PHYSICAL REVIEW A VOLUME 57, NUMBER 2 FEBRUARY 1998

Enhanced laser cooling and state preparation in an optical lattice with a magnetic field

D. L. Haycock, S. E. Hamann, G. Klose, G. Raithel,* and P. S. Jessen
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721
(Received 21 October 1997)

We demonstrate that weak magnetic fields can significantly enhance laser cooling and state preparation of Cs atoms in a one-dimensional optical lattice. A field parallel to the lattice axis increases the vibrational ground-state population of the stretched state $|m=F\rangle$ to 28%. A transverse field reduces the kinetic temperature. Quantum Monte Carlo simulations agree with the experiment, and predict 45% ground-state population for optimal parallel and transverse fields. Our results show that coherent mixing and local energy relaxation play important roles in laser cooling of large-F atoms.
[S1050-2947(98)50502-1]

PACS number(s): 32.80.Lg, 32.80.Pj, 42.50.Vk

Periodic dipole force potentials, commonly known as ''optical lattices'' [1], are a powerful means of trapping atoms in the regime of quantum center-of-mass motion. In optical lattices formed by near-resonance laser light, efficient laser cooling rapidly accumulates atoms in the few lowest bound states of the optical potential wells. Atoms have been trapped also in lattices formed by light detuned thousands of linewidths from atomic transitions [2], and therefore nearly free from dissipation. If confined near the zero point of motion and in a well-defined internal state, such atoms are an ideal starting point for quantum-state preparation and control [3], for studies of quantum transport [4] and quantum chaos [5], for the production of subrecoil temperatures by adiabatic cooling [1], and for the generation of squeezed minimum-uncertainty wavepackets [6]. Far-off-resonance lattices can be loaded by transferring atoms from a superimposed near-resonance lattice, with near-unit efficiency and no significant increase in vibrational excitation [7]. It is therefore important to optimize the cooling process in the near-resonance lattice, and to determine the maximum occupation that can be achieved for the desired quantum state.

In this Rapid Communication we study laser cooling of cesium atoms ($F=4$) in a shallow optical lattice, in the presence of magnetic fields in the tens of mG regime. Our results provide insight into laser cooling and transport mechanisms for atoms with large angular momentum F, as compared to the $F=1/2$ model system [1,8]. We show that such fields can significantly enhance laser cooling and state preparation, in support of a recently proposed cooling mechanism emphasizing the role of coherent mixing of ground-state magnetic sublevels [9]. Previous work has studied the influence of magnetic fields on laser cooling in optical lattices [10,11], but under conditions of deep potentials and strong fields, which are further from the quantum regime and not conducive to large populations in the kinetic ground state of the lattice. We note that it is common in the literature to focus on the total population of the kinetic ground state, i.e., the sum of the vibrational ground-state populations in both stretched states [12]. In coherent control experiments the simultaneous presence of atoms in both stretched states is problematic, because the symmetry between them is extremely sensitive to applied or stray magnetic fields, and to imperfections of the lattice light field. When the symmetry is broken these two subsets evolve differently, and the signature of coherent evolution can easily disappear. To overcome this difficulty one can devise a detection scheme sensitive to only one subset (not always possible), or simply prepare the atoms in one subset only. We demonstrate here that the application of a magnetic field parallel to the lattice axis brings us close to this goal, and can increase the total and vibrational ground-state populations of a *single* stretched state by ~80% and ~33%, respectively, over the zero-field maximum value. Moderate transverse magnetic fields are found to reduce the kinetic temperature of the atoms. Our results are in good overall agreement with quantum Monte Carlo wave-function (QMCWF) simulations [13]. The simulations further identify light- and magnetic-field configurations that should increase the ground-state population ~80% over the zero-field maximum value.

Our optical lattice is formed by two linear and cross polarized laser beams, counterpropagating along the z axis [one-dimensional (1D) lin⊥lin configuration] and detuned up to 20 linewidths below the $6S_{1/2}(F=4)\rightarrow 6P_{3/2}(F'=5)$ transition at $\lambda=852$ nm. The lattice is loaded from a vapor cell magneto-optic trap and 3D optical molasses, which produces a sample of 10^6 atoms in a volume ~300 μm in diameter. After the 3D molasses beams are extinguished the atoms are cooled and reach steady state in the 1D lattice. During this time magnetic fields can be applied parallel and transverse to the lattice quantization axis. At the end of the 1D lattice phase the laser beams are rapidly extinguished, and the momentum distribution measured by a standard time-of-flight (TOF) analysis, which records the distribution of arrival times at a ~0.2-mm-thick probe beam located 4.7 cm below the lattice [Fig. 1(a)]. For lattices that are not too shallow, the TOF and momentum distributions are indistinguishable from a Gaussian fit [Fig. 1(b)], and we characterize them by the kinetic temperature $T=\langle p^2\rangle/(k_B M)$.

To obtain information about the internal atomic state, we perform a Stern-Gerlach analysis, in which a magnetic field gradient is present during the TOF measurement [14]. The state-dependent magnetic dipole force is sufficient to sepa-

*Present address: National Institute of Standards and Technology, PHYS A167, Gaithersburg, MD 20899.

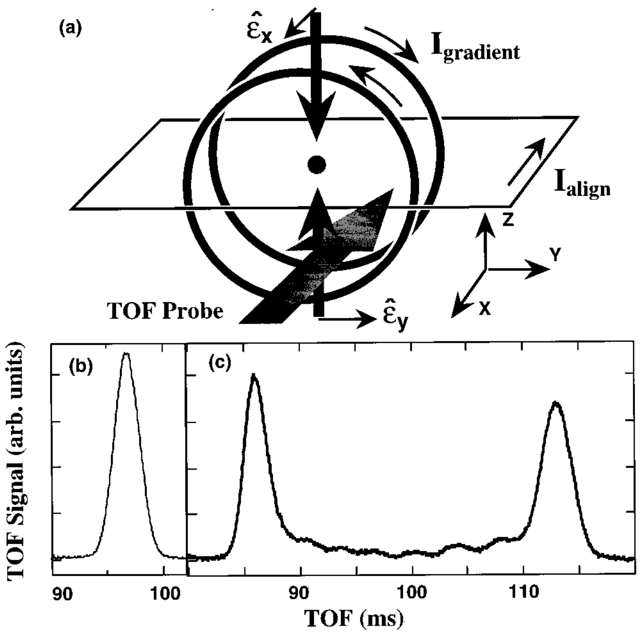

FIG. 1. (a) Experimental setup for TOF measurements. A pair of coils in the anti-Helmholtz configuration provides the magnetic-field gradient for Stern-Gerlach analysis. The square coil provides a bias magnetic field to maintain alignment of the atomic spin. (b) Typical TOF distribution without field gradient. (c) Typical TOF distribution with magnetic-field gradient. The states $|m=-4\rangle$ and $|m=-3\rangle$ are not resolved; we account for this in our fitting procedure.

rate the TOF signals of individual magnetic sublevels [Fig. 1(c)]. We have carried out a detailed analysis of the state-dependent trajectories for our experimental geometry, and accurately determined the connection between the width and amplitude of each Gaussian component, and the kinetic temperature T_m and population π_m for the corresponding magnetic sublevel $|m\rangle$.

The light field in a 1D lin⊥lin optical lattice consists of two standing waves of σ^+ and σ^- polarization, offset by $\lambda/4$. The combined light shift and magnetic field potential for the system is [1]

$$\hat{U}(z)=g_F\mu_B\hat{\mathbf{F}}\cdot\mathbf{B}+\sum_{F'} U_{F'}[\epsilon(z)\cdot\hat{\mathbf{d}}_{F'}]^*[\epsilon(z)\cdot\hat{\mathbf{d}}_{F'}], \quad (1)$$

where the summation extends over hyperfine excited states. In this expression $\epsilon_L(z)$ is the laser polarization, $U_{F'}$ is the maximum light shift, and $\hat{\mathbf{d}}_{F'}$ the electric-dipole operator for the $F\rightarrow F'$ transition. In the absence of transverse magnetic fields the lattice potential $\hat{U}(z)$ is nearly diagonal in the basis $|F,m\rangle$; the diagonal elements are the diabatic lattice potentials. Small off-diagonal elements between states $|F,m\rangle$ and $|F,m\pm 2\rangle$ occur due to Raman coupling by $\sigma^{\pm}$ components of the lattice. Local diagonalization of $\hat{U}(z)$ yields a set of $2F+1$ adiabatic lattice potentials that govern the motion of atoms at low momentum. Quasibound states in these potentials are Wannier spinors, which closely resemble localized anharmonic-oscillator states [9].

With no magnetic field [Fig. 2(a)] atoms are cooled and localized in the lowest adiabatic potential, where they occupy vibrational states with nearly pure $|m=F\rangle$ or $|m=-F\rangle$ character at alternating lattice sites. The admixture of other magnetic sublevels increases dramatically for states close to the upper edge of the lowest adiabatic potential, since these states have substantial amplitude in the area around the anticrossing at $\lambda/8$. In steady state atoms fill the available vibrational levels according to a nearly thermal distribution [1,12,15], with few atoms excited above the edge of the potential. Reference [9] suggests that this limit on the thermal energy is imposed by an efficient path for optical pumping out of these mixed states, which returns atoms to low-lying states of the original or neighboring lattice potential wells.

The application of a weak magnetic field parallel to the lattice axis modifies the adiabatic potentials, as shown in Fig. 2(b). Due to the magnetic energy $\delta E_m=g_F\mu_B Bm$, one type of potential wells is lowered and the other lifted, and the anticrossing shifted in position. Well localized states with nearly pure $|m=\pm F\rangle$ character still exist in the energy range below the edge of the lowest adiabatic potential, but there are an increased (decreased) number of states available in the deeper (shallower) wells. Previous work has shown that atoms preferentially populate the deeper wells, leading to a nonzero magnetization consistent with a spin temperature of roughly twice the kinetic temperature [11]. Figure 3(a) shows populations π_F and π_{-F} as a function of B_z for one set of lattice parameters, as measured in our experiment and calculated by QMCWF simulations. Maximum population in one of the stretched states $|m=\pm F\rangle$ occurs when the Zee-

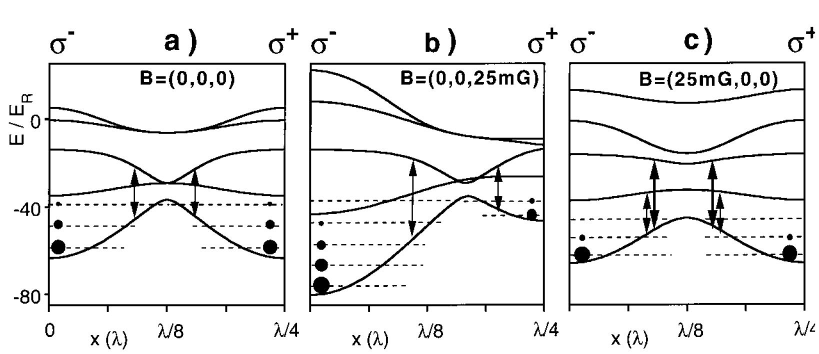

FIG. 2. Adiabatic lattice potentials for (a) no magnetic field, (b) longitudinal magnetic field, and (c) transverse magnetic field. The modulation depth of the $m=\pm F$ diabatic potential is $U_P=70E_R$, and the lattice detuning $\Delta=-20\Gamma$. For simplicity we show potentials for $F=2$; the arguments in the text apply for $F\geqslant 2$. Dashed lines and dots indicate vibrational states and their population; the arrows indicate Raman- and magnetically induced mixing.

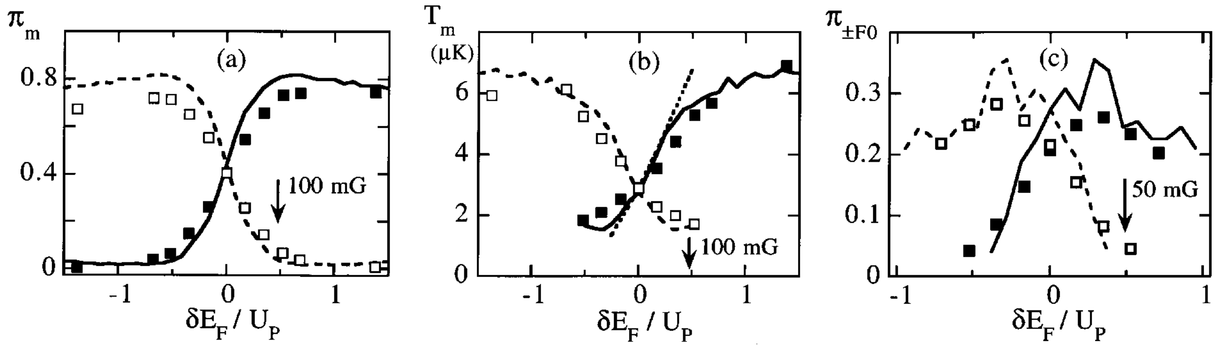

FIG. 3. (a) Population π_m and (b) temperature T_m in the magnetic sublevels $|m=F\rangle$ (open boxes) and $|m=-F\rangle$ (filled boxes), as a function of the parallel field B_z in units of $\delta E_4/U_P$. Lines are the corresponding results from QMCWF simulations. Lattice parameters are $U_P=135E_R$ and $\Delta=-20\Gamma$. (c) Vibrational ground-state population π_{m0} in potential wells with $|m=F\rangle$ (open boxes) and $|m=-F\rangle$ (filled boxes) character, as a function of $\delta E_4/U_P$. Lines represent QMCWF simulations. The lattice parameters are $U_P=70E_R$ and $\Delta=-20\Gamma$. The dotted line in (b) shows the expected variation of T_F, obtained by scaling the value at $B_z=0$ by the adiabatic well depth.

man shift δE_m is comparable to half the modulation depth U_P of the corresponding diabatic lattice potentials. Increasing the field further removes the anticrossings between lattice potentials, and leads to a loss of magnetization. Experimentally we find a maximum stretched state population of 0.70 ± 0.03 [16] at $U_P=70E_R$ and $\Delta=-20\Gamma$, gradually increasing to 0.76 at $U_P=280E_R$ (E_R is the recoil energy and $\Gamma=2\pi\times5.2$ MHz). Our simulations predict similar values for the populations; differences are consistent with uncompensated background fields of order 10 mG in the experiment.

In a parallel magnetic field the internal state mixing is significant only for states near the top of the lowest adiabatic potential. If atoms are efficiently cooled as soon as they enter these mixed states, then one would expect the mean kinetic energy to equal a constant fraction of the depth of the potential wells in which they are trapped. The kinetic temperature should therefore scale in direct proportion to *changes* of this depth. As illustrated in Fig. 3(b), our experiment and QMCWF simulations show that such a scaling law applies independently for atoms found in the states $|m=\pm F\rangle$, implying that internal-state mixing is a key element of the laser-cooling mechanism for atoms with large F. The existence of two distinct subsets of atoms with different temperatures also suggests that energy relaxation within each subset occurs faster than the exchange of atoms between the subsets. This in turn indicates that steady-state energy relaxation is to a large extent *local*, i.e., atoms in high-lying mixed states mostly return to low-lying states of the original potential well. Local cooling has implications for atom transport, and may explain why spatial diffusion constants for large-F atoms are more than an order of magnitude smaller than for the $F=1/2$ model system [8].

We can use the magnetically induced atomic polarization to enhance state preparation in our lattice. Because we measure TOF distributions for each of the states $|m=\pm F\rangle$, it is straightforward to model the atoms by anharmonic oscillators and determine the vibrational temperatures corresponding to the observed momentum spreads. This allows us to obtain the vibrational ground-state populations π_{F0} and π_{-F0} in the two types of potential wells. The approach is validated by the number of quasibound states, which we determine from the lattice band structure. For the parameters of Fig. 3(b) there are three bound states at $\delta E_m=0$, increasing to six (decreasing to 0) in the deep (shallow) wells when $\delta E_m=0.5U_P$.

The buildup of magnetization leads to a net gain in vibrational ground-state population of the deeper potential wells, though the gain is somewhat reduced by a simultaneous increase in temperature. Figure 3(c) shows populations $\pi_{\pm F0}$ vs B_z, for lattice parameters $U_p\approx70E_R$ and $\Delta=-20\Gamma$. For a given set of lattice parameters the populations π_{F0} (π_{-F0}) peak around $\delta E_F=-0.25U_P$ ($+0.25U_P$); at that point the magnetic field shifts the adiabatic potentials roughly as depicted in Fig. 2(b). The optimum parameters for state preparation are close to those of Fig. 3(c), which yielded our largest observed value of 0.28 ± 0.03 [16]. This constitutes a $\sim$33% increase above the value of 0.21 ± 0.03 observed at nominally zero field. Decreasing the lattice depth below $70E_R$ reduces the width of the central part of the momentum distribution, but non-Gaussian tails develop that cause a net loss of vibrational ground-state population. We have used QMCWF simulations to obtain the total populations in the bands corresponding to the vibrational ground states in the two types of potential wells. The simulations agree with the trends observed in our experiment, but show slightly higher maximum populations and sharp features possibly related to resonant mixing of degenerate states in different adiabatic potentials [15]. These discrepancies are likely due to uncompensated background fields and lattice beam inhomogeneity in the experiment.

Further evidence that laser cooling is linked to mixing of magnetic sublevels is provided by the behavior of our lattice when subjected to a weak transverse magnetic field. A transverse field introduces off-diagonal matrix elements in the lattice potential $\hat{U}(z)$, which modify the adiabatic potentials, as illustrated in Fig. 2(c). The magnitude of the anticrossing at $\lambda/8$ is significantly increased, indicating that magnetically induced mixing occurs much deeper in the potential than before. One would then expect a lower temperature in the presence of transverse fields, which is precisely what we observe in both experiment and QMCWF simulations. Figure 4 illustrates how the overall kinetic-energy temperature T reaches a minimum for nonzero B_x; this minimum shifts to higher values of B_x and becomes more pronounced in the

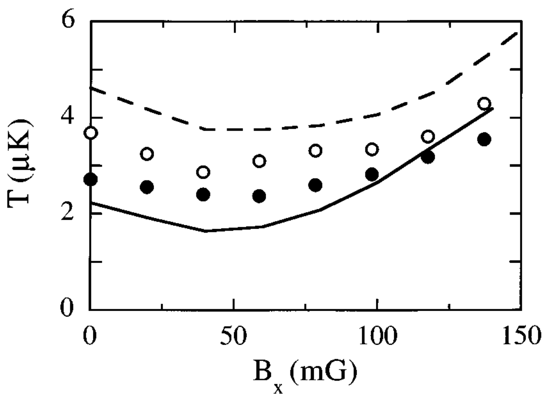

FIG. 4. Kinetic temperature T vs transverse field B_x, for parallel fields $B_z=0$ mG (filled circles), and $B_z=90$ mG (open circles), respectively. Solid and dashed lines are the corresponding QMCWF simulations. Lattice parameters are $U_P=108E_R$ and $\Delta=-21\Gamma$.

presence of a parallel field [17]. QMCWF simulations, including both parallel and transverse fields, are in qualitative agreement with our experimental observations. Differences in the details are readily explained by background fields of a few tens of mG in the experiment; in particular, the local maximum in temperature vs B_x is easily obscured by a small y component of the background field. We have occasionally observed a much clearer local maximum, which we ascribe to fortuitous values of our background field.

The use of transverse magnetic fields to enhance state preparation hinges upon the change in population of the vibrational ground state in the lowest adiabatic potential. Unfortunately the quasibound states in this potential cannot be associated with a single sublevel $|m=\pm F\rangle$, and our Stern-Gerlach analysis becomes of limited value. Insight is however readily available from our QMCWF simulations, which indicate that optimal magnetic field and lattice parameters ($B_x \approx B_z \approx 25$ mG, and $U_P \approx 70E_R$) will increase the ground-state population to as much as 0.45, corresponding to an 80% increase over the theoretical field-free value of 0.25.

In conclusion, we have obtained strong evidence that laser cooling in optical lattices is linked to coherent mixing of the magnetic sublevels, which occurs near the upper edge of the lowest adiabatic potential. This mixing, and consequently the laser-cooling process, can be substantially altered and enhanced by the presence of weak magnetic fields. In a parallel magnetic field the atoms separate in two subsets with different temperature, indicating that cooling occurs locally at each lattice site. We have further demonstrated that magnetic fields are useful for the preparation of significant atomic population in a specific internal and motional state of the lattice. Recently we have extended our approach to a 2D lattice, and expect it to work for the whole lin⊥lin class of optical lattices. If atoms are subsequently transferred to a far-off-resonance optical lattice one might proceed to eliminate excited vibrational states [2]; e.g., by reducing the lattice depth until only a single bound state is supported. This would leave behind a substantial fraction of atoms in a pure quantum state, and provide excellent initial conditions for quantum wavepacket manipulation. We are currently exploring a scheme for resolved-sideband Raman cooling, which could allow efficient preparation of ground-state populations approaching 100% [18].

The authors thank I. H. Deutsch, S. L. Rolston, and W. D. Phillips for helpful discussions. G.R. is supported by the Alexander-von-Humboldt Foundation. This work was supported by NSF Grant No. PHY-9503259 and Joint Services Optical Program No. F49620-94-1-0095.

[1] For a review see P. S. Jessen and I. H. Deutsch, Adv. At., Mol., Opt. Phys. **37**, 95 (1996).
[2] B. P. Anderson *et al.*, Phys. Rev. A **53**, R3727 (1996); T. Müller-Seydlitz *et al.*, Phys. Rev. Lett. **78**, 1038 (1997).
[3] C. Monroe *et al.*, Phys. Rev. Lett. **75**, 4011 (1995); D. M. Meekhof *et al.*, *ibid.* **76**, 1796 (1996).
[4] M. Ben Dahan *et al.*, Phys. Rev. Lett. **76**, 4508 (1996); S. R. Wilkinson *et al.*, *ibid.* **76**, 4512 (1996).
[5] F. L. Moore *et al.*, Phys. Rev. Lett. **73**, 2974 (1994).
[6] G. Raithel *et al.*, Phys. Rev. Lett. **78**, 2928 (1997).
[7] D. L. Haycock *et al.*, Phys. Rev. A **55**, R3991 (1997).
[8] S. Marksteiner, K. Ellinger, and P. Zoller, Phys. Rev. A **53**, 3409 (1996); C. Jurczak *et al.*, Phys. Rev. Lett. **77**, 1727 (1996); H. Katori *et al.*, *ibid.* **79**, 2221 (1997).
[9] I. H. Deutsch, J. Grondalski, and P. M. Alsing, Phys. Rev. A **56**, R1705 (1997).
[10] P. Van der Straten *et al.*, Phys. Rev. A **47**, 4160 (1993).
[11] D. R. Meacher *et al.*, Phys. Rev. Lett. **74**, 1958 (1995); G. Raithel *et al.* (unpublished).
[12] P. S. Jessen *et al.*, Phys. Rev. Lett. **69**, 49 (1992); P. Marte *et al.*, *ibid.* **71**, 1335 (1993).
[13] J. Dalibard *et al.*, Phys. Rev. Lett. **68**, 580 (1992); P. Marte *et al.*, Phys. Rev. A **47**, 1378 (1993).
[14] L. S. Goldner *et al.*, Phys. Rev. Lett. **72**, 997 (1994).
[15] J.-Y. Courtois, Ann. Phys. (Paris) **21**, 93 (1996).
[16] One standard deviation, combined statistical and systematic.
[17] The minima in T vs B_x call for caution if background fields are cancelled by minimizing the temperature.
[18] I. H. Deutsch and P. S. Jessen, Phys. Rev. A (to be published).