Laser cooling of lithium using relay chirp cooling

C. C. Bradley, J. G. Story, J. J. Tollett, J. Chen, N. W. M. Ritchie, and R. G. Hulet

Department of Physics and Rice Quantum Institute, Rice University, Houston, Texas 77251

Received September 25, 1991

We demonstrate a chirp-cooling technique that uses a laser with multiple FM sidebands to slow lithium atoms from initial velocities of as much as 1880 m/s to final velocities near zero. Compared with the use of a single sideband, this multisideband technique significantly reduces FM bandwidth requirements and provides a greater flux of slowed atoms.

The recent development of radiation pressure techniques known as laser cooling has provided a means for producing ultracold (≪1 K) samples of atoms and atomic ions.[1] These cold atomic vapors are currently being used in experiments in such areas as precision spectroscopy, improved time and frequency standards, ultralow energy atomic collisions, and quantum optics. In addition, they have potential for application in other areas, including investigations of quantum collective effects such as Bose–Einstein condensation. Laser cooling has been used to produce cold neutral-atom vapors by slowing atoms from atomic beams. In these experiments, a laser beam with its frequency tuned to near an atomic resonance counterpropagates with the atomic beam. Several methods have been developed to compensate for the changing Doppler shift as the atoms slow: the atomic resonance can be shifted as the atoms move through an inhomogeneous magnetic field, as in Zeeman-shift cooling[2]; the resonance can be broadened by the interaction with an intense laser beam[3,4]; the laser spectral bandwidth can be broadened so as to slow atoms over a range of velocities, as in white-light cooling[5]; and the laser frequency can be repeatedly swept by using a chirp-cooling technique.[6,7] In previous chirp-cooling experiments the frequency chirp was generated by either a laser diode[8] or an electro-optically FM dye laser beam.[7] Recently a fraction of the atoms in a lithium beam were slowed by using the Zeeman-shift method.[9] In this Letter we describe a multiple FM sideband relay chirp-cooling technique that we have used to bring a significant fraction of a thermal lithium beam to near zero velocity.

Lithium is an attractive atom for many laser-cooling applications. For a given temperature, the low atomic mass of lithium results in a relatively large de Broglie wavelength, which thereby enhances quantum effects. Furthermore the effect of quantum statistics can be investigated because one naturally occurring lithium isotope, ^{7}Li, obeys Bose–Einstein statistics and the other, ^{6}Li, obeys Fermi–Dirac statistics. Finally, because fine-structure-changing collisions are expected to be an important loss mechanism for laser-cooled trapped atoms[10] and because the excited-state fine-structure splitting of lithium is only 10 GHz (~0.5 K), this mechanism may be suppressed for lithium atoms by confining them by a reasonably deep trapping potential.

Although lithium is desirable for cold atom applications, the relatively slow spontaneous decay rate γ of its principal transition and the high temperature required to produce a lithium beam make it a relatively difficult atom to slow. For an atom of mass m slowed by the interaction with a laser tuned to a transition of wavelength λ, the maximum Doppler cooling acceleration is given by $a_D = \pi\hbar\gamma/m\lambda$ (for lithium, $a_D = 1.6 \times 10^6$ m/s^2).[1] With this acceleration, the distance required to stop an atom initially traveling at the most probable velocity v_0 in a beam characterized by the temperature T is

$$L = \frac{{v_0}^2}{2a_D} = \frac{3k_B T\lambda}{2\pi\hbar\gamma}, \tag{1}$$

where k_B is Boltzmann's constant. The Doppler shift corresponding to v_0 is

$$\Delta\nu = \frac{v_0}{\lambda} = \frac{1}{\lambda}\sqrt{\frac{3k_B T}{m}}. \tag{2}$$

This equals the range of detunings required to slow atoms from v_0 to zero velocity. For a lithium (^{7}Li) beam at 600°C, $v_0 = 1800$ m/s, $L = 1.0$ m, and $\Delta\nu = 2.6$ GHz. This large $\Delta\nu$ presents technical challenges for all beam-slowing methods.

Most implementations of chirp cooling use only a single frequency swept over detunings in the interval $\Delta\nu$ to zero. However, it is possible to reduce the required modulation bandwidth for frequency chirps derived from frequency modulation by using multiple FM sidebands to sweep over the detuning interval. One such method uses both the upper and the lower first-order FM sidebands, each swept through half the total detuning interval such that atoms are slowed first by the lower sideband then relayed to the upper sideband for additional slowing.[11] A more efficient method involves sweeping the carrier frequency such that atoms are first relayed from the lower first-order sideband to the carrier and then from the carrier to the upper first-order sideband.[12] With this technique, the period of each chirp cycle is one third as long as for a single chirped frequency. We describe a method that uses

0146-9592/92/050349-03$5.00/0

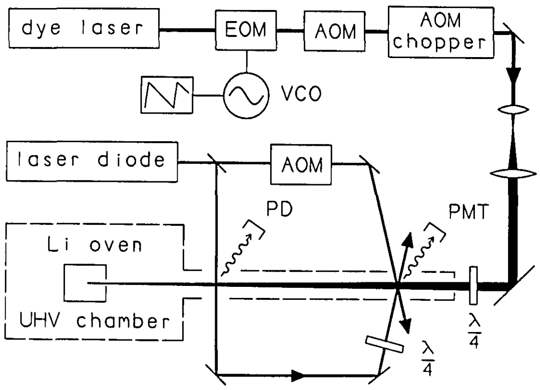

Fig. 1. Schematic of the experimental apparatus. Light from a frequency-stabilized ring dye laser tuned to near the 671-nm lithium $2S_{1/2}(F = 2) \leftrightarrow 2P_{3/2}(F = 3)$ transition was frequency modulated by an EOM, circularly polarized by a quarter-wave plate, and directed at the nozzle of a 600°C lithium oven. The EOM was driven by the amplified output of a VCO modulated with a sawtooth input voltage that caused the frequency of the first- and second-order FM sidebands to sweep. Optical pumping out of the $F = 1$ ground-state hyperfine level was effected by a portion of the cooling beam that passed through an 803-MHz AOM. The resulting atomic velocity distribution was recorded by scanning a probe laser (visible laser diode) through the resonance transition and recording the induced fluorescence with a gated PMT. A portion of the probe beam was used to obtain zero-velocity markers by intersecting the atomic beam at right angles and recording the resulting fluorescence with a photodiode (PD).

two simultaneously swept FM sideband orders, in which the first-order sideband is swept from $\Delta\nu/3$ to zero and the second-order sideband simultaneously sweeps from $\Delta\nu$ to $\Delta\nu/3$. With this method, atoms with higher initial velocities are slowed first by interaction with the second-order sideband then brought to rest by the first-order sideband. This two-sideband relay technique requires a FM bandwidth that is only one third that of single-frequency chirp cooling. Also, since the time per sweep for this method is two thirds that of a single frequency swept over the same range, high-velocity atoms begin slowing sooner on average, resulting in a compressed spatial distribution and a higher flux of slowed atoms.

The total detected slowed atom flux may be calculated by summing contributions from each velocity in the initial atomic beam velocity distribution. Because cooling is only in one dimension, the atomic beam diverges as it is slowed. For a small detection volume and low final velocities, only the atoms that finish slowing at or just before the detection region will significantly contribute to the measured slow atom flux. The range of contributing initial velocities is determined by the maximum velocity v_m affected by the cooling laser, the number of simultaneously swept frequencies, their spacing and sweep rates, and the detector position. Results of such a calculation show that compared with single-frequency chirp cooling, the two-order sideband relay method gives 26% more slowed atom flux for $v_m = 1800$ m/s. In addition, these calculations show that for this modulation bandwidth the two combined sideband orders should provide more than eight times the slowed atom flux than that produced by the first-order sideband alone. This large difference results from the three times larger frequency range obtained by combining the sideband orders. Consequently, for situations in which the modulation bandwidth and rf amplifier bandwidth are limiting factors, the multiple-order sideband method offers a significant improvement in slow atom flux over use of just a single sideband. This improvement is especially important for cooling atoms, such as lithium, that have large initial Doppler shifts.

Figure 1 shows a schematic representation of the experiment. A laser beam was frequency modulated by using a traveling-wave electro-optic modulator (EOM) of our design. This EOM consists of two 27 mm × 0.9 mm × 0.4 mm lithium tantalate crystals placed end to end inside a strip-line circuit. The rf modulating field and the laser field were velocity phase matched by using the partially filled waveguide method.[13] The rf bandwidth of this device has been tested to be greater than 2.5 GHz. Approximately 6 W of rf power is required to produce first-order sidebands of maximum intensity, such that 34% of the laser beam power is contained in each first-order sideband, while the unshifted carrier and the two second-order sidebands each contain 10% of the laser power. The rf power is supplied by amplifying the output of a 900–2000-MHz voltage-controlled oscillator (VCO). In this experiment there was ~50 mW of laser power in each first-order sideband and ~15 mW of power in each second-order sideband. By ramping the VCO control voltage, the FM sidebands were simultaneously swept. For two-order sideband relay cooling, the frequency of the lower first-order sideband was swept between −1850 and −900 MHz with respect to the carrier frequency, while the lower second-order sideband simultaneously swept over −3700 to −1800 MHz. The upper sidebands were sufficiently far from resonance that they did not have a significant effect on the atoms. The carrier frequency was set 900 MHz above the resonance frequency so that the overlapping frequency ranges of the two lower sidebands could slow the atoms from velocities of as much as ~1880 m/s to near zero velocity.

In order to maximize the slowed atom flux, it was necessary to entrain atoms not originally in the cycling transition and to repump those that fell out of it and into the $F = 1$ ground-state hyperfine level. This optical pumping was provided by a small fraction of the cooling beam that was shifted by the ground-state hyperfine splitting of 803 MHz by using an acousto-optic modulator (AOM). The power in these repumping sidebands was ~10% of that of their unshifted counterparts. The main cooling beam and the repumping beam were combined at a beam splitter and then focused just beyond the lithium oven nozzle. The cooling beam waist was 0.5 cm at the probing region, 1.6 m from the oven. Between cooling sweeps the VCO frequency was reset, and the cooling and repumping beams were turned off by an AOM chopper. During these brief (~100-μs) dark intervals the fluorescence induced

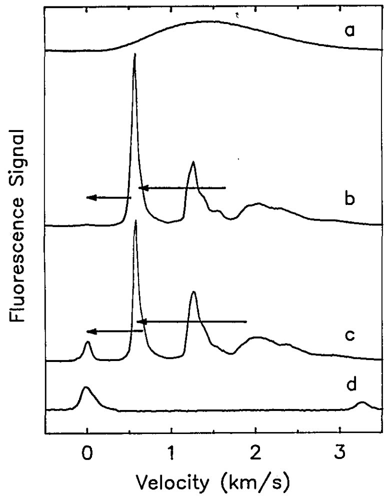

Fig. 2. Data showing the effect of multiple-order FM sideband cooling on the atomic velocity distribution. The horizontal axis corresponds to the probe laser frequency and is labeled by the corresponding atomic velocity. Trace a shows the original longitudinal velocity distribution. Trace b shows the final distribution for the case in which the frequency ranges of the first- and second-order FM sidebands do not overlap. Trace c shows the resulting distribution for overlapping sweep ranges. The horizontal arrows indicate the velocity ranges that correspond to the frequency spans swept by the first- and second-order sidebands. The majority of the zero-velocity atoms of trace c were relayed from the second-order sideband to the first-order sideband. The peak near 1200 m/s in traces b and c is due to cooling by the third-order sideband. The velocity origin and scale were determined with velocity markers shown in trace d.

by a probe beam was collected with a gated photomultiplier tube (PMT).

A visible laser diode operating at the 671-nm lithium $2S_{1/2} \leftrightarrow 2P_{3/2}$ transition wavelength was used to probe the velocity distribution.[14] The ~0.5-cm-diameter, 150-μW, circularly polarized probe beam passed through the atomic beam at an angle of 10° from transverse. The laser-diode linewidth was narrowed by optical feedback from a grating in the Littrow configuration, and, for long-term frequency stability, the laser-diode output was electronically locked to an interferometer fringe.[15] A 15-μW portion of the laser-diode beam was frequency shifted by 803 MHz with an AOM and sent through the atomic beam, symmetrically crossing the main probe. This second probe beam increased the fluorescence signal by optically repumping atoms out of the $F = 1$ ground state.

Figure 2 shows a comparison between the results of multiple-order FM sideband cooling in which the swept frequency ranges of the first- and second-order sidebands either did or did not overlap. The original longitudinal velocity distribution is shown by trace a for reference. For the next two traces (b and c), atoms were decelerated at a rate of 5.3×10^5 m/s^2 ($\sim 0.34 a_D$) while under the influence of the second-order sideband and half that while under the influence of the first-order sideband. In the nonoverlapped case (trace b) the first-order sideband has slowed atoms from initial velocities of as much as 500 m/s to near zero, while the second-order sideband slowed the more plentiful high-velocity atoms from as much as 1600 m/s down to 600 m/s. In the overlapped case (trace c) the first-order sideband slows atoms from initial velocities of as much as 640 m/s to near zero velocity, while the second-order sideband slows atoms from as much as 1880 m/s down to 600 m/s. This trace demonstrates that with overlap, atoms are relayed by the second-order sideband to the first-order sideband and thereby are slowed from the higher-velocity range all the way to near zero velocity. The velocity width of the slowed atom peaks is due mainly to the atoms' transverse velocities, since the probe beam is nearly transverse and is therefore most sensitive to transverse velocity.

In conclusion, we have efficiently slowed lithium atoms that have initial velocities of as much as ~1880 m/s down to near zero velocity by using a FM sideband relay chirp-cooling technique. This multisideband technique offers significant improvement over single-frequency chirp cooling because of its greater efficiency and smaller FM bandwidth and rf amplifier bandwidth requirements.

We gratefully acknowledge the financial support of the National Science Foundation, the National Institute of Standards and Technology, and the Welch, Shell, and Texaco Foundations. R. G. Hulet is an Alfred P. Sloan Research Fellow.

References

1. See the feature issue on laser cooling and trapping of atoms, J. Opt. Soc. Am. B **6**, 2020–2278 (1989).
2. J. Prodan, A. Migdall, W. D. Phillips, I. So, H. Metcalf, and J. Dalibard, Phys. Rev. Lett. **54**, 992 (1985).
3. V. I. Balykin, V. S. Letokhov, and A. I. Sidorov, Opt. Commun. **49**, 248 (1984).
4. M. Prentiss and A. Cable, Phys. Rev. Lett. **62**, 1354 (1989).
5. M. Zhu, C. W. Oates, and J. L. Hall, Phys. Rev. Lett. **67**, 46 (1991).
6. V. I. Balykin, V. S. Letokhov, and V. I. Mushin, JETP Lett. **29**, 560 (1979).
7. W. Ertmer, R. Blatt, J. L. Hall, and M. Zhu, Phys. Rev. Lett. **54**, 996 (1985).
8. R. N. Watts and C. E. Wieman, Opt. Lett. **11**, 291 (1986).
9. Z. Lin, K. Shimizu, M. Zhan, F. Shimizu, and H. Takuma, Jpn. J. Appl. Phys. **30**, L1324 (1991).
10. P. S. Julienne and J. Vigue, Phys. Rev. A **44**, 4464 (1991).
11. R. Blatt, Habilitation thesis (Universität Hamburg, Hamburg, Germany, 1987); J. Hall, Joint Institute for Laboratory Astrophysics, Boulder, Colo. (personal communication).
12. C. Solomon and J. Dalibard, C. R. Acad. Sci. Paris Ser. II **306**, 1319 (1988).
13. I. P. Kaminow and J. Liu, Proc. IEEE **51**, 132 (1963).
14. C. C. Bradley, J. Chen, and R. G. Hulet, Rev. Sci. Instrum. **61**, 2097 (1990).
15. C. E. Wieman and L. Hollberg, Rev. Sci. Instrum. **62**, 1 (1991).