Atom trapping in nondissipative optical lattices

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Laser-cooled ^{7}Li atoms have been confined in three-dimensional spatially periodic potentials that are nearly conservative. The potentials were formed from the intersection of four laser beams far-detuned from the optical resonance. By adjusting the relative orientations of the beams, lattices with primitive translation vectors larger than the laser light wavelength were created. We achieved an effective temperature of ~80 μK through adiabatic reduction of the confining potential strength, and prepared ensembles with effective temperatures of ~1.8 μK by initially confining atoms in weak potentials. [S1050-2947(96)50406-3]

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Recent laser cooling experiments have focused on the center-of-mass motion of ultracold atoms in spatially periodic light-induced potentials. Important results have included the discovery of sub-Doppler laser cooling mechanisms [1], observation of Lamb-Dicke confinement of atoms, and quantization of atomic motion [2]. A feature common to these studies is that the atom-laser interactions were in a regime where spontaneous emission damps the atomic motion.

In this Rapid Communication, we study the motion of lithium atoms in an optical lattice created by laser light far-detuned from the atomic resonance [3]. In this limit, optical dipole forces dominate nonconservative scattering forces. This has important consequences. First, it allows construction of lattices with potential-well periodicities greater than the wavelength of the lattice trapping light. Such lattices are capable of confining ensembles of atoms with mean kinetic energy less than the photon recoil limit $E_r=(\hbar k)^2/2m$ (k is the wave number of the lattice laser beam and m is the atomic mass). Because of the atom's greater position uncertainty, lower momentum uncertainty and thus subrecoil energies may be achieved with large periodicity wells. Ultracold atomic sources have important applications in precision measurements [4] as well as in studies aimed at observation of quantum many-body effects in dilute vapors [5]. Second, such lattices only weakly perturb the internal energy levels of the atom while providing strong spatial confinement. Thus, far-detuned lattices may provide an excellent environment for high-resolution spectroscopic studies. Finally, under certain conditions, the time between spontaneous emission events can be much longer than the time an atom resides in a primitive lattice cell. In that case, quantum coherence plays a significant role in wave-packet motion through the lattice, enabling studies of, for example, anomalous diffusion and localization [6].

In our experiment three-dimensional (3D) lattices of laser intensity maxima and minima were formed from the interference of four mutually intersecting laser beams. The frequency of the lattice laser beams was turned near the Li $2S\rightarrow 2P$ transitions. The ac Stark shifts of the $2S$ atomic energy levels due to the lattice laser beams were comparable to the 140-μK initial kinetic energy of the laser-cooled atoms. The detuning of these beams was far enough from the $2S\rightarrow 2P$ transitions that weak excitation to the $2P$ levels resulted in a spontaneous emission rate of less than one photon every 10 msec. Atoms were confined in lattices for times on the order of ~100 msec using laser detunings as large as 10 nm to the red and 1 nm to the blue of the $2S\rightarrow 2P$ atomic resonances. With red-detuned light, atoms were trapped near intensity maxima, while for blue-detuned light, atoms were trapped near intensity minima.

Once confined in the lattice, atoms were cooled by adiabatically reducing the intensity of the lattice laser light. Recently this technique has been used to cool Cs atoms to temperatures of ~6 T_r ($k_B T_r \equiv E_r$) in three dimensions [7], and previously to cool Li in one dimension to ~4 T_r [8]. In principle, cooling in lattices of periodicity greater than λ can produce effective temperatures below the single-photon recoil limit. Final temperatures, however, are also limited by the initial energy distribution of atoms confined in the lattice. In our experiments, final effective temperatures were ~26 T_r (80 μK), a factor of ~2 colder than the initial temperature in our optical lattice.

We have also demonstrated that large periodicity lattices can support rms momentum spreads of less than a photon recoil. This has been accomplished by reducing the initial intensity of the lattice light so that only the coldest atoms from the atomic source are confined by the lattice. Using this technique, we have prepared ensembles having an effective temperature of 0.6 T_r (1.8 μK).

The experimental details are as follows. The output of a dye laser tuned near the 671-nm $2S_{1/2}$-$2P_{3/2}$ resonance of lithium was split into four separate beams. The beams were made to intersect inside a UHV vacuum chamber with a base pressure of 5×10^{-9} Torr. The beams were focused to a $1/e^2$ diameter of 500 μm at the point of intersection and were aligned to propagate along the [1 0 0], [0 1 0], [0 0 1], and [1 1 1] directions. Due to the low spontaneous emission rates, lattice propagation vectors need not be chosen to balance spontaneous scattering forces. For laser detunings to the red of the $2P$ resonances, the beams were linearly polarized in the [0 1 1], [1 0 1], [1 1 0], and [1 1 0] directions, respectively. In this geometry, the corresponding primitive lattice translation vectors are $\mathbf{a}_1=\lambda(\sqrt{3}-2,1,1)/(3-\sqrt{3})$, $\mathbf{a}_2=\lambda(1,\ \sqrt{3}-2,\ 1)/(3-\sqrt{3})$, and $\mathbf{a}_3=\lambda(1,\ 1,\ \sqrt{3}-2)/(3-\sqrt{3})$. The corresponding nearest-neighbor spacings are $|\mathbf{a}_i|=1.13\lambda$ ($i=1,2,3$) (see Fig. 1). For blue detunings we used orthogonal-linear polarizations for the first three beams, and chose circular polarization for the beam along the [1 1 1]

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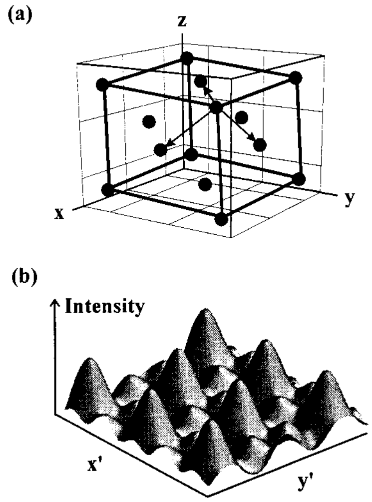

FIG. 1. (a) Schematic illustration of the red-detuned optical lattice geometry. The primitive translation vectors of the periodic lattice are shown with arrows, and the high-intensity regions by filled circles. (b) Cross-sectional view of the resulting interference pattern. The $\mathbf{x}'$-$\mathbf{y}'$ cut is perpendicular to the [1 1 1] axis.

axis to create pockets of near-darkness surrounded by regions of high intensity light. The spatial density of potential wells was $\sim 10^{12}$ cm^{-3}. By defining the lattice with just four beams, time-phase fluctuations in the relative phases of the interfering beams translate the lattice but do not alter the shape of the lattice potential [9].

Lattices with periodicity much larger than λ in three dimensions can be created by reducing the angles subtended by each possible pair of the four lattice beams. For example, if the beams propagate parallel to the axes defined by the vectors (0 1 0.1), (0 1 −0.1), (0.2 1 0), and (0.2 1 0), the magnitudes of the corresponding primitive translation vectors are $|\mathbf{a}_1| = 5.10\lambda$, $|\mathbf{a}_2| = 5.63\lambda$, and $|\mathbf{a}_3| = 34.68\lambda$ [10].

The periodic potential $U_0(\mathbf{x})$ induced by the ac Stark shift of the ground-state atomic energy levels is $U_0(\mathbf{x})/\hbar = \Sigma_i \Omega_{r,i}^2(\mathbf{x})/\Delta_i$, where $\Omega_{r,i}(\mathbf{x})$ is the Rabi frequency for the ith optical transition and Δ_i is the detuning from this transition. This expression is strictly valid in the limit where the detunings are much larger than the natural linewidths (5.8 MHz for the Li $2P$ resonances), and is an excellent approximation for the detunings in our experiments. In principle, the potential strength also depends on the polarization of the light at position $\mathbf{x}$ and the ground-state Zeeman sublevel of the atom. However, in the limit where the detuning is much larger than the excited-state fine-structure splitting, these dependencies become negligible. For Li, the $2P_{1/2}$ level is separated from the $2P_{3/2}$ level by only 10 GHz, so this approximation holds in our experiments. The power in each of the four beams was 50 mW for the red-detuned lattice, which gave a peak intensity of 560 W/cm^2 at each lattice well site. At an intensity of 560 W/cm^2 and detuning of 1 nm, the ground-state energy shift is $23E_r$. The lattice potential is conservative in so far as the atom does not spontaneously scatter lattice photons. Since the scattering rate is $\tau_s^{-1} \sim \Gamma(\Omega_r^2/\Delta^2)$ in the limit $\Delta \gg \Gamma$, high laser intensities and large detunings are required for deep lattices and low scattering rates. For 560-W/cm^2 intensity and 1-nm detuning, the scattering time is $\sim$12 msec. With a blue-detuned lattice, the linearly polarized beams each had 33-mW power, while the circularly polarized beam had 100-mW power, yielding a peak intensity of $\sim$300 W/cm^2.

We loaded atoms into the lattice from a magneto-optic trap (MOT). Our trapping apparatus has been described in detail in an earlier publication [11]. In brief, the MOT was loaded directly from the low-velocity tail of a highly divergent lithium atomic beam. A separate dye laser was used to generate the laser light for the MOT. A fraction of the laser trapping light was spectrally broadened by passing a beam through a 12.5-MHz resonant electro-optic modulator to produce a comb of sidebands ranging in frequency from 134 to 9 MHz to the red of the $2S_{1/2}$, $F=2 \rightarrow 2P_{3/2}$, $F=3$ transition. This beam was used to enhance loading efficiency into the MOT. A second beam, tuned 4.5 MHz red of this transition, copropagated with the spectrally broadened beam. Both beams passed through an 816-MHz resonant electro-optic modulator in order to prevent optical pumping into the $2S_{1/2}$, $F=1$ states. With a magnetic field gradient of 6 G/cm, and total laser power of 400 mW, we routinely achieved densities of 2×10^{11} atoms/cm^3 at temperatures of 140 μK after a 300-msec loading time. The initial size of the MOT was $\sim$200 μm $1/e$ diameter.

The method for loading atoms from the MOT into the dipole force lattice (DFL) depended on the detuning of the lattice laser light. For red lattice detunings, the lattice light was turned on during the final 6 msec of the MOT loading cycle, after which the MOT trapping beams and magnetic field gradient were turned off. For blue detunings, the DFL beams were turned on at the instant that the MOT light and magnetic field were turned off. When the blue-detuned lattice light was on concurrently with the MOT light, atoms were found to be ejected from the trapping region.

We optimized the loading parameters by maximizing the number of atoms loaded into the lattice. After confining atoms in the DFL for a fixed holding time following the turn-off of the MOT, the DFL was switched off (switching time $\sim$10 μsec) and the optical molasses light was turned back on for $\sim$100 μsec. Light scattered from the atoms during this interval was imaged onto a calibrated charge-coupled-device (CCD) camera. The number of atoms was then extracted from the video image of the atomic distribution.

To align the lattice beams, we loaded atoms into traps formed by the intersection of pairs of the four red-detuned beams. This was done at a detuning where the dipole forces from a single beam were not sufficient to support atoms against gravity, but where the forces from a pair of beams trapped atoms in the intersection region. By maximizing the number of atoms trapped for each of the six possible independent beam pairs we were able to optimize the mutual overlap of all four beams. The alignment was then checked by tuning the lattice laser to the blue of the atomic resonance, changing the beam polarizations to those for a blue-detuned lattice, and then verifying that atoms remained confined in the overlap region. In the blue-detuned lattice configuration, atoms are confined only when all four beams intersect.

The number of atoms remaining in the lattice as a function of holding time after the MOT was turned off is shown in Fig. 2. For these curves, the lattice laser beams were de-

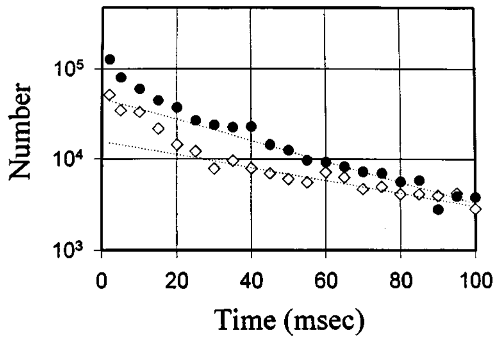

FIG. 2. Number of atoms remaining in lattice vs confinement time for detunings of 0.5 nm (circles) and 1.0 nm (diamonds).

tuned 0.5 and 1 nm to the red of the $2P$ resonance, corresponding to maximum well depths of $46E_r$ and $23E_r$, respectively. These curves are characterized by an initial fast decay followed by a longer exponential decay.

Spontaneous emission heats the atoms, taking them from bound states to nearly free states where they quickly leave the lattice region. The calculated time for an atom to gain enough kinetic energy to escape agrees well with the measured long exponential decay time. We verified this interpretation by measuring the loss rate for a lattice of the same strength, but having twice the spontaneous emission rate. This was done by reducing the intensity and detuning each by a factor of 2. The observed long exponential decay was twice as fast as that of the original lattice, which is consistent with the factor of 2 increase in the heating rate.

Another escape mechanism is diffusion of unbound atoms from the lattice region to the lattice edges. From Monte Carlo simulations of *classical* particle motion in the conservative lattice potential we find that, over the range of energies $-0.4\ U_{\max}<E\lesssim0.2\ U_{\max}$, particle motion is classically chaotic for the red detuned lattices ($-U_{\max}$ is the lattice potential minimum), as illustrated in Fig. 3(b) [12]. From these calculations, we estimate escape times of $\sim$10 msec for a 1-nm red-detuned lattice, in rough agreement with the observed fast decay rate. The fast decay is too rapid to be consistent with a collisional loss mechanism. Furthermore, lattice wells are expected to shield collisions for pairs of atoms in adjacent wells, and the probability of finding two atoms in the same well is small ($\sim$1%).

A third possible loss mechanism is tunneling to the edges of the lattice. We calculated the energy band structure for our lattice through standard application of the Bloch theorem in order to estimate the importance of this process. Figure 3(a) shows band energy as a function of quasimomentum along one of the reciprocal-lattice vectors for a red-detuned lattice $15E_r$ deep. For the lowest-lying energy bands, a tight-binding approximation [13] produced band energies that were consistent with the exact calculation. From the calculated dependence of nth band energy E_n on quasimomentum $\mathbf{q}$ we estimated the effective velocities $\mathbf{v}_{\text{eff}}=(1/\hbar)\nabla_{\mathbf{q}}E_n(\mathbf{q})$ in the lattice. We found that the maximum speeds range from 0.01 to 0.3 cm/sec in the lowest 15 bands. In the $\sim$100 msec duration of our experiment, the majority of atoms in these states travel significantly less than the spatial extent of the lattice. We also expect spontaneous emission to dephase the wave-packet coherences necessary to ensure ballistic transport. In this case, atomic motion becomes diffusive rather than ballistic, and the estimated escape times are substantially longer. Finally, other perturbations, such as temporal and spatial fluctuations in lattice strength, may also serve to localize atomic motion. We plan to study these mechanisms in future experiments.

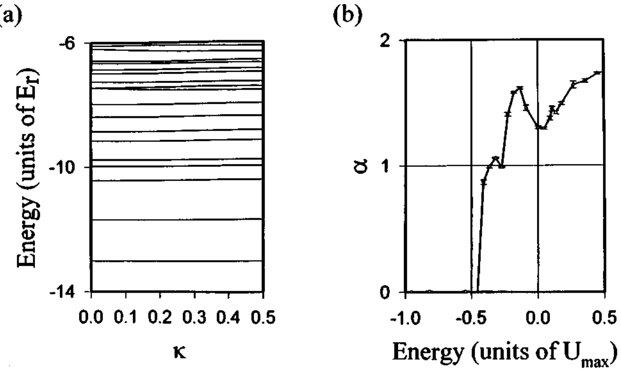

FIG. 3. (a) Energy vs quasimomentum for quasimomentum $\mathbf{q}=\kappa\mathbf{q}_1$, where the reciprocal-lattice vector $\mathbf{q}_1=(2\pi/\lambda)(1-\sqrt{3},\ 1,\ 1)/\sqrt{3}$ and $0\leq\kappa\leq0.5$. (b) Results of a Monte Carlo simulation of classical particle motion in the lattice. Particles of energy E were initially randomly positioned in a primitive lattice cell at time $t=0$. The subsequent mean-squared displacement $\langle\mathbf{x}(t)^2\rangle$ of the distribution was parametrized as Ct^{α}. For energies $-U_{\max}<E<-0.4U_{\max}$, $\alpha=0$, since particles are confined in potential minima (there is a saddle point in the potential at $-0.4U_{\max}$). For $\alpha=1$, motion is diffusive, while for $\alpha=2$ motion is ballistic.

We measured the velocity distribution of the trapped atoms using a time-of-flight technique. By imaging the size of the cloud a fixed delay (typically 2 msec) after the dipole trapping beams were shut off, we were able to infer the initial atomic velocity distribution from the ballistic expansion of the ensemble. The optical axis of the imaging system was in the [1 1 1] direction in the coordinate system used above to define the lattice propagation vectors. For strong red-detuned lattice potentials the measured velocity spreads were nearly as large as those of the atoms in the MOT. For weaker lattice potentials, only the coldest atoms in the MOT could be confined, and the measured velocity spreads were lower. For example, $\sim$4000 atoms were confined with an rms velocity spread corresponding to an effective temperature of 1.8 μK, nearly a factor of 2 below the single-photon recoil temperature of 3 μK. These measurements were made after a 10-msec holding time in the lattice, and the lattice beams were detuned 10 nm to the red of the $2P$ transition. The velocity distributions were observed to be nearly isotropic and nearly Gaussian. We checked for anisotropy in the third dimension by viewing the cloud from the [1 1 1] direction.

Atoms confined in the optical lattice were adiabatically cooled by slowly lowering the lattice potential. Atoms are cooled when the change in potential depth is slow enough that atomic population in a given energy band does not make nonadiabatic transitions to adjacent bands during the cooling period. In this limit, the atomic quasimomentum adiabatically maps onto real momentum as the potential is extinguished. Using this adiabatic approximation and knowing the initial distribution of atomic population in the energy bands allows the final momentum distribution to be calculated. For example, in a 1D lattice of periodicity a, atoms initially residing in the nth energy band have a final momentum $\mathbf{p_f}$ in the range $2\pi\hbar(n-1)/a<|\mathbf{p_f}|<2\pi\hbar n/a$ [7]. In principle, lattices with large periodicities are capable of yielding extremely low final momentum spreads. However, attaining such low effective temperatures requires a mechanism for loading atoms into the lowest energy bands.

Optimum adiabatic cooling results were obtained in a lattice configuration of tight, deep potential wells, where atoms were efficiently loaded into the lowest energy bands. By focusing the red-detuned beams to a 140-μm $1/e^2$ diameter we achieved a factor of 13 increase in laser intensity. The propagation direction of the [1 1 1] beam was reversed to reduce the lattice periodicity, and the laser was detuned $\sim$200 GHz to the red of resonance, resulting in an $\sim 20E_r$ energy splitting between the lowest-lying bands. By lowering the potential depth exponentially with a $1/e$ time constant of $\tau=400$ μsec just after turning off the MOT, the temperature of the ensemble was reduced by a factor of 2 to 80 μK. We note that cooling performance might be significantly enhanced by using other cooling methods (e.g., sideband cooling) to initially prepare atoms in the low-lying energy bands.

In summary, we have demonstrated atomic confinement in far-detuned optical lattices. The decreased scattering rate from far-detuned light has enabled the construction of lattices with periodicity greater than λ in three dimensions. Atoms were cooled by adiabatically reducing the intensity of the lattice light, and velocity-selected ensembles were prepared by trapping with weak lattices. Future work will investigate transport in these lattices, and evaluate their suitability for precision spectroscopic studies.

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[10] The primitive translation vectors have been derived using the following method. First, we form a set of reciprocal-lattice vectors $\mathbf{q}_1=\mathbf{k}_1-\mathbf{k}_2$, $\mathbf{q}_2=\mathbf{k}_1-\mathbf{k}_3$, and $\mathbf{q}_3=\mathbf{k}_1-\mathbf{k}_4$, where $\mathbf{k}_1$, $\mathbf{k}_2$, $\mathbf{k}_3$, and $\mathbf{k}_4$ are the propagation vectors for the lattice laser beams. From these we derive a set of lattice translation vectors $\tilde{\mathbf{a}}_1=2\pi(\mathbf{q}_2\times\mathbf{q}_3)/\mathbf{q}_1\cdot\mathbf{q}_2\times\mathbf{q}_3$, $\tilde{\mathbf{a}}_2=2\pi(\mathbf{q}_3\times\mathbf{q}_1)/\mathbf{q}_1\cdot\mathbf{q}_2\times\mathbf{q}_3$, and $\tilde{\mathbf{a}}_3=2\pi(\mathbf{q}_1\times\mathbf{q}_2)/\mathbf{q}_1\cdot\mathbf{q}_2\times\mathbf{q}_3$. We then form the set of translation vectors $\{i\tilde{\mathbf{a}}_1+j\tilde{\mathbf{a}}_2+k\tilde{\mathbf{a}}_3\}$ (i, j, and k integers) from which we extract the three primitive translation vectors. This algorithm has been checked with numerical calculations of the interference patterns.

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