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One-dimensional laser cooling of an atomic beam in a sealed vapor cell

C. J. Vale[a)]
Optical Technology Research Laboratory, Victoria University, Footscray 3011, Australia

M. R. Walkiewicz
School of Physics, University of Melbourne, Victoria 3010, Australia

P. M. Farrell
Optical Technology Research Laboratory, Victoria University, Footscray 3011, Australia

R. E. Scholten[b)]
School of Physics, University of Melbourne, Victoria 3010, Australia

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We describe a simple experiment that demonstrates one-dimensional laser cooling in a sealed vapor cell. A velocity selective optical pumping scheme was first used to define a collimated beam of atoms within the cell. A particular velocity group of atoms was labeled by optical pumping with one laser and detected by absorption with a second laser. Transverse cooling of this velocity group, which formed an atomic beam between the two laser beams, was then observed by applying a third laser beam, in analogy with transverse cooling of a conventional atomic beam.
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I. INTRODUCTION

Since the first proposals for using laser light to cool ions[1] and atoms[2] some 25 years ago, laser cooling has been a topic of great interest to the physics community. Many different cooling mechanisms have now been identified,[3] enabling the achievement of the coldest known temperatures, the observation of quantum collective effects in the formation of Bose–Einstein condensates,[4] and the production of coherent matter waves.[5]

Laser cooling of atoms provides an elegant way to directly observe the transfer of momentum from photons to atoms and provides a rich source of heuristic examples of laser and atomic physics. However, the investigation of these laser cooling processes has generally relied either on atomic beams[6–8] or on pumped vapor cell traps.[9,10] In this paper we describe one-dimensional transverse laser cooling of an atomic beam in a sealed vapor cell, that is, a simple glass cell without a vacuum pump. Optical pumping is used to label a particular velocity group of atoms, and those atoms are then detected by the absorption of a second spatially separated laser beam. A third laser is used to cool the velocity selected virtual atomic beam in one dimension, transverse to the beam propagation axis. The techniques described in this paper provide the basis of an undergraduate laboratory on atomic physics and in particular on optical pumping and laser cooling.

The use of spatially separated lasers to detect atoms moving between two locations in a vapor cell has previously been demonstrated, including measurements of Larmor precession,[11] spin coherences,[12] and collisional effects.[13] Reported attempts to observe the cooling of atoms in a sealed cell have not yet been successful, due to spurious optical pumping and poor velocity resolution.[14] The method described here has overcome these problems and has a resolution suitable for the quantitative investigation of laser cooling.

II. EXPERIMENT

Our method consists of two separated parallel narrow-linewidth laser beams, copropagating through a sealed glass vapor cell (Fig. 1). One laser labels a particular velocity group of atoms by optical pumping between ground state hyperfine levels, and a second laser, copropagating parallel to the first, is tuned to detect the same velocity group. The first laser is mechanically chopped, and the absorption of the probe laser is then measured synchronously with a lock-in amplifier. Any lock-in signal must be due to atoms that have traveled from the chopped laser to the probe, as the chopped laser is the only source of modulation at this frequency. Only atoms moving perpendicularly to the chopped laser were in resonance, and so an atomic beam is established between the two laser beams.

The virtual atomic beam has a rectangular cross section, propagating along the x axis with width (along z) defined by the length of the vapor cell (75 mm), and height (along y) defined by the diameters of the laser beams (1.0 mm at $1/e^2$). The velocity distribution along the laser beams (z) was defined by the velocity selectivity of the optical pumping and probe absorption process. In the direction perpendicular to both lasers and the atomic beam (y), the velocity spread was defined by the laser beam diameters and by their separation (5 mm), which was limited by the size of the vapor cell.

Our method was designed so that only atoms traveling perpendicularly to the chopped laser, that is, with $v_z=0$, are labeled. In Rb^{87}, we set the frequency of the chopped laser to the $5\,^2S_{1/2}F'=2$ to $5\,^2P_{3/2}F=2$ transition for $v_z=0$ atoms (Fig. 2). Atoms excited by this transition to the $F=2$ state may relax back to either the $F'=2$ ground state or to the $F'=1$ ground state, which is far off resonance with the laser. As atoms traverse the chopped laser, they may experience many cycles of excitation and relaxation, leading to significant transfer of population to the $F'=1$ state. Atoms with $v_z\neq 0$ are Doppler shifted out of resonance with the chopped laser and do not experience this labeling.

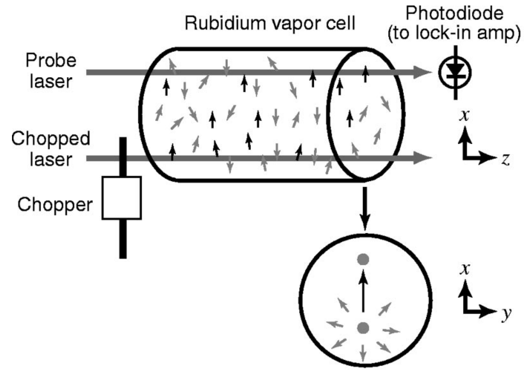

Fig. 1. Experimental arrangement for the observation of a vapor cell atomic beam. Two separated parallel laser beams copropagate through the cell. Atoms travel from one laser (chopped) to the other laser (probe), which detects only those atoms optically pumped by the first laser.

The probe laser is tuned to the $5\,^2S_{1/2}\,F'=2$ ground state to the $5\,^2P_{3/2}\,F=3$ excited state transition for $v_z=0$ atoms. Changes in the $F'=2$ ground state population (caused by the chopped laser being on or off) affect the absorption of the probe laser. This change in absorption will only be evident in the $v_z=0$ atoms, providing good velocity selectivity in the z plane, as detailed below.

Excitation via different excited hyperfine levels can spuriously label the atoms. Atoms with nonzero v_z can be excited to the $F=1,3$ excited states if the Doppler shift kv_z ($k=2\pi/\lambda$, $\lambda=780\,\mathrm{nm}$) is equal to the hyperfine splitting relative to the $F=2$ level. Atoms with $v_z=122\,\mathrm{m/s}$ ($kv_z=157\,\mathrm{MHz}$) will be excited to the $F=1$ excited state, and can then decay into the $F'=1$ ground state, leading to a significant imbalance in the ground state populations. However, because the chopped and probe lasers are tuned to different transitions, these atoms are easily distinguished from the $F=2$ channel: there is no excited state hyperfine level at 157 MHz below the $F=3$ excited state, and hence the probe must be detuned to match their v_z velocity. Similarly, atoms at $v_z=-208\,\mathrm{m/s}$ ($kv_z=-267\,\mathrm{MHz}$) will be excited to the $F=3$ state, but these are not labeled and hence not detected for any probe detuning because $F=3$ relaxation to the $F'=1$ ground state is dipole forbidden.

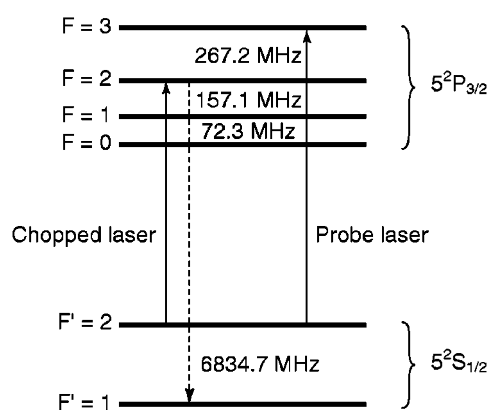

Fig. 2. Partial energy level diagram of Rb[87] showing chopped and probe laser transitions. The chopped laser pumps atoms from the $F'=2$ ground state to the $F'=1$ state. The probe absorption is sensitive to changes in the $F'=2$ ground state population.

The chopped laser also optically pumps atoms among the magnetic substates of the $F'=2$ ground state, via the $F=1,2,3$ excited levels. Differences in the transition strengths for these substates will contribute to the signal at zero probe detuning for $v_z=0$ atoms pumped via the $F=2$ state, and to the signals at $+157$ and $-270\,\mathrm{MHz}$ for the $v_z=122$, $-200\,\mathrm{m/s}$ velocity groups pumped via the $F=1,3$ levels.

III. APPARATUS

Three different external cavity diode lasers were used: a New Focus[15] model 6312 for the probe, one based on the design of MacAdam *et al.* for the chopped laser,[16] and one following Arnold *et al.* for cooling.[17] The latter is constructed almost entirely of relatively low cost commercial components and can be assembled quickly, with very little machining. It typically produces 40-mW output at 780 nm using 70-mW Sanyo diodes (DL-7140-201), with approximately 15% feedback from a gold coated grating (1800 lines/mm, Richardson Grating Laboratory 3301FL-330H).

We have used a variety of drivers to power the laser diodes, including a Newport model 505, ThorLabs LD1255, and an ultra-low-noise source.[18] All of these offer satisfactory levels of current stability, although the latter was noticeably less susceptible to noise at powerline frequency (50 Hz). The diode and its mount were temperature controlled to ± 1 mK using a 10 kΩ thermistor sensor and Peltier thermoelectric cooler using a standard feedback circuit.[16]

The laser frequencies were stabilized to Doppler-free atomic absorption references using synchronous frequency feedback locking.[19] The cooling laser frequency was modulated at 24 kHz (chosen to avoid mechanical resonances) using a small signal applied to a piezo disk behind the diffraction grating. The chopped and probe laser frequencies were also dithered at 24 kHz, but by modulation of their injection currents. A small fraction of the output of each laser was split off and used in a standard Doppler-free saturated absorption arrangement[20] with a room temperature vapor cell. The vapor cells used for laser locking were made following MacAdam *et al.*,[16] but the cell used for the main experiment was purchased.[21]

The dithered absorption signal was detected with a home-built lock-in amplifier[22] and fed back to the laser current or, for the cooling laser, to the piezo disk. The lock point of the cooling laser could be continuously scanned up to 50 MHz by Zeeman shifting the resonance with a magnetic field through the vapor cell.[23] The laser linewidth, determined from the width of the beat note between two lasers, was typically 750 kHz rms.

The laser absorption signals were measured with monolithic photodetectors[24] and a digital lock-in amplifier[25] locked to the optical chopper.[26]

IV. RESULTS

Figure 3 shows an example of the measured lock-in signal as a function of probe detuning, relative to the $F'=2$ to $F=3$ resonance. The chopped laser was locked to the $F'=2$ to $F=2$ transition. The top trace is a saturated absorption scan which indicates the detuning of the probe. All incident laser beams were linearly polarized along y, and the magnetic field was nulled with three pairs of Helmholtz coils to less than 2 μT. The vapor cell was at room temperature.

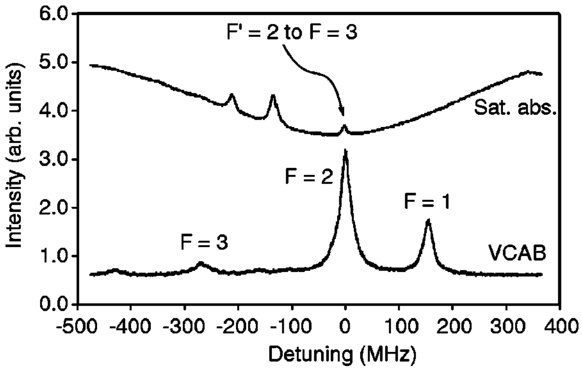

Fig. 3. Lock-in amplifier signal as the probe laser frequency is scanned through the $F'=2$ to $F=3$ transition. The top trace is a saturated absorption scan of the probe used to calibrate the probe frequency. The chopped laser was locked to the $F'=2$ to $F=2$ transition. VCAB denotes the vapor cell atomic beam signal (probe transmission signal measured through the lock-in).

The peaks at probe detunings of 0 and 160 MHz correspond to chopped laser excitation to the $F=2$ and $F=1$ levels, and therefore to the velocity groups of atoms that experience a large degree of optical pumping to the $F'=1$ ground state. The small peak at $-270\,\mathrm{MHz}$ is due to atoms optically pumped between magnetic substates within the $F'=2$ level via the $F=3$ level.

Whether due to pumping to the $F'=1$ level or pumping between magnetic substates of the $F'=2$ level, the large peak at zero detuning in Fig. 3 is due only to those atoms traveling perpendicularly to the two laser beams. The velocity selection process therefore defines an atomic beam, with a Maxwellian spread of velocities along x, the propagation axis.

The spread of transverse velocities of this atomic beam around $v_z=0$ is defined by the power-broadened Lorentzian absorption profiles for the chopped and probe lasers. With the laser frequency fixed on resonance, the absorption for each laser in the two-level approximation is proportional to[20]

$$A(v_z)=\frac{s}{(4(kv_z/\Gamma)^2+s+1)}, \tag{1}$$

where kv_z is the detuning due to the Doppler shift, $\Gamma=6\,\mathrm{MHz}$ is the natural linewidth of the transition,[3] and $s=I_L/I_s$ is the saturation parameter of the laser. The quantity I_L is the laser intensity and I_s is the saturation intensity. The peak intensities of the chopped and probe lasers were measured to be 5.0 ± 0.3 and $4.5\pm0.3\,\mathrm{mW/cm^2}$, that is, $s=3.0\pm0.2$ and $s=2.7\pm0.2$. The linewidth of each laser was less than 2 MHz, a negligible contribution to the width of the velocity distribution. The transverse velocity distribution of the vapor cell atomic beam is determined by the convolution of the absorption profiles for each laser, giving a full width at half maximum of $6.0\pm0.3\,\mathrm{m/s}$.

V. OBSERVATION OF LASER COOLING

To observe laser cooling of the vapor cell atomic beam, a third laser was added, parallel to the chopped and probe lasers, and retro-reflected upon itself (Fig. 4). The red-detuned cooling laser cooled the atoms along the laser axis, therefore increasing the number of atoms within resonance of the chopped laser and in the vapor cell atomic beam. Similarly, with the cooling laser blue detuned, we would expect a decrease in the lock-in signal, arising from atoms being heated out of the velocity range of the chopped laser and hence out of the vapor cell atomic beam.

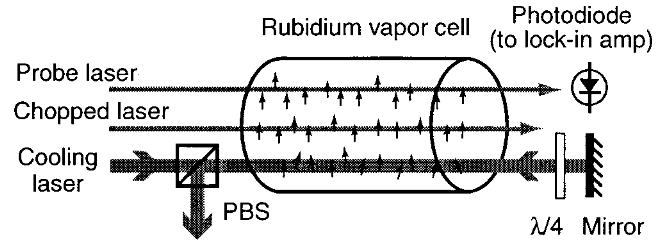

Fig. 4. Experimental arrangement used to observe laser cooling of the vapor cell atomic beam. A third laser was added to cool the atoms before they reached the chopped laser. Atoms that would not normally be part of the vapor cell atomic beam were cooled into the velocity range excited by the chopped laser, increasing the number of atoms in the beam. $\lambda/4$ represents the quarter-wave retarder and PBS represents the polarizing beamsplitter.

In our experiment, a quarter-wave retarder and polarizing beamsplitter were used to minimize optical feedback to the cooling laser. These formed a lin$\perp$ lin standing wave in the vapor cell, and hence polarization gradient cooling[3] was also active. However, for our laser parameters this cooling mechanism is significant only for low velocity atoms[8] ($|v_z|<1\,\mathrm{m/s}$), which already lie well within the capture range of the chopped and probe lasers, and hence had minimal effect on our measured signals.

The cooling laser frequency was scanned over a small range through the $5\,^2S_{1/2}F'=2$ to $5\,^2P_{3/2}F=3$ transition. The laser beam was expanded to 2.4 mm by 5.2 mm ($1/e^2$ full widths, y by x) to increase the cooling time. The chopped and probe lasers were locked to the transitions shown in Fig. 2, and the lock-in signal was monitored as a function of cooling laser detuning for several intensities, as shown in Fig. 5.

The amplitude of the cooling signature increased as the intensity of the cooling laser was increased, reaching approximately 10 % relative to the zero detuning level for the highest cooling laser intensity and a detuning of 5 to 7 MHz below resonance. A corresponding decrease in the signal occurred for a similar blue detuning.

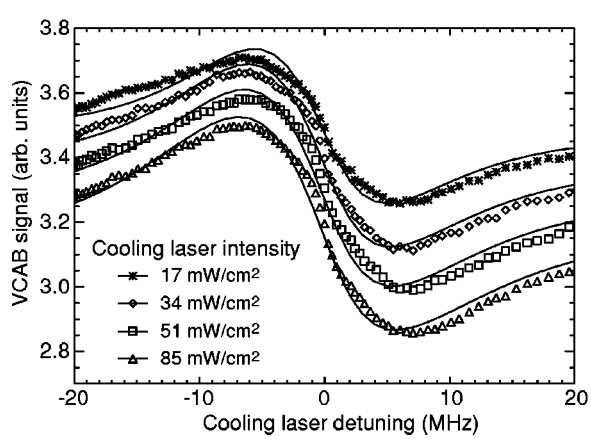

Fig. 5. Measured and predicted lock-in amplifier signals as a function of cooling laser detuning for various cooling laser peak intensities. The symbols are experimental results and the solid lines are theoretical curves.

The strongest Doppler cooling force is expected at a detuning of $\Gamma/2=3$ MHz,[3] corresponding to a transverse velocity of ± 2.3 m/s. These atoms are already inside the ± 3 m/s velocity spread of the atomic beam. Larger detunings will more effectively cool atoms outside the normal capture range of the chopped laser, and hence have a greater influence on the flux of atoms in the virtual atomic beam.

The high intensity of the cooling laser and subsequent power broadening leads to pumping of a small fraction of atoms into the $F'=1$ ground state via the $F=2$ excited state, reducing the number of atoms available for the vapor cell atomic beam. Optical pumping loss is apparent from the steadily decreasing offset of the lock-in scans in Fig. 5 as the laser intensity was increased.

A theoretical model was developed to calculate the expected number of atoms in the atomic beam as a function of the cooling laser parameters. A random series of atomic velocities was generated with a Maxwellian distribution along the primary propagation axis x and along the transverse axis z. The effect of the cooling laser was simulated using a finite step technique to calculate the change in the atomic transverse velocity, Δv_z, in a short time interval Δt. The momentum imparted from the laser field to the atom in each time interval was calculated using the continued fraction technique of Minogin and Serimaa.[27] A time step of $\Delta t=0.2\,\mu$s was used over a fixed distance of 1.5 times the $1/e^2$ beam width. The number of atoms in the transversely cooled velocity-selected atomic beam was then calculated as the integral of the product of the cooled transverse velocity distribution with the transverse velocity distribution of atoms selected by the chopped and probe lasers [see Eq. (1)]. Reducing Δt did not noticeably affect the results.

The number of atoms in the atomic beam is plotted as the predicted vapor cell atomic beam signal in Fig. 5. A scaling factor and offset determined by least-squares fitting were applied to the theoretical curves to account for arbitrary scaling and background of the experimental results and optical pumping losses. A flat detuning dependence was assumed for the optical pumping, which should be valid given the large detuning from the $F'=2$ transition.

The primary channel for optical pumping losses is via excitation to the $F=2$ excited state and decay to the $F'=1$ ground state. Equation (1) can be used to estimate the excitation probability. With the cooling laser detuned by $\Delta=267$ MHz, we have $\Delta^2/\Gamma^2 \gg s$ in the denominator, and

$$A=\frac{s}{4(\Delta/\Gamma)^2}. \tag{2}$$

That is, excitation to the $F=2$ state, and hence loss due to optical pumping, will increase linearly with laser intensity. The scaling factors and offsets are consistent with this linear loss model, as shown in Fig. 6.

There is clearly good quantitative agreement in both the intensity and detuning dependence of the theoretical and experimental results of Fig. 5. Differences may be due to imperfections in the experimental technique (for example, laser beam misalignment) or from limitations in the two-level model. The model could be improved by using a full multilevel description of the atoms when calculating the radiation pressure force,[8] and by including a detailed calculation of the

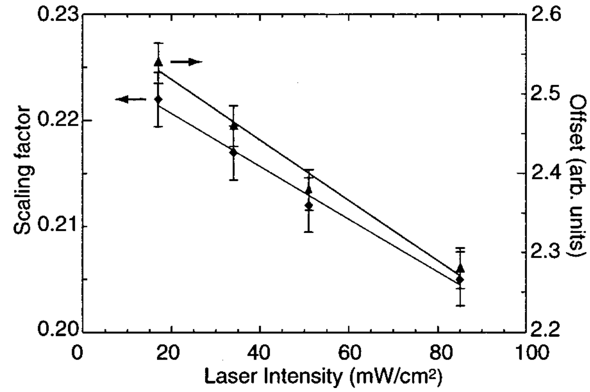

Fig. 6. Scaling and offset between theoretical and experimental results. A straight line fit illustrates the linear effect of optical pumping losses.

optical pumping losses. However, the close agreement we observe, even with the relatively simple theory, provides clear evidence of laser cooling.

VI. CONCLUSION

In conclusion, we have demonstrated one-dimensional laser cooling in a sealed vapor cell. A collimated atomic beam was defined within the cell by velocity selective optical pumping and detection. The method provides a simple and low-cost demonstration of laser cooling of atoms, suitable for an undergraduate laboratory, with reduced complexity and cost in comparison to pumped atom traps.[10] The velocity selected atomic beam in a vapor cell has potential applications in experiments which require monitoring the time evolution of atoms under the influence of a perturbing field, such as the measurement of magnetic fields by Larmor precession.[28]

Further enhancements may be possible, for example, by using a two-photon excitation and detection scheme, with laser beams intersecting perpendicularly to each other, which could perform point-to-point measurements in a cell rather than the beam-to-beam geometry described here. A weak repump laser beam, tuned to the $F'=1$ to $F=2$ transition, could be added collinearly with the cooling laser to eliminate optical pumping losses and enlarge the cooling signature. The transverse velocity selectivity of the labeling process could also be improved using two lasers to drive a Raman transition between the $F'=2$ and $F'=1$ ground states. The linewidth of this transition would be far narrower and provide a substantial improvement in resolution, which would be particularly desirable for further laser cooling studies.

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[a]Present address: Sussex Centre for Optical and Atomic Physics, University of Sussex, Brighton BN1 9QH, UK.

[b]Electronic mail: r.scholten@physics.unimelb.edu.au

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A DOSE OF HUMILITY

In dealing with the origins of various portions of acoustics, the author of this book recalls a cautionary saying of his own, 'nothing was ever discovered or written for the first time; somebody else always did it earlier.' While this is an obvious oversimplification, not to say a contradiction, it is a good guiding principle. In covering a period of two hundred years, there is no doubt that some historical circumstances will be incorrectly cited in this text. While every effort has been made to give proper credit, apologies are made in advance for any errors.

Robert Beyer, *Sounds of Our Times: Two Hundred Years of Acoustics* (Springer Verlag, New York, NY, 1998) p. 4.

Submitted by Alan DeWeerd.