Stopping Atoms with Laser Light

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We have produced a sample of free sodium atoms at rest in the laboratory by decelerating atoms in an atomic beam using momentum transfer from a counterpropagating, resonant laser beam. These atoms have a density of about 10^5 cm^{-3} and a velocity spread of about 15 m/s full width at half maximum corresponding to a kinetic temperature less than 100 mK.

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In this Letter we report the production of a stationary "gas" of atoms whose effective temperature is 100 mK. The measured velocity distribution of the atoms has a full width at half maximum (FWHM) as low as 15 m/s and can be centered at $v=0$. The interest in such an atomic sample lies in its possible application to such diverse problems as elimination of motional effects in high-resolution spectroscopy or precision measurement, ulta-low-energy collision, and neutral-atom trapping. This latter possibility is especially interesting: Although neutral-atom trapping has historically attracted much attention,[1-8] and recent specific proposals for stable optical or laser traps look quite promising,[7,8] trapping has not been realized largely because suitably slow atoms were not available.[9] While previous laser-cooling efforts in our laboratory at the National Bureau of Standards[10-12] and in Moscow[13,14] produced very slow atoms, the shallow laser and magnetic traps being proposed require a still slower sample. The present work provides just such a sample.

Our previous technique for laser deceleration and velocity compression (cooling) of an atomic beam has been described in detail elsewhere.[1,2,15,16] Briefly, atoms in a thermal atomic beam with a mean velocity of about 1000 m/s are cooled by directing a near-resonant laser beam opposite to their motion. The atoms absorb and then fluoresce the light, changing their velocity by $h\nu/Mc$ for each absorption. As the atoms in the beam scatter light and slow down, their changing Doppler shift would take them out of resonance with the laser so that they would eventually cease to celerate. However, we compensate for the changing Doppler shift by Zeeman tuning the atomic levels along the beam path using a spatially varying magnetic field produced by a nonuniform solenoid. With this compensation all atoms initially slower than some selectable maximum are decelerated to a final narrow velocity group. This process is appropriately called laser cooling. Both the selectable maximum and the final velocity are determined by the laser frequency and intensity and by the magnetic field strength and its gradient. A continuous atomic beam with final velocity as low as 200 m/s can be achieved, or the atomic beam can actually be stopped in the solenoid.

We measure the velocity distribution by detecting the fluorescence from atoms excited by a second, very weak laser propagating nearly parallel to the atomic beam. This signal is proportional to atomic density. Because of the Doppler shift, the intensity of this fluorescence depends resonantly on the atomic velocity, and a slow scan of this laser's frequency results in a fluorescence signal that reflects the velocity distribution. This is done in an observation region about 40 cm beyond the end of the solenoid in order to avoid effects from its fringe field. The velocity resolution of this detection method is limited to 6 m/s by the natural lifetime of the excited atoms. The zero of velocity (atomic resonance) is determined unambiguously by using a saturated-absorption cell that allows Doppler-free detection of the Na resonances.

Atoms are stopped or brought to very low velocities only in the solenoid.[17] In order to observe these slower atoms, we shut off the cooling laser light and wait until atoms of the desired velocity drift into the observation region. However, during the drift time of several milliseconds, these slower atoms spread out both longitudinally and transversely, thereby reducing their density: Atoms slower than about 30 m/s cannot be seen. The stopped atoms, which have very high density in the solenoid, can never be detected in the

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observation region. Furthermore, their location in the solenoid in a strong magnetic field gradient makes it difficult or impossible to observe or otherwise use these atoms. For example, simple configuration laser traps will not work in a magnetic field because of Zeeman splittings. While it may be possible to construct a trap at the end of the solenoid,[18] it would be difficult to optimize both trapping and solenoid fields.

In order to produce a stationary sample of atoms in the observation region, we first decelerate them in the solenoid to a low velocity. We then turn off the cooling laser beam, and allow the atoms to drift into the observation region. At this point we further slow them with a short (100–400 μs) decelerating pulse (DP) of light from the cooling laser. The velocity of the atoms present in the observation region at the start of the DP is determined by the delay between turning off the cooling laser light and turning it on again for the DP. This velocity is only slightly affected by changes of the cooling-laser frequency over the range used in these experiments. By varying the delay from 6 to 10 ms, this velocity can be varied from 70 to 40 m/s. The time of the initial cooling light and the DP is accomplished by a chopping wheel with appropriate apertures. A 0.02-T field is applied in the observation region to Zeeman tune the slow atoms into resonance with the fixed-frequency cooling laser. (If the laser were frequency switched or a separate laser with a different frequency were used for the DP, the magnetic field could be eliminated.)

In this way we have produced a sample of decelerated atoms with a velocity width as small as 15 m/s FWHM. With proper choice of delay time and DP length the distribution can be centered at zero velocity. In Fig. 1 we show measurements of the velocity distribution obtained with the DP, and then with the DP having various laser frequencies for a fixed time duration and intensity. We have studied a large range of values of these and other parameters, and the data here are truly typical. Each trace results from a frequency scan of the analyzing laser lasting about 2 min. The base line visible at the high-frequency end of the trace is from uncooled atoms shifted into resonance by the magnetic field. It is clear from Fig. 1 that with the proper laser frequency we can decelerate atoms to $v=0$, and even reverse their direction (negative velocity), without a substantial increase in the width of the velocity distribution. The smallest velocity widths were obtained with longer delay times and shorter DP lengths than used for the data of Fig. 1. Widths of 15 m/s are obtained around $v=0$ for 8-ms delay and 100-μs DP; a sample is shown in Fig. 2.

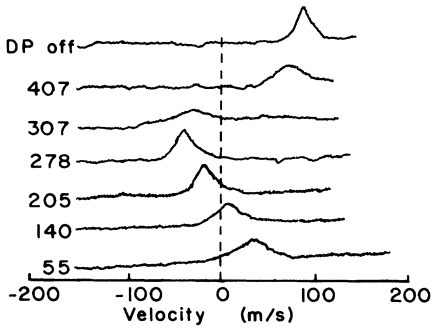

FIG. 1. Velocity distributions obtained with a 250-μs decelerating pulse (DP) having an intensity of about 1 W/cm^2 (15% accuracy) beginning 5.8 ms after the cooling laser beam was cut off. The various traces are for different cooling-laser detunings (in megahertz) from atomic resonance.

We have calculated the effect of the DP on the velocity distribution for comparison with our data. The atomic deceleration a is given by a power-broadened Lorentzian absorption curve that depends on velocity through the Doppler shift:

$$\frac{a}{a_{\max}}=\frac{I_D}{4U^2+(1+I_D)}, \tag{1}$$

where $U=(\Delta+v/\lambda)2\pi\tau$, $I_D=2(\Omega\tau)^2=I_{\text{lab}}/(6\ \text{mW/cm}^2)$, and $a_{\max}=h\nu/2Mc\tau$. Here I_D is the dimensionless intensity parameter as defined by Citron *et al.*,[19] $\Omega=\mu E/\hbar$ is the Rabi frequency and depends on the laser field E, μ is the optical transition dipole moment, τ is the lifetime of the $3P$ state of Na (about 16 ns), Δ is the laser detuning from the Zeeman-shifted atomic resonance frequency (Hz), and M is the atomic mass. This equation of motion $dv/dt=a(v)$ is readily integrated and the resulting cubic equation is solved by standard means for the velocity as a function of time in terms of the initial conditions and experimental parameters (laser intensity and frequency, magnetic field, pulse duration). The result is used to calculate the final velocity distribution from the experimentally measured initial distribution.

The measured and predicted shifts of the peak of the velocity distribution caused by the DP are plotted against laser frequency in Fig. 3. Some of the experimental values are from the data of Fig. 1 and the only adjustable parameter is the laser intensity, which is within the uncertainty of the measured value. Note that the largest velocity change occurs when the laser is resonant with atoms whose velocity is midway between the initial and final velocity; in this case that middle velocity is approximately zero. In a field of 0.02 T, zero-velocity atoms are resonant at a detuning of 280 MHz. Both Figs. 1 and 3 show that tunings higher or lower than this yield smaller velocity changes. Obviously the simple calculation described above provides a very good description of the effects of the DP. We have performed a Monte Carlo simulation of the deceleration process and it also gives good

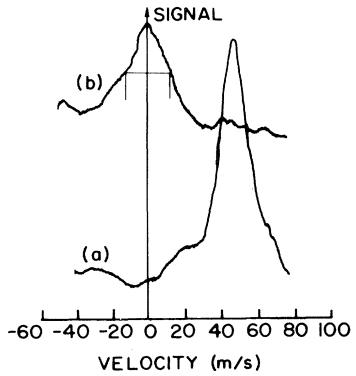

FIG. 2. Trace *a* shows a velocity distribution 13 m/s wide (FWHM) centered at 54 m/s before a DP was applied. It is not distorted much by the probe because the atoms move through the observation region in less than 100 μs. Trace *b* shows a velocity distribution 15 m/s wide (FWHM) centered at 0 m/s after a DP. Because these atoms remained in the probe beam for more than 300 μs, the velocity distribution has been distorted, weakened, and broadened by several meters per second. Both curves have been broadened by the natural width associated with the probing process, 6 m/s.

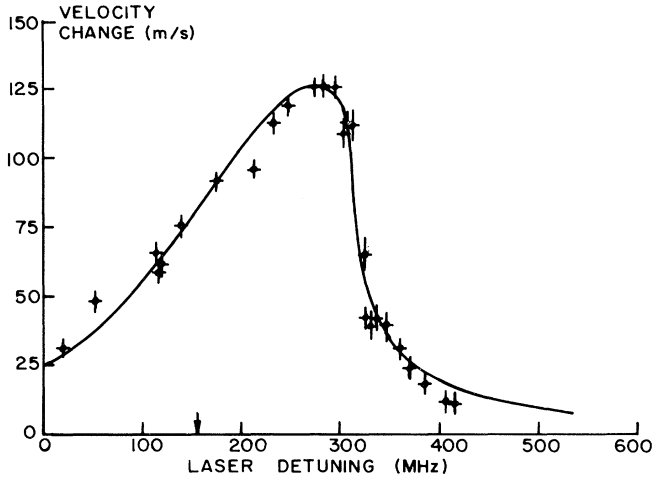

FIG. 3. Velocity change vs cooling-laser frequency for a 250-μs DP. Arrow indicates the frequency which is resonant with the atoms before application of the DP.

agreement with the data and the analytic calculation.

We observe (and the calculations predict) that for laser frequencies higher than that producing the maximum velocity shift, the width of the final velocity distribution increases (heating) compared with the original one. This broadening is seen most strongly in Fig. 1 on the trace with 307-MHz detuning. While we also calculate that for lower laser frequencies the distribution should narrow (cooling), we have not yet observed this effect. (We are now investigating a number of possible reasons for our failure to observe this cooling. We believe that the probe perturbs the velocity distribution, accelerating and heating the atoms; this notion is supported by our model calculations.) The heating and cooling is analogous to laser heating and cooling in ion traps[20] with blue or red tuning.

By comparing the signal from the uncooled atomic beam to the signal from stopped atoms, and knowing the total atomic flux, we can estimate the density of atoms stopped by the DP from 70 m/s to be more than 10^5 cm^{-3}. Figure 3 shows that atoms as fast as 130 m/s can be stopped, and these would yield densities as high as 10^6 cm^{-3}. Such a sample is well suited for a neutral-atom trap.

A stable laser trap[7] with volume 2×10^{-4} cm^3 could capture Na atoms with velocities of several meters per second, and so even a conservative estimate leads to more than one such atom in the trap. The volume of the stopped-atom sample is several cubic centimeters, and so more atoms are expected to drift into the trap. Fluorescence from a single atom in a laser trap should be readily observable. A radiation-pressure trap proposed by Ashkin[8] could contain several orders of magnitude more atoms in a larger volume.

A magnetic trap can be made from a pair of opposing coaxial current loops separated by about 1.25 radii forming a spherical quadrupole field.[21] For 5-cm-diam loops with 2500 At, such a trap will contain 5-m/s atoms in a 25-cm^3 volume. We could expect to trap more than 10^5 atoms in such a trap, which could provide the necessary magnetic field to tune the atoms for stopping.

In the following Letter Ertmer *et al.*[22] describe a different method for producing stopped atoms with a similar velocity spread. With two methods for production of a suitably slow sample of atoms, it now seems clear that both laser and magnetic trapping are likely to be achieved in the near future.

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