Laser Deceleration of an Atomic Beam

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Deceleration and velocity bunching of Na atoms in an atomic beam have been observed.
The deceleration, caused by absorption of counterpropagating resonant laser light,
amounts to 40% of the initial thermal velocity, corresponding to about 15 000 absorptions.
Atoms were kept in resonance with the laser by using a spatially varying magnetic field
to provide a changing Zeeman shift to compensate for the changing Doppler shift as the
atoms decelerated.

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We report a definitive observation of the deceleration and velocity bunching of neutral atoms in a thermal beam by momentum transfer from a counterpropagating resonant laser beam. Although ions trapped by electromagnetic fields have been cooled by laser light,[1] such traps are not deep enough to confine thermal neutral atoms for similar cooling. A sample of slow neutral atoms could alleviate problems such as transit time and second-order Doppler effects in atomic clocks and precision spectroscopy. They may also be used for very-low-energy scattering or be deposited into shallow traps for further cooling.

Frisch first reported the deflection of atoms by resonant light in 1933,[2] but the availability of tunable lasers has recently stimulated new interest in controlling the motion of atoms with light. Cooling[3] and trapping[4] of atoms with lasers have been proposed, and deflection,[5] and steering and focusing,[6] of atomic beams with lasers have been reported.

Although observable deflection can be accomplished by scattering a small number of photons, transfer of the momentum of a large number of photons is required for the thermal atoms to experience a significant change of momentum along the beam direction. The velocity change caused by scattering n photons resonant with the $3S$ to $3P$ transition in Na (yellow D line) is $nh\nu/Mc \simeq 3n$ cm/s. When the transition is saturated by resonant light of intensity large compared with 10 mW/cm^2, so that the atom spends half its time in the $3P$ state (lifetime $\simeq 16$ ns), the maximum deceleration of $a = (3 \text{ cm/s})/(32 \text{ ns}) \simeq 10^8$ cm/s^2 is achieved. Then atoms with $v_0 = 10^5$ cm/s are stopped in about 1 ms over a 50-cm path having scattered about 30 000 photons.

Two processes limit deceleration by this method: Atoms experience a Doppler shift out of reso-nance with the laser as they slow down, and atoms are optically pumped. Optical pumping occurs when atoms are excited from one of the two Na hyperfine ground states (HFGS) to a $3P$ state that decays to the other HFGS. Since these HFGS are separated by 1.77 GHz and the natural linewidth is 10 MHz, atoms pumped to this other HFGS are not resonant with the laser. Both the Doppler shift and the optical pumping problems can be solved by using a spatially varying magnetic field applied along the laser–atomic-beam axis. The field both Zeeman tunes the decelerating atoms into constant resonance with the fixed-frequency cooling laser and produces selection rules and Zeeman shifts that strongly discriminate against optical pumping.

We use a circularly polarized cooling laser tuned to induce the σ^+ transition from the $F=2$, $M_F=2$ sublevel of the $3S_{1/2}$ ground state to the $F=3$, $M_F=3$ sublevel of the $3P_{3/2}$ excited state (neither of these states is mixed by the magnetic field). In this case the selection rules demand that transitions occur only between this particular pair of states with maximum M_F. Imperfect polarization, angular divergence, or misalignment of the laser and magnetic field axes allow transitions to other than the $F = M_F = 3$ excited state. Nevertheless, if the magnetic field is at least 0.04 T, either the matrix elements for unwanted excitations are so small or those transitions are Zeeman shifted so far out of resonance that little optical pumping results. For example, the probability of the π transition from the $F=M_F = 2$ ground state to the $F=3$, $M_F=2$ excited state, much weaker than the σ^+ transitions at zero field, is further reduced by a factor of 10 at 0.02 T and a factor of 100 at 0.05 T. Also, the detuning for the allowed π transition to the $F=2$, $M_F=2$ state is 400 MHz at 0.02 T and almost 1000 MHz at 0.05 T. We estimate that the combined effect of

alignment errors and finite magnetic field allows undesired transitions to be 10^{-4} times as probable as the desired σ^+ transition.

Because the Zeeman shift γ_Z of the frequency of the σ^+ transition is a constant (14 GHz/T), the changing Doppler shift of an atom experiencing uniform deceleration a can be cancelled by a magnetic field varying as $B = B_b + B_0(1 - 2az/v_0{}^2)^{1/2}$. For $B_0 \simeq 0.12$ T, the Zeeman shift matches the Doppler shift of atoms from velocity v_0 $= 10^5$ cm/s down to zero. Slower atoms begin decelerating upon reaching the magnetic field whose Zeeman shift matches their Doppler shift. Thus all atoms of velocity $v_0 \lesssim \lambda\gamma_Z B_0$ are bunched into one slow velocity group. With a constant bias field B_b of at least 0.04 T, the field described above solves both the Doppler-shift and optical-pumping problems.

This use of a changing magnetic field to follow the changing atomic Doppler shift "adiabatically" is similar in principle to the use of a rapidly changing laser frequency proposed by Letokhov[7] to follow the changing Doppler shift. Balykin, Letokhov, and Mishin[8] have reported deceleration of a Na beam with this technique, using the same frequency-scanned laser simultaneously to produce velocity analysis of the atomic beam. This procedure produces ambiguous results because the velocity distribution is inferred from the Doppler line shape which is distorted by optical pumping.[9] Our procedure avoids these problems by using a second, weak laser to perform the velocity analysis. Furthermore, the use of a magnetic field to achieve adiabatic cooling results in a continuous, rather than a pulsed,

production of slow atoms.

Our apparatus is shown schematically in Fig. 1. A 500 °C oven with a 600 °C nozzle produces a slightly supersonic Na beam that is then collimated to ~0.01 rad. About 50 cm from the source the beam enters a 60-cm-long solenoid. Three layers of wire wound on the entire 60-cm length provide the bias field B_b, while additional windings on only part of the solenoid produce the spatially varying part of the field.

The 30-mW cooling laser is aligned so that its 5-mm-diam beam overlaps the atomic beam for the entire 1.6-m length of the apparatus; the 80-μW analyzing beam crosses these two at ~6°, overlapping them in a region a few centimeters long in the field of view of a photomultiplier (PMT). (The laser linewidths are about 10 MHz.) This region is far enough away from the 9-cm-diam solenoid to be in nearly zero field. The output of the PMT is amplified and fed to a boxcar integrator triggered by the 100-Hz chopper interrupting the cooling beam.

The boxcar's dual 50-μs gates are set to observe fluorescence induced by the analyzing laser after the cooling beam has been blocked by the chopper (fall time ~15 μs). Gate A is set 50 μs after the cooling beam turns off and gate B is set 4 ms later. The A signal therefore comes from atoms that have traversed the solenoid while the cooling light was on (drifting only a few centimeters during the 50-μs delay) while the B signal comes from atoms that were never in the cooling laser light.

As the analyzing laser's frequency is scanned slowly, the observed fluorescence gives the ve-
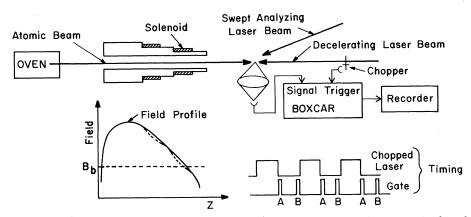

FIG. 1. Schematic diagram of apparatus including optical and electronic arrangement. A plot of B vs z, with and without the turns in the small shaded area of the solenoid, is shown. Note the regions of large dB/dz (steep slope on broken curve). The timing of the boxcar gates A and B relative to the chopping of the decelerating laser is shown at the lower right-hand side.
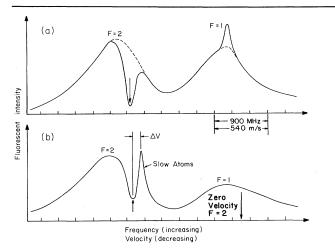
FIG. 2. (a) A scan of the probe laser with no field
and highly attenuated deceleration laser shows the ve-
locity distribution and hyperfine peaks (B trace, dashed
line) and the optical pumping of $F = 2$ atoms into the
$F = 1$ state (A trace, solid line). (b) A uniform 0.075-T
field with the laser at full power results in a deep,
broad optical-pumping hole for $M_F \neq 2$, $F = 2$ atoms and
a narrow, slow-speed peak in the middle of it produced
by nonadiabatic deceleration. Tic marks are from a
300-MHz free spectral range etalon. Arrows indicate
the velocity group resonant with the cooling laser.

FIG. 3. Solid curve taken at full laser power with
tapered field (maximum $\cong$ 0.06 T). Peak C is fluores-
cence from slow $F = 2$ atoms. The arrow R indicates
the velocity group resonant with the cooling laser at
maximum field Zeeman shifted by $\Delta\nu_Z$, L indicates
the resonant velocity group at zero field, and Z indi-
cates zero velocity for $F = 2$ atoms. The quantity $\Delta\nu_c$
is the Doppler shift corresponding to the deceleration.
The dashed curve is a B trace clearly showing the ab-
sence of atoms with velocities near that of peak C. Tic
marks are from a 300-MHz free spectral range etalon.

locity distribution of the atoms in the beam, high-
er frequency corresponding to lower velocity be-
cause of the Doppler shift. The A signal gives
the velocity distribution as modified by the cool-
ing laser, while the B signal gives the unmodi-
fied velocity distribution. The signal is compli-
cated by the 1.77-GHz hfs splitting of the ground
state that results in two peaks, separated by the
hfs and showing the velocity distribution of atoms
in the $F = 1$ and $F = 2$ HFGS. The 15–60-MHz
hfs splitting of the $P_{3/2}$ state is unresolved. When
the probe laser is weak the two peaks have simi-
lar shapes, but are scaled by the 3:5 ratio of
populations in the two ground states.

Figure 2(a) shows the A signal obtained when
the cooling laser is attenuated by a factor of 10^4
to about 3 μW, tuned to be in resonance with F
$= 2$ ground-state atoms, and no magnetic field is
applied. The $F = 2$ atoms are pumped to $F = 1$
producing a hole in the $F = 2$ velocity distribution
and a corresponding peak in the $F = 1$ distribu-
tion. At higher power the hole and peak are
made broader and stronger. Figure 2(b) shows
the effect of applying only a uniform bias field
of 0.075 T, raising the laser to full power, and
retuning it to compensate for the Zeeman shift.
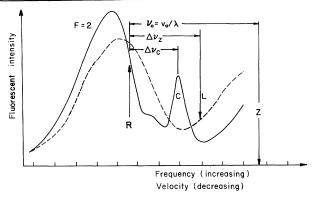Atoms in the field are not optically pumped out

of the $F = 2$ ground state, and so repeated absorp-
tions occur. This results in a hole in the $F = 2$
velocity distribution, but there is no correspond-
ing peak in the $F = 1$ distribution. Therefore,
the hole is *not* the result of optical pumping. A
peak does occur, however, just on the low-veloc-
ity side of the hole because many atoms are
transferred to a slower velocity group by repeat-
ed absorptions. The velocity change is about 15%
of the initial velocity and is limited by the Dop-
pler shifting of the cooled atoms out of resonance
with the cooling laser. Minogin[10] has analyzed
this nonadiabatic cooling problem theoretically,
and our results are in qualitative agreement.

To achieve adiabatic cooling, we connected the
additional windings on the solenoid to produce a
spatially varying magnetic field. The results
are shown by the solid curve of Fig. 3. The
arrow R indicates the velocity group resonant
with the cooling laser at the peak value of mag-
netic field (0.06 T). The arrow L indicates the
velocity group resonant at zero field [determined
by optical pumping as in Fig. 2(a)] and is sepa-
rated from R by the Zeeman shift $\Delta\nu_Z = 0.06\gamma_Z$
$= 840$ MHz. Atoms slower than v_0 are decelerated
and bunched into the highly populated velocity
group at peak C (much higher than the uncooled
distribution shown by the dashed B trace).

In order to determine the magnitude of v_0

(Doppler shift $= \nu_0$) a small part of the analysis laser beam was directed perpendicular to the atomic beam so that there is no first-order Doppler shift. The arrow Z in Fig. 3 indicates the frequency at which fluorescence is induced by this laser beam and therefore marks the resonant frequency of zero-velocity $F = 2$ atoms in zero field. The distance from Z to the arrow R gives $v_0 = 1180$ m/s. The observed velocity change Δv_c is $\simeq 40\%$ of v_0 and corresponds to about 15 000 absorptions.

The maximum deceleration we can achieve is now limited by the total change in the magnetic field. A larger field change could result in further deceleration but the adiabatic requirement allows a certain maximum gradient. Since the maximum deceleration is $a = 10^8$ cm/s^2, this maximum $dB/dz = a/\gamma_Z \lambda v$ where the λ is from the Doppler shift and $\gamma_Z = 14$ MHz/T. For $v \simeq 10^5$ cm/s, $(dB/dz)_{max}$ is 1 mT/cm (10 G/cm). Our solenoid is already at this limit.

We tested this analysis of the limitation on cooling by disconnecting those turns on the solenoid indicated by the shaded areas in Fig. 1. This produced two regions where dB/dz was too large (steep part of broken curve), with little change in the field between these regions. We found that atoms could not decelerate adiabatically from one end of the solenoid to the other.

A larger change in the magnetic field, over a longer path, will be needed to achieve greater cooling. We believe that we can reduce the atomic velocity by at least a factor of 10 from thermal velocity before transverse heating effects,[11,12] caused by the random reemission, and increased angular divergence become important problems.

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[12]Recent data taken with a new 1.1-m-long solenoid show peak C at velocity less than 25% of v_0. It is much narrower and taller than that shown in Fig. 3. This advance will be described in a later publication by the present authors and J. V. Prodan.