Slowing and Cooling an Atomic Beam Using an Intense Optical Standing Wave

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We have demonstrated a new slowing and cooling technique which uses a standing-wave laser field collinear with a thermal Na atomic beam to produce a continuous supply of slow atoms, with most probable velocities ranging from −40 to +80 m/s. The velocity spread can be ~10 m/s (150 mK), the density $>10^8$, and the peak density in phase space ~100 times that at the peak of the original Maxwell-Boltzmann distribution.

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In recent years great progress has been made in manipulating atoms using light. Numerous methods of slowing and cooling atomic beams have been suggested[1-4] and demonstrated.[2-5] These cold beams can be used to do high-resolution spectroscopy and to improve time and frequency standards. In addition, experiments using cold atoms have shown that measurements made on atoms moving at thermal velocities cannot be simply extended to cold atoms.[6] These results have increased the interest in further studies of collisions between cold atoms, collisions of cold atoms with surfaces, and the collective behavior that can result when the spacing between atoms approaches the de Broglie wavelength of the atoms. Thus, simple, compact, and reliable methods of producing a continuous, dense source of cold atoms with a controllable velocity distribution are of great interest.

We have demonstrated that a continuous supply of slow atoms can be produced using a strong standing-wave laser field collinear with an atomic beam, as shown schematically in Fig. 1. We used interaction lengths from 55 to 17 cm. Using an interaction length of 27 cm, we typically obtained an atomic beam with density of approximately $1\times10^8/\mathrm{cm}^{-3}$, a most probable velocity of 12 m/s, and a width in velocity space of less than 12 m/s. In addition, we used counterpropagating fields of different frequencies to produce a beam with a most probable velocity of −40 or +80 m/s. Finally, we suggest modifications which should narrow the velocity distribution and increase the peak density.

In order to understand the physical principles underlying these results, consider a beam of atoms with resonant

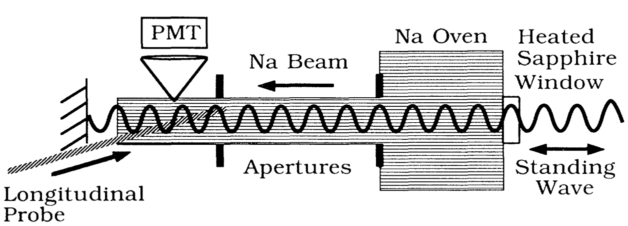

FIG. 1. Schematic of the experimental setup.

frequency ω_0 propagating in the $+z$ direction, where two counterpropagating collimated light fields of equal intensity and the same polarization are superimposed on the atomic beam as shown in Fig. 1. The light will exert a force on the atoms, changing the distribution of atoms in phase space. We will begin by considering only the z component of this force and assuming that both fields have the same frequency ω, where the detuning $\Delta=\omega-\omega_0<0$.

If the interaction between an atom and one or both of the fields is sufficiently weak that the probability of a stimulated transfer of photons between fields is much smaller than the probability of a spontaneous emission, then the dominant process producing a net change in momentum will be the absorption of a photon from one of the fields followed by a spontaneous emission. The net force will be in the direction of propagation of the field which is Doppler shifted nearer resonance; consequently, a moving atom will be pushed in the direction opposite to its velocity. This principle is the basis of "optical molasses." Optical molasses in its original form used weak fields to cool atoms to very low temperatures.[7] Such weak fields interact significantly only with atoms whose velocities are Doppler shifted within a natural linewidth Γ of the field frequencies. For a Na atom with a Γ of 10 MHz, this represents a velocity spread of only 6 m/s which is a negligible fraction of the thermal velocity distribution, which has a full width at half maximum of 600 m/s.

In contrast, if the fields are strong, the interaction can extend to atoms whose Doppler-shifted frequencies are within the power-broadened linewidth Γ_P, where Γ_P can be made arbitrarily large by increasing the intensity of the fields. Though intense fields will interact with more of the atoms in the beam, the atoms will not necessarily be slowed. In the strong-field case, stimulated processes between the two fields can be much more important than spontaneous emissions; therefore, it is important to consider stimulated processes in which atoms transfer photons from one of the counterpropagating fields into the other.

Consider the interaction between an intense standing-wave field with $\Delta < 0$ and an atom moving slowly enough that at each point in space the ρ_{gg} and ρ_{ee} (the probability of an atom being in the ground and excited states, respectively) are approximately those for a stationary atom. It is convenient to treat this system in terms of the dressed states ($|s\rangle$, $|w\rangle$), which are the eigenstates of the atom-field system neglecting spontaneous emission.[4,8] An atom in state $|s\rangle$ (the strong-field seeking state) is attracted to the intensity maxima, and an atom in $|w\rangle$ (the weak-field seeking state) is attracted to the intensity minima. At the nodes of a standing-wave field, the intensity is zero; therefore, $\rho_{gg}=1$. For a field detuned below resonance in the weak-field limit, the ground state $\rightarrow |s\rangle$; consequently, near the field nodes, where the intensity is weak, the atoms will almost all be in $|s\rangle$. As the atoms move away from the node, their motion will be accelerated because they are in $|s\rangle$ and moving toward an intensity maxima. In contrast, at the antinodes of the standing wave where $\rho_{gg} \cong \rho_{ee}$, the atoms are almost evenly distributed between $|s\rangle$ and $|w\rangle$. Those atoms which are still in $|s\rangle$ when moving away from the antinode will be pulled back toward the intensity maxima. This deceleration is equal to the acceleration experienced by an atom in $|s\rangle$ moving away from the nodes, so an atom remaining in $|s\rangle$ while moving through the standing wave will have no net gain in kinetic energy; however, near the antinodes some of the atoms do not remain in $|s\rangle$, but are transferred to $|w\rangle$ by spontaneous emission. These atoms will not be decelerated when moving away from the antinodes, but will instead be accelerated again since they are now attracted to the intensity minima, producing a net gain in kinetic energy. Thus, on average, slowly moving atoms gain kinetic energy as they pass through the field, so their motion is accelerated.

The argument above holds only for atoms moving slowly enough that they interact strongly with both fields, which requires $|kv| \ll \Gamma_P$, where k is the wave vector of the fields and v is the velocity of the atom. For fields where $|\Delta| \gtrsim \Gamma_P$ and atoms with $|kv| \gtrsim \Gamma_P$, a stimulated transfer between fields will be much less probable than a spontaneous emission, so the conditions for optical molasses will again be obtained, which means that these fast moving atoms will be slowed by the field. Thus, for a field with a sufficiently high intensity and detuning, slow moving atoms will be accelerated and fast moving atoms will be slowed; therefore, there must be some velocities $\pm v_f$ which mark the boundaries between these regions in velocity space. In the absence of collisions or diffusion,[9] all of the atoms will eventually collect at one of these stable points.[10]

Increasing the laser intensity or decreasing the detuning increases the height of the standing-wave potential, so the maximum value of the force F and the slope dF/dv at v_f both increase. In addition, increasing the intensity increases Γ_P, which widens the range of velocities which can be cooled, and moves v_f toward higher velocities. Given these changes in the force, one would predict that increasing the intensity of decreasing the detuning should increase the number of cooled atoms, decrease the width of the distribution, and move the peak of the distribution to higher velocities.[11] In contrast, if the intensity is decreased to the point that stationary atoms are not saturated then there will be no v_f, and the slowed velocity distribution will be symmetric about zero and have a Doppler width of $\sim\Gamma_P$. At very low intensities $\Gamma_P \rightarrow \Gamma$, and optical molasses should be obtained.

Increasing intensity can also result in additional peaks in the force versus the velocity curve which may be much larger than the peak due to the spontaneous force alone. These peaks, which are the result of multiphoton interactions between the two fields,[12] can decrease the distance required to slow atoms to v_f, and can also result in additional zero crossings with very steep slopes.

Figure 2 shows a plot of the acceleration averaged over half a wavelength versus the velocity for such a field calculated using the continued-fraction method.[13] The maximum value of the acceleration due to the spontaneous force is 1×10^6 m/s^2 for this transition in Na. It can be seen from the figure that the stimulated force can be much larger than the spontaneous force alone, and that there is significant slowing over most of the Maxwell-Boltzmann distribution, which is shown by the circles. Also, the figure shows that the force has eleven zero crossings, six of which are stable points rather than the one or two stable points which occur at lower intensities. Thus, for cases with a fixed interaction length, it may be advantageous to use a field which is focused near the source and expands as the atoms cool.

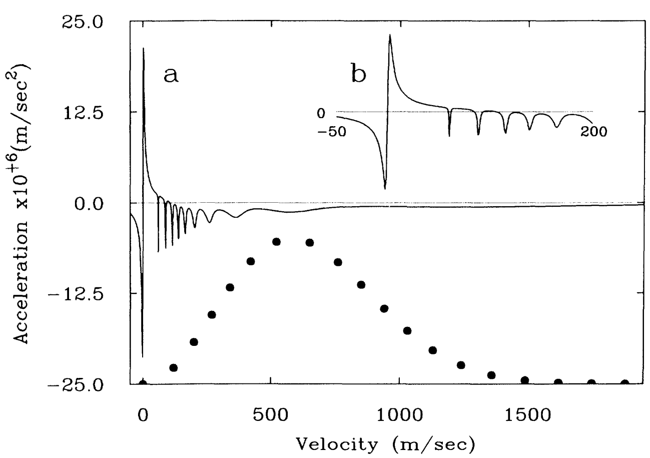

FIG. 2. (a) Acceleration vs velocity for a standing wave with $\Delta = -1.2$ GHz, $I = 560$ W/cm^2 which is the peak intensity at the oven. The intensity at the observations region can be more than 10 times smaller. The circles represent the Maxwell-Boltzmann distribution for a Na beam at 200 °C. (b) An expanded version of (a).

The abscissa in the acceleration versus velocity curves in Fig. 2 represents the velocity in the frame of reference where the two fields have the same frequency, which need not be the laboratory frame. If the two fields are allowed to have different frequencies in the laboratory frame, the frequency difference between the fields can be adjusted so that atoms accumulate at any desired velocity in the laboratory frame, producing an atomic beam with a very narrow velocity distribution about any desired central velocity. It should be noted that stable points are insensitive to laser frequency jitter, if the same laser is used as a source for both fields since jitter does not affect the frequency difference between the fields.

In addition to the spatially averaged force discussed above, there is a variation in force along the standing wave due to the periodic variation in intensity with position which averages to zero over half a wavelength. An atom in a nonuniform light field with $\Delta < 0$ will experience a net push in the direction of increasing intensity, so slow atoms can be trapped at the antinodes of the field[14] for some time before collisions or diffusion due to fluctuations in the force allows the atom to overcome the potential barrier.[9] This trapping can result in additional increases in the density of the atomic beam.

So far, we have considered only the forces collinear with the standing wave. The intensity gradient in the transverse direction will draw atoms toward the high-intensity region if the field is detuned below resonance[15]; therefore, atoms will be pushed toward the center of the field, unless their longitudinal velocity is so large that they are Doppler shifted to the blue of the counterpropagating field, in which case they will be pushed away from the center of the beam. Thus, the most probable velocity may be lower and the number of slow atoms in the beam may increase.[15] Our experiments show that in the presence of the copropagating beam only, where there is a longitudinal acceleration, the peak of the velocity distribution is displaced toward lower velocities by about 150 m/s, and is twice as high as the original.

Our experimental apparatus consists of a standing wave collinear with a Na atomic beam as shown in Fig. 1. The atomic beam is produced by an oven with a window at one end where the waist of the standing wave is ~0.13 mm. We used interaction lengths from 17 to 55 cm. The separations given in the following are for a 27-cm interaction length, which corresponds to the data in Fig. 3. The atomic beam is collimated by two apertures 1.5 mm in diameter separated by 10 cm, where the first aperture is approximately 1 cm from the window. The light passed through a lens before being reflected back on itself to form the standing wave. The copropagating and counterpropagating fields were mode matched by adjusting the separation between the lens and the mirror using a translation stage. The chamber is surrounded by a solenoid which provides a constant magnetic field of approximately 10 G along the direction of propagation of the atomic beam. This field established a quantization axis, so for appropriately polarized light, the loss of atoms due to optical pumping to the $F=1$ ground state is not very large. We operate the oven over a temperature range from 100 to 250 °C, and maintain the window at a temperature about 20 °C above that of the rest of the oven, to avoid depositing sodium on it. The atoms are observed at a point about 17 cm from the second aperture, where the collection angle is ~0.03 sr. The final window of the chamber is ~20 cm past the observation region.

The laser is tuned approximately 1.2 GHz below the resonance of the $3S_{1/2}(F=2)\rightarrow 3P_{3/2}(F=3)$ transition. The velocity distribution of the atoms is determined by measuring the fluorescence from a weak, pulsed, circularly polarized probe field which is nearly resonant with the same transition. The probe fluorescence is collected in a direction perpendicular to both the probe beam and the standing wave and monitored using a photomultiplier tube, as shown in Fig. 1. The probe is focused to several hundred μm in diameter. The probe field pulses are 30 μs long, at a repetition rate of a few Hz. The standing-wave field is turned off using an acousto-optic modulator (AOM) during the time that the probe field is on. The AOM also isolates the laser of the retroreflected light. The velocity profile of the atoms is then determined by measuring the probe fluorescence as a function of probe frequency, with the standing-wave frequency held constant. The probe intersects the atomic beam at a 2-mrad angle, so the velocity resolution is approximately 6 m/s. The frequency of the probe is calibrated using a Doppler-free absorption signal from a Na cell. The measured velocity distribution was independent of the intensity of the weak probe.

The solid lines in Fig. 3 show the fluorescence when

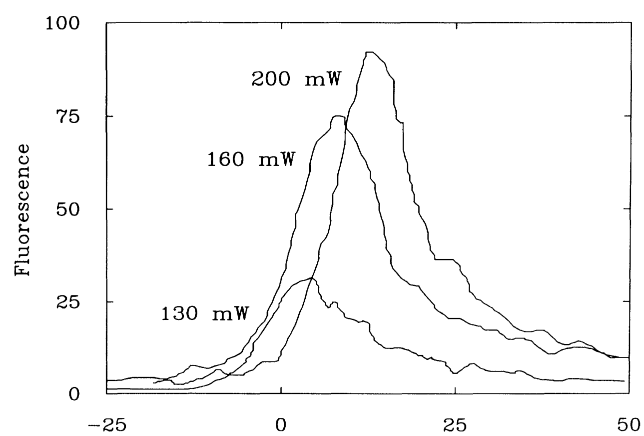

FIG. 3. Fluorescence vs velocity for standing waves with powers of 200, 160, and 130 mW as marked, $\Delta = -1.2$ MHz, and an oven temperature of 200 °C.

the atoms are slowed by standing waves with average powers of 130, 160, and 200 mW in each of the counterpropagating fields as marked in the figure. For the 200-mW standing wave, the peak of the distribution occurs ~ 12 m/s, and the width of the distribution is less than 12 m/s, which is approximately 60 times narrower than the uncooled beam. In addition, the density in phase space of the cooled beam is approximately 100 times that of the uncooled beam.

The curves for the lower intensity standing waves indicate that the height of the peak decreases with decreasing intensity and moves toward lower velocities, while the width of the curve increases. At intensities below saturation for atoms with zero velocity, the cooled distribution became a broad symmetric peak centered at zero velocity. These results are consistent with the behavior of the force curves discussed in detail above. The decrease in width with increasing intensity suggests that further increases in intensity may result in still narrower velocity distributions. In the velocity range shown in Fig. 3, the signal in the absence of the standing wave is indistinguishable from zero, as is the signal in the presence of the co-propagating field alone. In addition, we observed that decreasing the detuning produced a change in the cooled velocity distribution similar to increasing the intensity. We also introduced a frequency shift between the two fields by inserting an AOM in the return field. This enables us to produce atomic beams with velocities of -40 to $+80$ m/s and widths of ~ 20 m/s.

The atomic beam density can be increased by increasing the temperature of the oven. In our apparatus, oven temperatures above 250 °C produce significant self-defocusing of the light[16]; however, a shorter light path and/or a larger detuning of the standing wave could allow higher operating temperatures.

We have shown that a very simple and robust experimental apparatus can produce a continuous supply of slow atoms with a most probable velocity which can be tuned by varying the frequency difference between the two counterpropagating fields. Finally, the velocity distribution may be narrowed by increasing the intensity, and the peak density may be enhanced by increasing the temperature of the oven, and by increasing both the intensity and detuning of the fields.

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