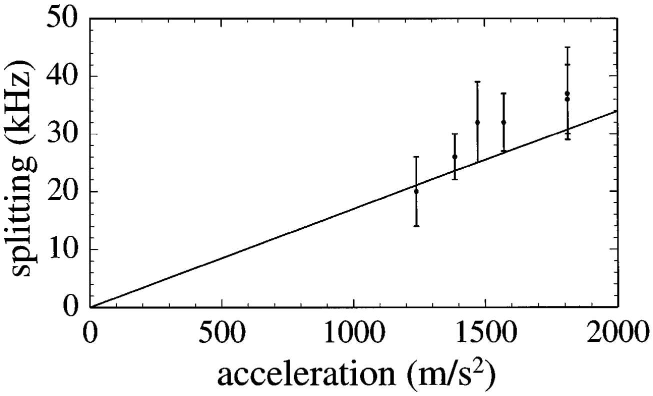

FIG. 5. Splitting between Wannier-Stark ladder resonances as a function of standing-wave acceleration. Each splitting was measured from a spectrum as shown in Fig. 4, for a range of different accelerations, and with the other parameters kept the same. The theoretical prediction of $\Delta\nu = aM/2\hbar k_L$ is shown by the solid line.

A simple physical picture of quantum interference from multiple temporal slits can be used to describe the Wannier-Stark ladder. A two-slit temporal interference effect was previously observed with nanosecond pulses interacting with an atomic beam of sodium [14]. The probability for absorption of a weak ac probe was derived for the case of a one-dimensional lattice in an external dc electric field [15]; however, the interpretation of the results as a quantum interference effect was not discussed. Consider an atom in the lowest energy band undergoing Bloch oscillations across the first Brillouin zone. The resonance condition for a weak phase modulation (frequency ν_p) occurs at $\pm k_0$, as shown in Fig. 1. During one Bloch period T_B the atom experiences two resonant drives separated in time. The probability for an atom to make a transition to the second band after undergoing N Bloch oscillations was shown [15] to be proportional to

$$\frac{\sin^2(\beta_b N/2)}{\sin^2(\beta_b/2)}, \qquad (2)$$

where β_b is a function of ν_p. This is the result for multiple-slit interference and is most familiar in the context of optics [16]. Temporal quantum interference provides physical insight for the appearance of the Wannier-Stark ladder, but it cannot predict the details of the spectrum (Fig. 4), such as peak height, width, and exact location of the resonances.

In summary, we have observed Wannier-Stark ladder resonances by direct probe spectroscopy of the band structure of atoms in an accelerating potential. These results, combined with the recent observation of atomic Bloch oscillations [17], establish atom optics as an exciting testing ground for quantum transport in lattices.

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