Observation of atomic tunneling from an accelerating optical potential

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We observe quantum tunneling of cold sodium atoms from an accelerating one-dimensional standing wave of light. Atoms are trapped in a far-detuned standing wave that is accelerated for a controlled duration. For sufficiently large values of the acceleration, we observe an exponential decay in the number of atoms that remain trapped as a function of the interaction time. We show that this loss is due to quantum tunneling, and compare the decay rates with Landau-Zener theory. We also observe oscillations in the tunneling rate as a function of the acceleration which are due to quantum interference effects. [S1050-2947(97)50702-5]

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Tunneling in the center-of mass motion of atoms should become an important process at the low temperatures that are now achieved with laser cooling. This can appear, for example, as a loss mechanism for atoms confined in an optical lattice constructed from interfering beams of light. While atomic motion in these structures has become an active area of research [1,2], tunneling has been obscured by spontaneous scattering [3].

An alternative atom optics system where tunneling can be significant has appeared in our efforts to develop a cold atomic beam for interferometry. Our approach has been to launch laser-cooled atoms in the potential created by an accelerating, far-detuned, standing wave of light. This system was previously used to study Wannier-Stark ladders [4] and Bloch oscillations [5]. The results reported in this Rapid Communications provide an observation of tunneling in atom optics, and the high degree of experimental control has enabled a quantitative comparison with theory.

We consider atomic motion in an accelerating standing wave of light. For sufficiently large detuning from atomic resonance, the atoms remain in their internal ground state and experience an effective one-dimensional potential given by $V_0\cos[2k_L(x-at^2/2)]$, where $k_L=2\pi/\lambda_L$ is the wave number, and a is the acceleration of the standing wave [6]. The well depth V_0 is the amplitude of the optical dipole potential. It is proportional to the laser intensity and inversely proportional to detuning from atomic resonance. We neglect variations of the potential in the two transverse directions, which is justified for beams that are sufficiently large compared to the size of the atomic cloud.

To obtain a simple physical picture of the atomic tunneling process, it is instructive to transform the potential into the comoving coordinates of the accelerated atoms, $V_0\cos(2k_Lx')+Max'$, where M is the mass of the atom and x' is the coordinate in the accelerated frame. This is a periodic series of wells that is tilted. What is the largest acceleration that can be imposed on an atom for a given well depth? The classical answer to this question is given by $a_{cl}=2k_LV_0/M$, and for accelerations smaller than this value a particle can be trapped in one of the wells. Once trapped, it cannot escape from the potential. Quantum mechanics, however, allows for tunneling from the wells to the continuum, in striking contrast to the classical prediction. Tunneling leads to a loss rate for much smaller values of the acceleration, and is the ultimate limiting factor for this atom accelerator.

A complementary model of tunneling from the accelerating periodic lattice can be developed using the concept of energy bands [7,8]. To briefly describe this picture, consider the band structure of the reciprocal lattice. Atoms are initially prepared in the lowest band. When the standing wave is accelerated, the wave number changes in time and the atoms undergo Bloch oscillations across the first Brillouin zone. As the atoms approach the band gap, they can make Landau-Zener transitions to the next band. Once the atoms are in the second band, they rapidly undergo transitions to the higher bands and are effectively free particles [8].

The experimental study of this system relies on cooling and trapping of atoms to prepare the initial conditions. A magneto-optic trap (MOT) [9] was used to trap and cool sodium atoms as described previously [10]. The resulting cloud of approximately 10^5 atoms was a spatial Gaussian distribution with $\sigma_x=0.15$ mm. The momentum distribution was also Gaussian with a width of $\sigma_p=6\hbar k_L$ centered at $p=0$ (in the laboratory frame). After the cooling and trapping stage, the MOT laser beams and magnetic field gradient were turned off.

A counterpropagating pair of linearly polarized laser beams from a second single-mode stabilized dye laser was then turned on to form the optical standing wave. Both beams were spatially filtered and the beam waists were measured to be 1.9 mm at the center of the trap. The power in each beam was adjusted for different runs in the range of 30–45 mW, and digitized on separate calibrated photo diodes. The frequency of the beams was tuned in the range 18–24 GHz from the $(3S_{1/2},F=2)\rightarrow(3P_{3/2},F=3)$ transition at 589 nm. (Both red and blue detunings were used in the experiments and the results are independent of the direction.) The detuning was monitored on a NIST Lambda Meter with an accuracy of 100 MHz. These parameters yielded a range of well depths $V_0/h=55-110$ kHz (2.2–4.4 in units of the single-photon recoil energy). Under these conditions there was only a single quantized energy state in each well leading to only one relevant tunneling rate.

With the two beams at the same frequency, the resulting standing wave is stationary in the laboratory frame. The frequency stability between the two beams of the standing wave

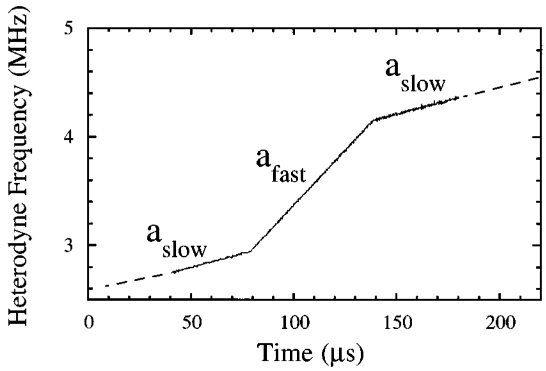

FIG. 1. Three-stage acceleration process used to study tunneling. This figure is a digitized heterodyne signal of the two counter-propagating beams, taken as the frequency difference was varied. The vertical axis is in units of MHz, and the horizontal axis is in units of μ s. A slope of 5.1 kHz/μs corresponds to an acceleration of 1500 m/s^2.

was measured by optical heterodyne to be better than 5–10 kHz over several minutes. An acousto-optic modulator was used to introduce a frequency shift between the counter-propagating beams; a frequency shift of 100 kHz gives a drift velocity of one photon recoil ($v_r = 3$ cm/s). The standing wave was accelerated by linearly ramping this shift [4].

Atoms initially trapped in the MOT can be (1) trapped and accelerated by the standing wave for the duration of the experiment, (2) trapped for some time before tunneling out of the wells, or (3) not trapped at all by the standing wave. The first category of atoms is the one of interest: the number of atoms in this group is proportional to the survival probability for the duration of the acceleration. To distinguish these surviving atoms from those that were lost from the wells, we implemented a three-step acceleration sequence using an arbitrary waveform generator to drive the acousto-optic modulator.

Figure 1 shows how the acceleration was varied to separate each category of atoms in velocity. After the MOT fields were turned off, the standing wave was turned on for 20 μs with zero acceleration; a portion of the cold atoms was trapped in the potential wells at that point. The potential was then accelerated at a (typical) rate $a_{slow} = 1500$ m/ s^2 until the standing wave reached an intermediate velocity v_{int} (typically 1.05 m/s). This stage separated the trapped atoms from the rest of the distribution. The loss from the wells due to tunneling is negligible during a_{slow}. The acceleration was then switched to a higher value (a_{fast}) in the range 4500–10000 m/ s^2, which changed the tilt of the potential, thus increasing the tunneling probability between the bound state and the continuum. After a controlled period of time T, the acceleration was switched back to a_{slow} in order to isolate the surviving atoms from those that had tunneled. This acceleration was maintained until the standing wave reached the final velocity v_f (typically 2.4 m/s), after which the beams were turned off.

In the detection stage, the atoms drifted in the dark for 3 ms, leading to a spatial separation of the velocity classes. The atoms were then exposed to an optical molasses [9] that effectively froze their motion for short times during which the fluorescence was recorded on a charge-coupled-device

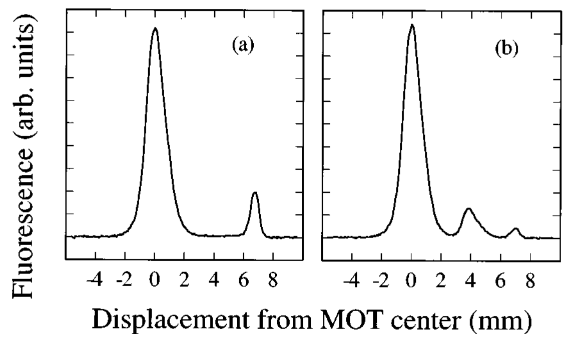

FIG. 2. Distribution of atoms after exposure to an accelerating standing wave. The displacement is the distance from the atoms' initial location in the magneto-optic trap. The fluorescence is proportional to the number of atoms at a given displacement. In (a) a fraction of the atoms was trapped by the standing wave and accelerated for 1500 μs to a final velocity of 2.2 m/s. The atoms then drifted ballistically for 3 ms, allowing them to separate spatially from the main distribution. Here $V_0/h = 92$ kHz. In (b) a fast acceleration of 10000 m/ s^2 was turned on for a duration of 47 μ s leading to substantial tunneling.

camera [10]. Intensity fluctuations in the trapping laser were stabilized to approximately 1% to enable good background subtraction of scattered light. The resulting two-dimensional (2D) images were integrated to give the 1D distribution along the standing-wave axis. A binning window on the 2D images limited the measurement to a set of atoms that were colder than the initial conditions in one of the transverse directions [4].

The two-peaked distribution shown in Fig. 2(a) represents atoms trapped and accelerated to v_f, for $a_{slow} = 1500$ m/s^2 and $T = 0$. The large peak centered around $x = 0$ corresponds to atoms that were not trapped by the standing wave. The small peak at $x = 7$ mm corresponds to atoms that remained trapped and were accelerated to v_f; the area of this peak is proportional to the number of these atoms. The clean separation of the two peaks for a_{slow} indicates that tunneling is negligible, and this is supported by a theoretical analysis described below. The distribution in Fig. 2(b) is for the case when $a_{fast} = 10000$ m/ s^2 and $T = 47$ μs. It shows a three-peak distribution. The middle asymmetric peak represents atoms that tunneled out of the wells, and the peak on the right represents the surviving atoms. The normalization is taken to be the total area under these two peaks, which is proportional to the number of atoms initially prepared in the lowest band.

To determine a decay rate, we varied T and measured the survival probability with all the other parameters fixed. The result of a typical run is displayed in Fig. 3(a), and clearly demonstrates an exponential decay in the survival probability. The slope of this curve is a measurement of the tunneling rate Γ.

In order to claim that the loss of atoms is due to tunneling, it is necessary to rule out other loss mechanisms that would also appear as an exponential decay. Several possibilities are amplitude and phase noise of the optical potential, switching between different accelerations, and spontaneous scattering. The amplitude and phase noise were studied using photodiode signals and optical homodyne measurements, respectively. The signal levels of phase noise in these experiments

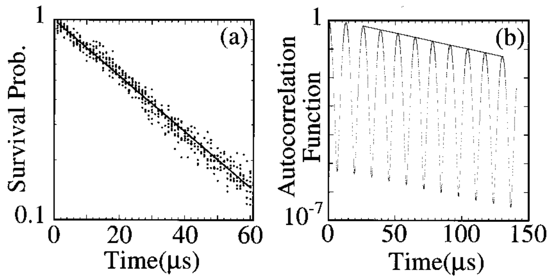

FIG. 3. (a) Example of experimentally measured survival probability for $a_{slow}=1200$ m/s^2, $a_{fast}=4500$ m/s^2, and $V_0/h=50.8$ kHz as a function of the duration of the fast acceleration. Note that the vertical axes are logarithmic. The solid line is an exponential fit to the data. (b) Theoretical autocorrelation function (squared modulus of the projection of the time-evolved state onto the initial state) for the case $a=4500$ m/s^2, and $V_0/h=55$ kHz. The solid line is an exponential fit to the peaks of the oscillations, starting from the third peak to avoid short-time, nonexponential effects.

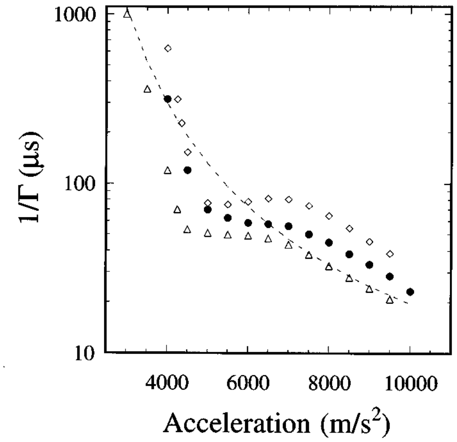

FIG. 4. Tunneling rate as a function of acceleration. The experimental data are marked by solid dots. The uncertainty in the exponential fits that determine Γ are typically $\pm 2\%$, and the uncertainty in the acceleration for the range shown is ± 50 m/s^2. The dashed line is the prediction of LZ theory. The experimental well depth was $V_0/h=72$ kHz with an uncertainty of $\pm 10\%$. The data are bracketed between quantum simulations for wells depths of $V_0/h=60$ kHz (empty triangles) and $V_0/h=72$ kHz (empty diamonds), and the LZ prediction is for an intermediate value $V_0/h=66$ kHz.

were far below those required to cause any observable loss of atoms in our previous study of Wannier-Stark ladders [4]. Depletion of the trapped atoms could be induced by adding a much larger level of phase noise. The amplitude of each run was monitored on a digital storage oscilloscope, and traces with amplitude spikes were rejected. Fast switching between different accelerations has high-frequency components that could possibly drive atoms out of the wells. We checked this by varying the switching times but did not observe any such loss. Spontaneous scattering could induce loss from the accelerating potential and must be minimized in order to study tunneling. For the experiments described here, the probability of spontaneous scattering is estimated to be 10% for an interaction time of 1 ms. Since the period of large acceleration was at most 200 μs, the spontaneous scattering probability during that crucial interval is negligible. In general, we did not observe any loss of atoms during a_{slow}, which would have appeared as a shoulder between the two peaks.

We now show that the observed decay rates are in good agreement with the predictions of quantum mechanics. Figure 4 displays our measurements of $(\Gamma)^{-1}$ as a function of acceleration. The well depth in this case is $V_0/h=72$ kHz with an uncertainty of $\pm 10\%$. The corresponding band structure in the absence of acceleration has one band contained within the wells with a width of 5 kHz. The gap between the first and second bands is 70 kHz, and the second band has a width of 40 kHz. The dashed curve is a theoretical prediction of the tunneling rate from Landau-Zener (LZ) theory $\Gamma_{LZ}=(a/2v_r)\exp(-a_c/a)$. Here $a_c=2\pi(E_{gap}/2)^2/2\hbar^2k_L$ is a critical acceleration, where E_{gap} is the energy gap between the first and second bands [8,11]. This formula is derived from a simple two-level model with an avoided crossing between the levels, assuming that the transition only occurs at the avoided crossing. It is frequently used in atomic and molecular physics to describe collisions; however, it is difficult in those cases to obtain the LZ rates from first principles due to the complexity of the potential curves. The present atom optics system provides a unique opportunity for absolute comparison with theory, and it is interesting to see how the tunneling rates compare with the LZ prediction. We see that the experimental points (solid dots) approximately follow the LZ prediction, but clearly display oscillations as a function of the acceleration. At large values of the acceleration, the results approach the LZ curve, while at the smaller values the deviations become larger and sharper.

What is the physics behind these oscillations? The LZ model assumes that the inter-band transitions occur only at the band gaps (the points of closest approach between the bands), and that there are no correlations between successive periods of the Bloch oscillation. In the present system, the band curvature is not large, and transitions are no longer limited to the gap but can occur at different points along the band. A theoretical analysis of this problem shows that, in a single Bloch period, there are contributions to the tunneling probability at points of both nearest and farthest approach between the bands, where their curvature is zero [12]. Contributions from other points along the band cancel out. This leads to interference effects in the tunneling probability that depend on the Bloch period. The period of oscillation is proportional to a, while the amplitude of the oscillation is inversely proportional to a. At smaller values of the acceleration, deviations about the LZ prediction are considerably larger. This is physically reasonable because coherent effects become dominant when tunneling is suppressed. The extreme case is the coherent regime of Bloch oscillations and Wannier-Stark ladders where tunneling from the trapped state plays no role. The interplay between coherent and irreversible effects has been studied theoretically and observed, for example, in atomic physics experiments [13,14]. The present experiments, however, enable a detailed study of these effects in a much simpler setting, and with no adjustable parameters.

These oscillations are also seen in the quantum simulations shown in Fig. 4 where the time-dependent Schrödinger equation is solved for $a=a_{fast}$. The initial condition is simply taken to be the lowest state of the potential with $a=0$ and its survival probability is calculated from the projection of the time-dependent solution onto the initial state. As seen from Fig. 3(b), this autocorrelation function exhibits Bloch oscillations with decaying amplitude. The decay of the peaks is clearly exponential and the computed time constant for this ideal calculation provides the tunneling rate used in the comparison with experiment. The largest experimental uncertainty for this comparison with theory is in the well depth V_0 ($\pm 10\%$), and the experimental data are bracketed between two numerical simulations. Given the high sensitivity of tunneling rate to the well depth, the agreement with *an ideal simulation* over the range of accelerations is quite good, and further confirms the observation of tunneling.

In summary, we have observed tunneling of cold atoms from an accelerating optical potential. Future directions include the study of the effects of noise on quantum tunneling, and the study of the tunneling probability for short times where deviations from exponential decay should occur [15].

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