Slowing Atoms with σ^- Polarized Light

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We have modeled and experimentally investigated the "Zeeman tuned slowing" of rubidium using σ^- polarized laser light. Previous studies have all used σ^+ light. We find that important details of the slowing process enable this new method to produce significantly slower and more intense atomic beams than for the σ^+ case. An additional advantage: σ^- slowing exhibits much weaker dependence on laser wavelength and intensity.

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In the past few years the use of laser light to influence the positions and velocities of neutral atoms has led to the development of a wide range of tools for manipulating atomic samples [1]. Indeed, we appear to be near the dawn of an age of "atom optics," where combinations and permutations of these tools enable atomic beams to be controlled in a fashion similar to the way conventional optics control laser beams [2].

This fire of activity was kindled by the discovery of ways to obtain slowly moving atoms. In 1982, Phillips and Metcalf [3] demonstrated the "Zeeman tuned slowing" technique by decelerating a thermal source of sodium atoms to velocities under 200 m/s. In 1985, Ertmer *et al.* [4] showed that by suitably "chirping" a laser beam's frequency near the sodium $D2$ resonance, it was possible to produce pulses of very slow sodium atoms. Today, many experiments begin with an initial stage of laser slowing to produce an atomic sample for further study.

Both chirped cooling and standard Zeeman tuned slowing have shortcomings in producing atoms slow enough to do those things people really want to do with slow atoms such as loading a magneto-optical trap, feeding an "atomic funnel," or sourcing an "optical molasses" [1]. Chirped cooling has inherent duty-cycle losses associated with its pulsed operation. Standard Zeeman tuned slowing, which uses σ^+ laser light to drive a $\Delta m_F = +1$ (see Fig. 1), can produce a cw beam of very slow atoms within the Zeeman tuning magnets, but extracting these atoms from the magnetic field is *extremely* inefficient at the low velocities frequently required for experiments. In the original apparatus of Phillips and Metcalf, for example, it was necessary to turn off the slowing laser light to obtain sodium atoms with velocities less than 200 m/s.

We have pursued the ideas behind Zeeman tuned slowing, and found a new, and, for most purposes, better way to do it. We have slowed rubidium atoms using σ^- polarized light and cycling atoms between the $m_F = -2$ and $m_F = -3$ states of the $5s$ and $5p$ manifolds, respectively.

The differences between using the σ^+ and σ^- transitions are more pronounced than might be expected. Most importantly, with σ^- light, the major obstacle to getting slow atoms out of the magnetic field is removed. Specifically, our σ^- implementation of Zeeman tuned slowing *is* able to produce and efficiently extract intense cw beams of atoms suitable for the applications mentioned above. In addition, the sensitivity of the slowing to laser frequency and power that is characteristic of standard, σ^+ Zeeman tuned slowing is significantly eased.

Interestingly, σ^- slowing is implemented when one of the magnets typically found in a σ^+ slowing apparatus is simply energized in the reverse direction. Hence, many groups presently using σ^+ slowing may readily try σ^- slowing.

Our experiments on Zeeman tuned slowing use only *diode* lasers. This is notable in that we run a total of three lasers for the slowing and diagnostic work. An equivalent experiment using the alternative dye-laser technology would rank near the top end of what is generally recognized as "small-scale" physics. Our apparatus is modest in size and running even more lasers to carry out additional atom optic functions poses no significant challenge.

In laser slowing, an atom decelerates as it receives the momentum of photons from a laser beam propagating counter to the direction of the atomic motion. We consider slowing rubidium using the $D2$ transition with a light wavelength of 780 nm. Each absorbed laser photon gives a slowing atom a velocity "kick" of only 0.60 cm/s. Consequently, the key to making laser slowing work is to find a way to scatter tens of thousands of photons from an

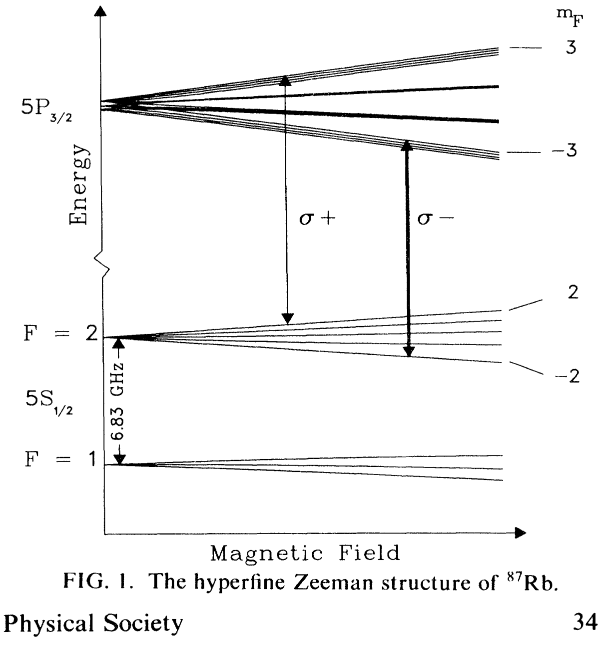

FIG. 1. The hyperfine Zeeman structure of ^{87}Rb.

atom as quickly as possible. In the original Zeeman tuned slowing scheme, this is accomplished by using σ^+ polarized laser light to excite resonantly the $m_F=2$ state in the s manifold to the $m_F=3$ state in the p manifold (Fig. 1). Dipole radiation selection rules allow spontaneous decay of the excited state *only* back to the original $m_F=2$ state. Therefore, after a time on the order of the spontaneous emission lifetime of the rubidium $5p$ state (26 ns) the atom is ready to be cycled again.

During Zeeman tuned slowing, atoms pass through a specially tapered magnetic field which is designed to keep the atomic transition resonant with the laser by compensating the slowing atom's changing Doppler shift with an equal and opposite Zeeman shift. The magnetic field serves a second function: It defines a quantization axis and reduces the probability that a slowing atom will be "optically pumped" out of the cycling process to a state not resonant with the laser. An additional constant field is frequently added to the tapered field to further discriminate against undesired pumping transitions.

At this level, σ^- slowing is very similar to σ^+ slowing except that an increasing magnetic field is required for σ^- slowing in contrast to the decreasing field used in σ^+ slowing.

An important difference comes in considering the details of the slowing process and, in particular, the physics that determines the final velocity of slowed atoms exiting the magnetic field. The deceleration of an atom due to laser light detuned from resonance $\delta\nu$ is

$$a=\frac{h}{8\lambda\tau M}\,\frac{I_D}{4\pi^2\tau^2(\delta\nu)^2+\frac{1}{4}(1+I_D)}\,, \tag{1}$$

where M is the atomic mass, λ is the light wavelength, τ is the transition's spontaneous radiation lifetime, and the laser intensity I_{las} is described by the dimensionless saturation parameter of Citron *et al.* [5], $I_D=I_{\text{las}}/(1.6\ \text{mW/cm}^2)$. In σ^+ slowing, for atoms traveling down the magnet ($+z$ direction) to remain resonant with the laser and slow, the following "adiabatic" condition must be nearly maintained:

$$v(z)=\lambda[\mu B(z)-\Delta\nu]\,, \tag{2}$$

where $v(z)$ is the velocity (positive or negative) of slowing atoms at position z, λ is the laser light's wavelength, $B(z)$ is the magnitude of the magnetic field (positive), μ is the electron magnetic moment divided by Planck's constant, and $\Delta\nu$ is the detuning of the laser from the zero-field, zero-velocity atomic resonance. To slow atoms, $\Delta\nu$ must be positive and $B(z)$ must be decreasing along z. A major difficulty in extracting low velocity atoms from σ^+ slowing is as follows. If atoms of near-zero velocity are to be produced at a finite field value, of necessity, somewhere further downstream, at lower fields, atoms of still lower velocities and even negative velocities will be resonant with the laser. As a result, it is difficult to produce very low velocity atoms in σ^+ slowing—very slow atoms tend to be turned around. The velocity of atoms that *do* get out is found by integrating Eq. (1). The functional dependence of the atomic resonant frequency upon magnetic field means that for *any* arrangement of σ^+ slowing the problem of very low velocities resonating with the laser light will arise at some level (Bagnato *et al.* [6] have minimized the problem with special field designs).

For the case of σ^- light, the condition on the atoms for adiabatic slowing is

$$v(z)=\lambda[-\mu B(z)-\Delta\nu]\,. \tag{3}$$

To slow atoms, $B(z)$ must *increase* and $\Delta\nu$ must be negative. In σ^- slowing, atoms are resonant with the laser until they reach the maximum field, near the exit and then they stop being resonant. Slower velocity atoms are *not* resonant further downstream and hence the circumstances that tended to turn low velocity atoms around in σ^+ slowing do not occur. The velocity of atoms that come out may still be obtained by solving Eq. (1), but the result, to first order, is that atoms leave with the velocity given by Eq. (3) at the field maxima, where they were last resonant with the laser. The final velocity depends only weakly on laser intensity [7].

These points are well illustrated by our modeling. We have studied both kinds of slowing by solving Eq. (1) for the experimental parameters of our apparatus. Our apparatus is able to do either kind of slowing; it was actually designed for σ^+ slowing. In Fig. 2 we show model results for the final velocity of atoms as a function of the slowing laser detuning for the light intensity in our experiment. While, in principle, it is possible to use σ^+ light to get exactly the right deceleration to produce arbitrarily slow atoms, the steep slope at low velocities indicates that atoms traveling less than 50 m/s are very susceptible to being turned around before they exit—a shift in laser frequency of less than 5 MHz will do it. We find a similar strong dependence on laser intensity. σ^- slowing is much less sensitive to laser parameters down to velocities as low as 10 m/s for the conditions in our experiment.

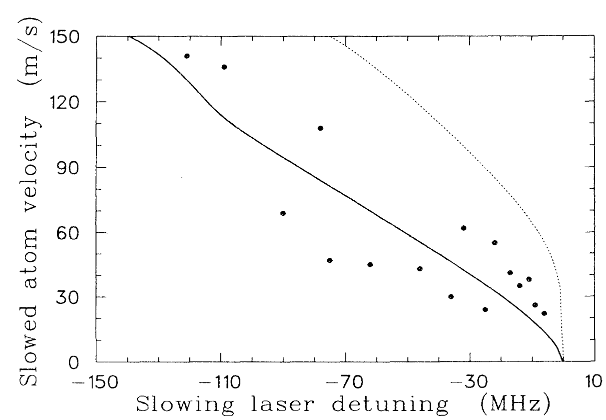

FIG. 2. Dependence of velocity of slowed atoms on the tuning of the slowing laser. Dots and the solid line are experimental and theoretical model results, respectively, for σ^- slowing. The dashed curve gives model results for σ^+ slowing.

We have tried σ^- slowing on ^{87}Rb. A schematic of the experiment is shown in Fig. 3. A beam of rubidium atoms from a 175 °C oven passes through an appropriately tapered magnetic field and into an experimental chamber. Propagating counter to the atomic beam is a circularly polarized laser beam to slow the atoms. We have 12 mW of laser power available; the beam is roughly circular and Gaussian in shape and is focused at the oven. It has a diameter of about 1.5 cm as it enters the slowing solenoid magnets. Downstream 75 cm from the end of the magnets is an observation region. Here the velocity distribution of the atoms after the slowing process is determined. A weak probe laser that intersects the atomic beam axis at an angle of 55° is swept in frequency. The velocity dependence of the Doppler shift allows the atomic beam fluorescence versus probe laser detuning to be interpreted as the velocity distribution of the atoms. We image a fraction of the fluorescence from this probe region onto a photodiode detector. A computer sweeps the probe beam's frequency while recording the fluorescence signal (see Fig. 4). Simultaneously, Doppler-free saturated absorption reference spectra are taken from a Rb cell.

As the atoms exit the slowing region they may be optically pumped by the slowing laser to one of the states in the $F=1$ hyperfine level of the ground-state manifold. To be detected they must be returned to the $F=2$ level. This is done by a third, "repumping" laser beam that is tuned to the $F=1$ to $F=2$ transition between the ground- and excited-state manifolds, respectively.

We used the technique of Dahmani, Hollberg, and Drullinger [8] to reduce the linewidths of the slowing and probing lasers from their nominal "free-running" values of around 50 MHz to "optical-feedback-narrowed" values of under 5 MHz.

Two 60-cm-long solenoidal magnets, a "bias" magnet and a "profile" magnet, are used to generate the fields that Zeeman tune the atoms. The bias magnet provides a constant 800-G field over the region in which slowing occurs. It provides a well-defined quantization axis and shifts the frequency of the light used for slowing far from the zero-field resonance. Hence atoms do not scatter light from the slowing laser once they exit the slowing magnets. The profile magnet generates a tapered field designed to slow atoms with a constant deceleration. In our apparatus, we can do regular σ^+ slowing by energizing the two magnets such that their fields add. Reversing the current in just the bias field achieves two conditions necessary and sufficient to implement σ^- slowing. First, the direction of the quantization axis is changed. Second, the magnitude of the net field now *increases* in exactly the fashion required for constant acceleration σ^- slowing.

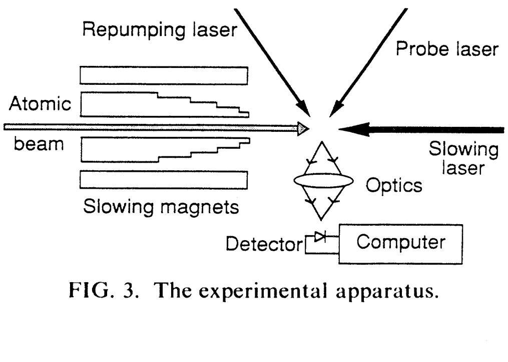

FIG. 3. The experimental apparatus.

The strength and length of the profile field determine what fraction of the initial velocity distribution of the atoms coming from the oven are slowed. We typically slow to very low velocities atoms that leave the oven with speeds of less than about 200 m/s. The peak of the oven distribution occurs at a velocity near 350 m/s.

Our experimental results are summarized in Figs. 2 and 4. An important result is that σ^- slowing does work. This result was by no means certain, *a priori,* considering the need to successfully cycle the transition tens of thousands of times and the potential sensitivity of the process to the differences in the optical pumping rates between σ^+ slowing and σ^- slowing. To our knowledge, however, the simple two-level model described above contains all the relevant physics of the slowing process. We have studied the slowing by varying the frequency of the slowing laser and measuring the velocity distribution of the atoms downstream. Figure 4 shows a series of such measurements. Figure 2 compares the model predictions of slowed atom velocities with velocities of the slowed atom peaks taken from the experimental data. The only free parameter was an overall shift in the frequency scale which was needed because we do not know bias field to the precision necessary for this comparison. The experimental data in Fig. 2 are a collection of measurements truly representative of day-to-day operation. The scatter is consistent with that expected from frequency drifts of the slowing laser as the data are acquired. We have similarly studied σ^+ slowing.

Our experimental data are in harmony with the theoretical picture suggested by Fig. 2. Specifically, our σ^+ slowing calculations indicate a high sensitivity to laser frequency and intensity for atoms with velocities less

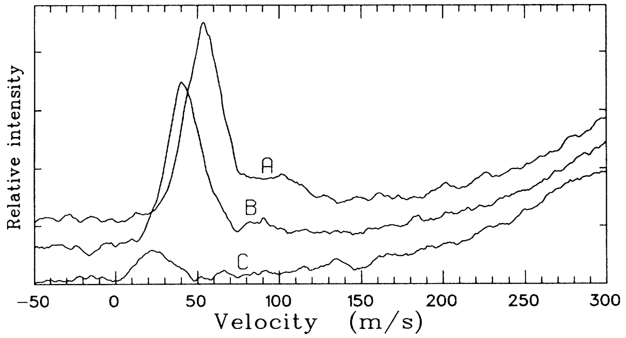

FIG. 4. Fluorescence signals for three slowing laser tunings. Curves *A*, *B*, and *C* correspond to slowed atom velocities of 60, 40, and 200 m/s, respectively.

than 50 m/s. Experimentally, we find that the best we can do with σ^+ slowing is to produce very small numbers of 40-m/s atoms. With σ^- light, slowing to 40 m/s is easy; in fact, we are able to get atoms as slow as 10 m/s. Again, this is consistent with the theoretical picture suggested by Fig. 2.

The detection efficiency of our light measurement system is known to within a factor of 2 and, consequently, we can estimate absolute numbers of slowed atoms. The 40-m/s peak shown in Fig. 4 corresponds to a beam intensity of 2×10^{10} atoms cm^{-2}s^{-1}. While we made modest attempts at maximizing this, we expect that higher slow-atom beam intensities may be readily obtained by working with a more intense initial beam, slowing atoms from the peak of the velocity distribution, or merely measuring closer to the exit of the slowing magnets.

As Fig. 4 suggests, for very low velocities we find a fairly sharp decrease in the number of slowed atoms seen in the detection region as the exit velocity approaches zero. This may be explained partly by spreading of the atom beam due to the transverse velocities of the atoms as they drift toward the detection region. However, we suspect that part of the decrease is caused by defocusing of the atomic beam by the magnetic-field gradients at the exit of the slowing region and are investigating this numerically.

In conclusion, we have demonstrated that it is possible to implement Zeeman tuned slowing using σ^- polarized light. We find experimental results consistent with a two-level description of the slowing. Our studies of the process, both modeling and experimental, indicate that it is superior to σ^+ slowing in the sense that it can produce larger quantities of slower atoms and reduces the sensitivity of the velocity of the slowed atomic sample to the frequency and intensity of the laser light. We feel that, because of the latter feature, the most important applications may involve the slowing of "exotic" species (nonalkalis) for which available laser power is insufficient to saturate the slowing transition or is subject to large fluctuations. Finally, it may be possible to "retrofit" many existing experiments by simply changing the field direction in one of the magnets.

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[7] In ours and most other existing slowing experiments, the cycling transition is strongly saturated and the velocities of atoms produced depend only weakly on the laser intensity—even for σ^+ slowing. As increasingly exotic species are slowed, e.g., calcium [N. Beverini *et al.*, J. Opt. Soc. Am. B **61**, 1288 (1989)] today, and perhaps hydrogen and positronium tomorrow, available laser intensities may be small and fluctuating. The very weak laser intensity dependence of final velocity that is characteristic of σ^- slowing may prove invaluable to these experiments.

[8] B. Dahmani, L. Hollberg, and R. Drullinger, Opt. Lett. **12**, 876 (1988).