Unity Occupation of Sites in a 3D Optical Lattice

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An average filling factor of one atom per lattice site has been obtained in a submicron scale far-off-resonance optical lattice (FORL). High site occupation is obtained through a compression sequence that includes laser cooling in a 3D FORL and adiabatic toggling between the 3D FORL and a 1D FORL trap. After the highest filling factor is achieved, laser cooling causes collisional loss from lattice sites with more than one atom. Ultimately 44% of the sites have a single atom cooled to near its vibrational ground state. A theoretical model of site occupation based on Poisson statistics agrees well with the experimental results. [S0031-9007(99)08673-1]

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Atoms in optical lattices have recently been employed in experiments investigating wave packet dynamics [1], atom optics [2,3], and laser cooling [4–8]. The near perfection of the optical lattice potential and the ease with which it can be controlled have also allowed its use in studying traditionally condensed matter phenomena such as Bragg scattering [9,10], Bloch oscillations [11], and the Wannier-Stark effect [12]. These experiments do not depend on interactions between atoms, but experiments that do would be possible if optical lattices could be occupied more fully. For instance, simple condensed matter models based on periodic arrays of weakly interacting particles could be studied [4,13,14]. Quantum statistics should have observable effects in a dense lattice, and it may be possible to achieve Bose-Einstein condensation (BEC) by purely optical means without evaporative cooling. Cold collisions in one, two, and three dimensions can be studied in dense lattices. It may also be possible to construct quantum logic gates and ultimately quantum computers in highly occupied optical lattices [15].

Optical lattices are typically loaded from a magneto-optical trap (MOT), where densities above 10^{12} atoms cm^{-3} are unattainable due to radiative repulsion and light-assisted collisions [16–18]. This has limited the filling fraction in a submicron scale optical lattice to below 10% [6]. In this Letter, we present an experiment that attains an average filling fraction of one atom per lattice site. When the atoms are then laser cooled, light-assisted collisions leave no sites with multiple atoms. After cooling, 44% of the sites have a single atom near the vibrational ground state.

Our path to high lattice occupancy requires a way to cool atoms trapped in a far-off-resonance lattice (FORL) and an adiabatic compression sequence to increase the spatial density. After laser cooling atoms in a 3D FORL made from three orthogonal standing waves (see Fig. 1), we shut off the horizontal lattice beams adiabatically, so that a 1D FORL trap remains [6]. The atoms are left stacked in pancake-shaped distributions, confined to 50 nm in the vertical direction and 0.4 mm horizontally. The trap depth is 200 μK, but the atoms have less than 1 μK initial kinetic energy, so they are all near the top of their trajectories in the transverse, Gaussian-shaped potential. The atoms collapse toward the center of the trap, all arriving there at about the same time a quarter cycle later. At the moment of peak density we turn the horizontal lattice beams back on adiabatically, trapping 85% of the atoms at lattice sites. We finally laser cool the atoms again in the 3D FORL.

Our experiment runs at a 2 Hz repetition rate. We observe atoms by fluorescence detection using a short (36 μs), high intensity ($\sim 1000 I_{\mathrm{sat}}$) resonant laser pulse, so that all atoms contribute photons to the far field at the maximum possible rate of $\Gamma/2$ ($\Gamma = 5.2$ MHz) [19]. The fluorescence light is imaged from the horizontal direction by a numerical aperture = 0.13 lens onto a charge-coupled device camera and digitized. The number and density are determined to an accuracy of 20% by fitting Gaussians to the atomic spatial distributions, assuming cylindrical symmetry. Temperature measurements are made by imaging after ballistic expansion.

We start the cycle by trapping 10^9 Cs atoms at 10^{12} atoms cm^{-3} in a MOT, the details of which are given elsewhere [19]. After turning off the MOT, we turn on a 1D FORL trap, which consists of a collimated, retroreflected, vertically oriented, linearly polarized laser beam. In 30 ms the trapped atoms equilibrate and the

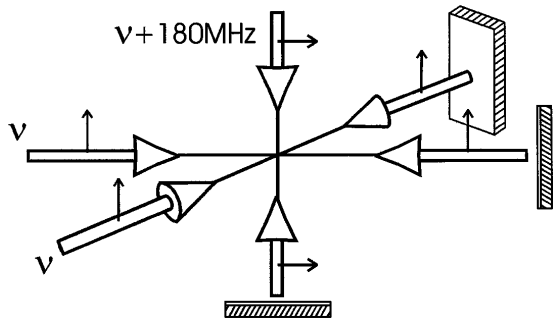

FIG. 1. Directions, polarizations, and frequencies of the 3D FORL beams.

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untrapped atoms fall away. A cylindrically symmetric sample of atoms is thereby prepared [6].

Next, we divert power from the 1D FORL into two orthogonal, horizontal standing waves, both vertically polarized. This forms a 3D FORL as shown in Fig. 1. A 180 MHz frequency difference is imposed between the horizontal and vertical beams. The relative phase between the two horizontal lattice beams is stabilized in a servo loop and locked to $0° \pm 3°$. Each of the three retroreflected laser beams has an e^{-2} radius of ~ 480 μm and a power of ~ 270 mW. The lattice light is 165 GHz to the red of the $6S_{1/2}$ $F = 4$ to $6P_{3/2}$ transitions. The result is a base-centered tetragonal lattice with 200 μK depth, $\lambda/2$ spacing in the vertical direction and 640 μK depth, with λ spacing in the horizontal plane. The trap oscillation frequencies are 180 and 160 kHz, respectively, much larger than the spontaneous scattering rate for lattice photons of 500 Hz.

Atoms in a 3D FORL can be polarization gradient cooled with independent cooling light as long as the ac Stark shift due to the trapping light is sublevel independent [6]. Alkali atom ac Stark shifts are sublevel independent when the light is linearly polarized and detuned far from the excited state hyperfine structure. Then the cooling light optically pumps to the lowest energy state, as Sisyphus cooling requires, even if the magnitude of the light shift due to the trap is large. The imposed frequency difference between beams with different polarizations makes our 3D lattice effectively linearly polarized. Although the polarization at a given point in space and time is elliptical, it has the opposite sense after a half a beat period (3 ns). Averaged over the much longer cooling photon scattering time (>1 μs), the ac Stark shifts are the same as for linearly polarized light.

To laser cool the atoms in the 3D FORL, the MOT molasses light is turned back on, detuned -19Γ from the $F = 4$ to $F' = 5$ cycling transition. We first cool at 14 mW cm^{-2} (single beam) with intense repumping so that atoms bind to sites quickly and are less likely to collide. The molasses intensity is then lowered to 7.5 mW cm^{-2} and the repumping light is turned off, yielding the lowest possible temperature. With only the FORL beams to provide repumping, the fraction of atoms in the upper hyperfine ground state p is 5%. Shelving atoms in the lower hyperfine state minimizes heating due to the reabsorption of scattered photons and allows cooling to an average kinetic energy of 10 μK. Without the 3D FORL we could not make p this small without atoms picking up significant energy due to gravity while they are in the dark state, or sustaining significant collisional loss during the 20 ms that is required for complete equilibration.

After cooling in the 3D FORL 10^8 atoms remain, at a density of 6×10^{11} atoms cm^{-3}. The horizontal lattice is turned off adiabatically by 1000-fold in 200 μs [6], and then the light is completely extinguished. In the 1D FORL that remains, the atoms are stacked in ~ 1400, 400 μm radius, 50 nm thick pancakes with a horizontal temperature of <700 nK. The pancakes collapse horizontally as their constituent atoms experience a dipole force due to the transverse Gaussian profile of the remaining vertical beam.

Figure 2 plots the peak density averaged over a lattice spacing as a function of evolution time in the 1D FORL. The time to peak compression is 4 ms, which we have verified depends inversely on the intensity of the 1D FORL. A classical Monte Carlo calculation of the 2D dynamics without collisions shows that the damping in Fig. 2 is largely explained by the anharmonicity of the Gaussian potential.

In such oscillations we have seen the density increase by more than an order of magnitude, to as high as 8×10^{12} atoms cm^{-3}, higher than the density of 3D lattice sites, $n_{1s} = 6.5 \times 10^{12}$ cm^{-3}. Note that the local density within a pancake is then 8×10^{13} atoms cm^{-3}. Our calculation predicts a 6 times larger maximum density. Published values for the cold collision cross section [20] imply that elastic collisions are important here, and we have seen evidence that suggests they are what limit the peak density. Inelastic collisions are less important, causing a loss of 10% of the atoms per oscillation cycle.

We have also performed the complementary compression by turning off only the vertical lattice beams. Vertical filaments of atoms remain in the 2D lattice and collapse to a maximum density a quarter cycle later. The oscillations and resulting peak density are similar to what is described above. The 1D and 2D collisions that occur in these experiments should have an unusual threshold behavior, which we plan to study in the future [21,22].

At the peak compression in Fig. 2, the average horizontal kinetic energy of the atoms is 54 μK. In order to lock in the transient density gain the horizontal lattice beams are adiabatically turned back on at the moment of peak compression. The light is turned on in 1 μs to $\frac{1}{3}$ of its final intensity and then increased according to $I(t) = I_0(1 - At)^{-2}$ with $A = 4$ kHz [23]. A Monte

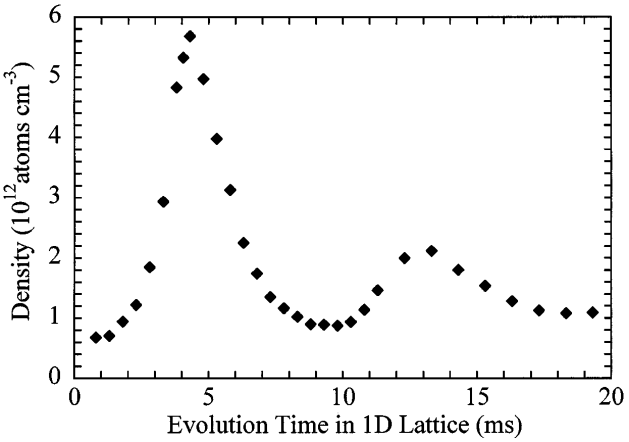

FIG. 2. Peak density, averaged over a lattice spacing, as a function of free evolution in the 1D FORL.

Carlo calculation of the atoms' classical trajectories indicates that 88% of the atoms should be bound after the turn-on.

When the 3D lattice reaches its full intensity, we turn on the same cooling light that earlier yielded the minimum temperature. Figure 3 shows the peak density as a function of the cooling time for two different initial densities, using identical parameters from the time the MOT is shut off. Each curve can be fit to the sum of four decaying exponentials with decay times that differ by orders of magnitude. The amplitude of each of the four decays differs between the two curves, both absolutely and as a fraction of the total. Yet the characteristic decay times are the same. These and similar curves provide compelling evidence of high lattice occupancy.

It is easiest to analyze the later parts of these decay curves first. After 20 ms the decay is purely exponential with a time constant of 730 ms. These atoms, whose density we label n_1, do not collide with each other, so they must all be bound alone at lattice sites. They are lost only in background gas collisions. The salient feature of these curves is that a high initial density, n_0, makes for a relatively high n_1, but a relatively small n_1/n_0. This is readily explained by a model in which atoms are bound to lattice sites. High initial density means that a larger fraction of the atoms are at multiply occupied sites, which leads to more inelastic collisions in the first 20 ms. In contrast, if the atoms were not bound at lattice sites, the lower curve could be translated to later times and made to overlay the higher curve. Clearly this is not possible with these curves.

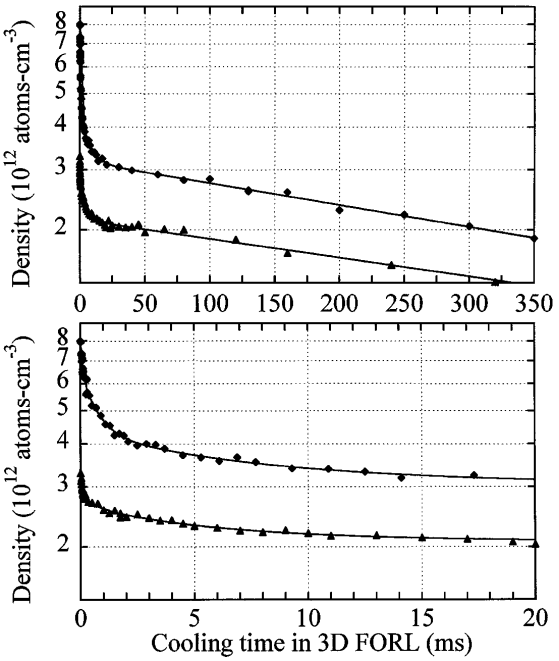

FIG. 3. Decay from the 3D FORL during the final cooling, for two different initial densities. The lower panel is an expanded version of the first part of the upper panel. The fits are the sum of four exponential decays with time constants 0.07, 0.8, 6, and 730 ms. The time constants do not depend on the initial density, but the relative amplitudes of the four features do. The first two decays are due to multiply occupied lattice sites, the third is due to unbound atoms binding at occupied sites, and the last is from lone bound atoms colliding with the background gas.

The exponential decay that dominates between 2 and 20 msec, whose amplitude we label n_{ub}, is due to unbound atoms. We determine this by making the horizontal lattice beam turn-on totally nonadiabatic. Our simulations predict that this will lead to many more initially unbound atoms, and by far the most significant change in the decay that we observe is a doubling of n_{ub}. The decay time, which is comparable to the characteristic cooling time in the lattice, does not depend on n_0 or n_1. We conclude that this loss is due primarily to unbound atoms that cool and bind at sites, and collisionally decay if there is already another atom there.

The dominant loss between 0 and 2 msec is due to collisions between atoms at multiply occupied sites. We conclude this because the decay rate of atoms at the same lattice site does not depend on the bulk atom density. The bulk density differs between the curves by a factor of 2.5, yet the decay constants are the same to within the statistical error of 15%. If these collisions involved at least one unbound atom, the decays would not be exponential and the rates would depend linearly on the bulk density.

The decay rate from multiply occupied sites is at least 2 orders of magnitude greater when there is cooling light, and it is proportional to p. We thus infer that these are cooling light-assisted inelastic collisions [24]. In steady state each atom scatters only one photon every 100 μs, so it takes very few photons to cause loss. This is not surprising, as the density of two atoms at one lattice site is between 10^{14} and 10^{16} atoms cm^{-3}, depending on their temperature. Determination of exact inelastic collision rates is complicated by the fact that both p and the separation between atoms at the same lattice site change as a function of time. When variations in p are taken into account, all the curves fit reasonably well to the sum of two exponential decays whose rates are constrained to differ by a factor of 3, the faster one being due to two-body losses at sites with three atoms. However, because the fits are insensitive to the relative amount of loss associated with the two decays, it is difficult to distinguish loss at a two-atom site from loss at a site with higher occupation. Accordingly, we do not differentiate among them, but instead combine them in a single decay amplitude, n_m.

Atom-atom interaction energies are negligible compared to trapping energies, and inelastic collisions are negligible during the final horizontal lattice beam turn-on. We therefore model the initial distribution of bound atoms using Poisson statistics. The measured values for n_1, n_m, and n_{ub} do not directly correspond to the initial densities, n_{10}, n_{m0}, and $n_{\mathrm{ub}0}$. First, when a site occupied with an odd number of atoms loses atoms in pairs, it ultimately leaves a single atom [25]. Second, the $n_{\mathrm{ub}0}$ atoms either

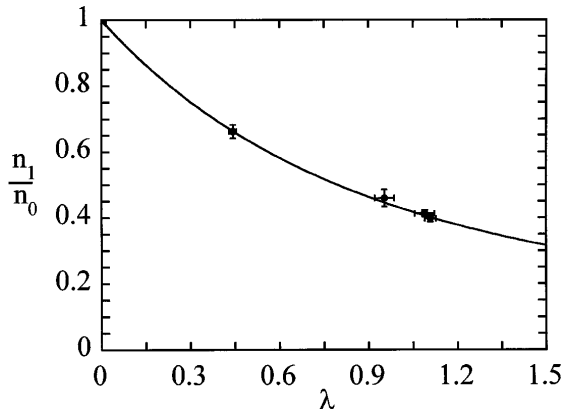

FIG. 4. The remaining fraction of the initial peak density after all cold collisions have occurred, as a function of n_0/n_{1s}. The experimental density has been rescaled by 0.90 to obtain the best fit.

cause the loss of a bound atom or themselves get bound at a site. Using these empirically motivated assumptions, we derive the theoretical predictions,

$$n_1 = \frac{n_{1s}}{2}(1 - e^{-2\lambda});$$
$$n_{ub} = n_{ub0} - \frac{n_{1s}}{2} e^{-2\lambda}(e^{2n_{ub0}/n_{1s}} - 1),$$

where $\lambda = n_0/n_{1s}$. The values for n_1 do not depend on n_{ub0} in this model.

Figure 4 shows as a function of λ the fraction of atoms remaining after cold collision losses. The associated theoretical curve has no free parameters. Optimum agreement with theory occurs when we rescale our density measurements by a factor of 0.90, which is well within the density measurement error. Thus our two independent ways of determining the lattice occupation number are in good agreement. With high initial density, 44% ± 1% of the lattice sites have atoms after multiply occupied sites decay. After adiabatic release, the atom temperature is 350 nK. Their bulk phase space density is 0.037, 6 times higher than any previous result obtained without evaporative cooling or by all-optical means [8].

The model and our data imply that 15% ± 5% of the atoms are initially unbound, in agreement with our Monte Carlo calculation. Thus the initial filling fraction in the lattice is 0.95 ± 0.06 for the point in Fig. 4 with $\lambda = 1.12$. It is possible that some unbound atoms collide and are lost before they are bound, or that some initially bound atoms become unbound after an elastic collision. Ignoring these processes tends to underestimate the initially bound fraction, but does not have a major effect on the final lattice occupancy calculation, and hence on the theory curve in Fig. 4.

If cooling two atoms at a site leads to inelastic collisions, then the theoretical maximum for lattice occupation after cooling is 0.50. The 0.44 final occupation reported here approaches that limit. The site percolation threshold for a cubic lattice is only 0.31 [26], so a pervading cluster of atoms at adjacent sites is created in this experiment. That seems to be the appropriate limit in which lattice-bound atoms can start to model a weakly interacting condensed matter system.

Higher occupation with atoms near the vibrational ground state requires that either laser cooling be avoided, by loading the lattice with a Bose condensate [8,14,27], or that a way be found to cool atoms at multiply occupied sites without significant collisional loss. A possible approach is Raman sideband cooling [5], which entails minimal excitation to the excited state. If atoms at multiply occupied sites can be cooled to their vibrational ground state, then the compression techniques presented here could lead to bulk phase space densities that exceed the BEC threshold without any evaporative cooling. Then when the lattice depth is decreased adiabatically, long range coherence should develop spontaneously.

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[1] G. Raithel *et al.,* Phys. Rev. Lett. **78**, 2928 (1997); A. Gorlitz *et al.,* Phys. Rev. Lett. **78**, 2096 (1997); P. Rudy *et al.,* Phys. Rev. Lett. **78**, 4096 (1997); C. F. Bharucha *et al.,* Phys. Rev. A **55**, 857 (1997).
[2] C. S. Adams *et al.,* Phys. Rep. **240**, 143 (1994).
[3] J. H. Thywissen *et al.,* J. Vac. Sci. Technol. B **15**, 2093 (1997).
[4] P. S. Jessen and I. H. Deutsch, Adv. At. Mol. Opt. Phys. **37**, 95 (1996).
[5] S. E. Hamann *et al.,* Phys. Rev. Lett. **80**, 4149 (1998).
[6] S. L. Winoto *et al.,* Phys. Rev. A **59**, R19 (1999).
[7] H. Perrin *et al.,* Europhys. Lett. **42**, 395 (1998).
[8] V. Vuletic *et al.,* Phys. Rev. Lett. **81**, 5768 (1998).
[9] G. Birkl *et al.,* Phys. Rev. Lett. **75**, 2823 (1995).
[10] M. Weidemuller *et al.,* Phys. Rev. Lett. **75**, 4583 (1995).
[11] M. B. Dahan *et al.,* Phys. Rev. Lett. **76**, 4508 (1996).
[12] Q. Niu *et al.,* Phys. Rev. Lett. **76**, 4504 (1996).
[13] E. V. Goldstein *et al.,* Phys. Rev. A **53**, 2604 (1996).
[14] D. Jaksch *et al.,* Phys. Rev. Lett. **81**, 3108 (1998).
[15] G. K. Brennen *et al.* (to be published).
[16] E. L. Raab *et al.,* Phys. Rev. Lett. **59**, 2631 (1987).
[17] W. Ketterle *et al.,* Phys. Rev. Lett. **70**, 2253 (1993).
[18] C. G. Townsend *et al.,* Phys. Rev. A **53**, 1702 (1996).
[19] S. L. Winoto *et al.* (to be published).
[20] M. Arndt *et al.,* Phys. Rev. Lett. **79**, 625 (1997).
[21] I. I. Fabrikant *et al.,* Bull. Am. Phys. Soc. **43**, 1307 (1998).
[22] M. Olshanii, Phys. Rev. Lett. **81**, 938 (1998).
[23] A. Kastberg *et al.,* Phys. Rev. Lett. **74**, 1542 (1995).
[24] T. Walker and P. Feng, Adv. At. Mol. Opt. Phys. **34**, 125 (1994).
[25] While in principle all the atoms at a three-atom site could be lost together, we see no evidence in the decay of a higher loss rate associated with this process. Furthermore, if we incorporate three-body losses into our model the agreement with experiment is significantly worse.
[26] D. Stauffer and A. Aharony, *Introduction to Percolation Theory* (Taylor and Francis, Washington, DC, 1992).
[27] M. H. Anderson *et al.,* Science **269**, 198 (1995).