Slowing and Cooling Atoms in Isotropic Laser Light

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We demonstrate cooling and slowing of atoms in isotropic laser light. As the atoms slow, they compensate for their changing Doppler shift by preferentially absorbing photons at a varying angle to their direction of motion, resulting in a continuous beam of slow atoms unperturbed by an intense slowing laser beam. We point out several novel features of slowing and cooling in isotropic light, and show that it can be superior to cooling with directed laser beams.

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In the past few years, a large variety of methods to manipulate atoms with laser light has been demonstrated [1]. Techniques for slowing, cooling, deflecting, and focusing atomic beams are now widely used to prepare dense samples of cold atoms. All methods used to date are based on the interaction of atoms with one or several directed beams of laser light. The effect of *isotropic* light on an atom's motion was considered only in the earliest discussions of cooling atoms with light [2,3] in which a spectral distribution of the light wider or comparable to the Doppler width was assumed. In this paper, we discuss the use of monochromatic isotropic light for slowing and cooling atoms, and show that an atomic beam can be efficiently slowed in a cavity filled with near-resonant isotropic laser light. We also show that isotropic light can be more effective at cooling than standard six-beam optical molasses, which is sometimes considered to be equivalent to isotropic light.

In an isotropic "gas" of near-resonant photons of frequency ω_l, atoms whose resonance is at ω_a will preferentially absorb photons at an angle θ with respect to the atom's velocity $\mathbf{v}$, satisfying the Doppler resonance condition

$$\omega_a = \omega_l + kv\cos\theta . \quad (1)$$

For red detuning ($\omega_l < \omega_a$) the atom preferentially absorbs photons from a "ring" in the hemisphere toward which it is moving. As the atom slows, the ring moves to smaller angles, eventually becoming a spot. As the atom slows below

$$v_f = (\omega_a - \omega_l)/k \equiv \delta/k , \quad (2)$$

it is exposed only to off-resonant light, and decelerates much more slowly. Since the atoms preferentially absorb photons at an angle $\cos\theta = v_f/v$, the resultant deceleration during the slowing process is given by

$$a = a_0\cos\theta = a_0 v_f/v , \quad (3)$$

where $a_0 = hk\gamma/m$, and γ is the photon scattering rate.

The use of isotropic light to slow a thermal atomic beam can be regarded as a novel way to compensate for the changing Doppler shift as the atoms slow, by "automatic" variation of the angle of photon absorption. This distinguishes isotropic light slowing from other atom-slowing schemes which have been demonstrated, such as Zeeman slowing [4,5] (where ω_a is shifted), chirped slowing [6,7] (where ω_l is shifted), and "white light" slowing [8] or power-broadened slowing [9] (where the resonance condition is extended over a widened velocity range). Because the monochromatic radiation appears to the atom as being uniformly spread out over the frequency range $\omega_l - kv$ to $\omega_l + kv$, isotropic light slowing can be regarded as a particularly simple implementation of white light slowing. Isotropic light slowing can be also considered as the first realization of angle-tuned slowing [1,4,10], in which laser beams intersect an atomic beam at varying angles to compensate for the changing Doppler shift, but avoiding complicated variations in the angle of incidence of the laser light along the atomic beam [10].

As a result of the isotropy of the radiation in isotropic light, the deceleration is always antiparallel to the velocity, leading to a decrease in the absolute value of the velocity and not just of one vector component. Transverse heating from spontaneous emission in the early stages of the slowing process is damped in later stages. In this way, isotropic light slowing overcomes a second disadvantage of angle-tuned slowing—the increased transverse momentum spread of the atomic beam due to the larger number of photons that have to be scattered [1,4] because of the $\cos\theta$ factor in Eq. (3). If atoms are slowed from an initial velocity v_i to a final velocity v_f, this results in a higher brightness of the slow-atom beam by a factor $(v_i/v_f - 1)/\ln(v_i/v_f)$, a factor of ~ 4 for $v_i/v_f = 10$. This improvement increases to a factor of v_i/v_f if multiple frequencies are used in the slowing process, as discussed below [11].

To demonstrate the ability of isotropic light to slow a beam of atoms, we have used the technique to slow a thermal beam of Na by more than 200 m/s. Maximum deceleration is achieved when the atomic transition is saturated. For isotropic illumination of an atomic beam of length L and diameter d, this requires a photon flux proportional to the surface area $\sim Ld$, whereas for collinear illumination employed in previous slowing techniques the flux required is proportional to the cross section $\sim d^2$, a factor of L/d smaller. For slowing in isotropic light, it was therefore necessary to use an enhancement cavity to recycle photons, and build up the photon density in our experiment.

The cavity consisted of a 30-cm tube with a 0.6-cm-diam inner bore made of Spectralon [12], a material with nominally 99.1% diffuse reflectivity, which was illuminated with $\sim$450 mW of laser light via six equidistant holes to ensure homogeneous illumination (Fig. 1). The laser power was almost equally divided among the main laser frequency, and sidebands at the hyperfine splitting $\omega_{hf} = 2\pi \times 1.7$ GHz of Na, which were generated to provide simultaneous excitation of the $F=1$ and $F=2$ ground-state levels. This led to a photon energy density inside the cavity of ~ 1 W/cm$^2 c$ per sideband, yielding a saturation parameter ≥ 1 for Na atoms moving with velocities ≤ 300 m/s through the cavity. The cavity enhancement factor of ~ 100, which is very easy to obtain for isotropic light, more than compensates for the factor L/d; thus the power requirements for slowing in isotropic light are comparable to collinear white light slowing [8].

A thermal beam of sodium, collimated to $\sim$10 mrad, was passed through the cavity (Fig. 1), and the velocity distribution of the emerging atoms was determined using fluorescence excited by a laser beam intersecting the atomic beam at an angle of 45° approximately 10 cm after the cavity. A second laser beam intersecting at 90° was used to generate zero-velocity reference peaks on all the spectra recorded. The probe laser beam had sidebands at the Na hyperfine splitting ω_{hf}, rendering the detection of atoms of a given velocity independent of their hyperfine state, thereby eliminating sensitivity to optical pumping either inside or outside the slower. Experiments with chopped slowing laser and gated detection showed that the measured velocity distributions were unaffected by the weak diffuse light in the probing region.

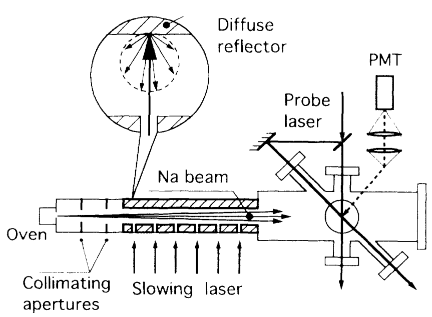

FIG. 1. Schematic diagram of the experimental setup. A thermal sodium beam passes through the bore of a tube of diffusely reflecting material which is filled with laser light via six equally spaced small apertures. The velocity distribution of the atoms is determined from fluorescence-excitation spectra produced by laser beams perpendicular and at 45° to the atomic beam.

The probe fluorescence spectra (Fig. 2) show distinct slow-atom peaks produced by the isotropic laser light, with final velocities slightly below the value v_f predicted by Eq. (2), probably due to off-resonant slowing. No depletion of atoms in the velocity range just above the slow-atom peak is observed because isotropic light slowing replenishes this region from still higher velocities. Figure 2(a) shows a probe fluorescence scan for atoms emerging from the cavity with a final velocity of $\sim$150 m/s. By comparing the area of the slow-atom peak relative to that of the original velocity distribution, we obtain a capture range of $\sim$200 m/s. With an estimated flux of atoms in our thermal beam of $\sim 2\times10^{11}$ atoms/s, this corresponds to a slow-atom flux of 5×10^9 atoms/s, which is larger than that recently achieved using white light slowing [8]. A considerable improvement in the slow-atom flux would result from a better diffuse reflector, in rough proportion to the reduction of the loss below its current value of about 1%, though consideration must also be given to limits set by losses through the open ends

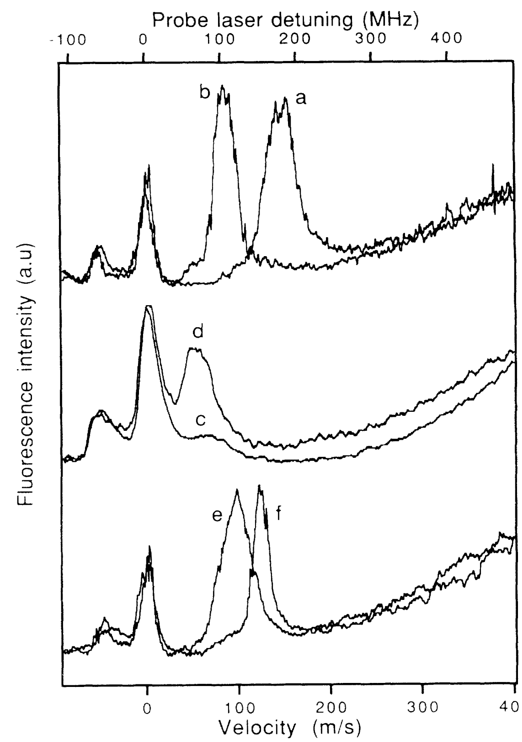

FIG. 2. Shifting the frequency of the last section of the slower is an efficient manner of down shifting the velocity of the slow atoms (a)→(b). We attribute the reduction in width of the velocity distribution in (a) to reduced off-resonance scattering. Two laser frequencies (d) can also lead to a greatly increased flux of slow atoms than just one (c). The flux enhancement is due to the increase in capture range of the slower by the reduced angle at which photons are absorbed for high velocities. Blueshifted light of the appropriate frequency can also be mixed in to prevent off-resonance slowing, giving a considerably narrower velocity distribution [(f) vs (e)]. In all spectra, peaks due to the 90° zero-velocity marker are shown for reference.

of the diffuse reflector. Improvements by an order of magnitude may be possible, and are under investigation.

The use of multiple light frequencies can considerably enhance the performance of the isotropic light slower. By reducing the detuning of the light in the last segment ($\sim$2.5 cm) of the slower, we were able not only to decrease the average velocity of the emerging atoms (150 to 80 m/s), but also to narrow the velocity distribution [Figs. 2(a) to 2(b)]. As the spread in slow-atom velocities is mainly determined by variations in the amount of off-resonant slowing for different atoms, the width of the slow-atom peak is minimized by reducing the opportunity for off-resonant slowing below v_f. These results also serve to illustrate how a short region of isotropic light can be an extremely simple and efficient method of down shifting the velocity of an intense slow beam, such as produced by a conventional Zeeman slower, which on its own is inefficient at slowing atoms below $\sim$150 m/s [4,5,13].

Multiple light frequencies can also be used to increase the velocity capture range of the slower. Monochromatic isotropic light is inefficient at slowing atoms over a large ratio (> 2 or 3) of initial to final velocity, due to the absorption of photons at large angles at the higher velocities [Eq. (3)]. We have demonstrated an increased capture range by increasing the redshift of the light in all segments of the slower relative to the last section by 90 MHz. The reduced angle at which photons are absorbed in the early sections of the slower leads to an $\sim$tenfold increase in flux ($\sim 10^9$ atoms/s) for final velocities of $\sim$50 m/s [Figs. 2(c) to 2(d)]. A close approximation to a continuous frequency variation could be achieved by using a separate diode laser for each segment, with the added advantage that only the last diode laser would need to be stabilized as the final velocity is determined only by the last segment.

Isotropic light accelerates atoms with velocity $v > v_a = |\omega_a - \omega_l|/k$ [$\cos\theta < 0$, Eq. (1)] if it is to the blue of resonance. It is possible to narrow the velocity distribution of the atoms emerging from the slower atoms by mixing into the cavity weak blueshifted light of the appropriate frequency, such that v_a is just below v_f. The blueshifted light accelerates atoms if they slow below v_f [Eq. (2)], balancing the off-resonant slowing [8,14]. This is demonstrated in Fig. 2(f) which was obtained by mixing blueshifted light (at a frequency of $\omega_l + 2\pi \times 350$ MHz) with $\frac{1}{10}$ intensity of the redshifted light into the cavity. The decrease in the flux of atoms is probably due to the fact that the blueshifted light is also in resonance with the atoms during the entire slowing process, leading to a reduction in the velocity capture range [11].

Isotropic light slowing has an interesting and in some cases radically different behavior than other techniques for slowing atoms. For example, in isotropic light, the equilibrium velocity distribution is isotropic and only depends on $|\mathbf{v}|$. Cooling with isotropic light is therefore an interesting one-dimensional model system for three-dimensional laser cooling. Another significant difference is that all other slowing techniques rely on cycling transitions between two states, whereas in isotropic light slowing, all ground and excited hyperfine states are involved [as long as $k(v - v_f)$ is larger than the excited state hyperfine splitting]. This results in an increase of $\frac{4}{3}$ in the "maximum" possible deceleration for an $S_{1/2} \rightarrow P_{3/2}$ transition, due to the higher fraction of atoms in excited states. Furthermore, we have shown that isotropic light slowing can be applied to transitions which may have dark states, like the $S_{1/2} \rightarrow P_{1/2}$ transition in Na [11].

Red-detuned isotropic light is sometimes considered equivalent to six-beam "optical molasses" [15]. In fact, isotropic light slowing is superior to optical molasses for slowing atoms because all atoms with $v > v_f$ are *in resonance* with photons at some angle θ. In red-detuned isotropic light, an atom experiences a deceleration proportional to the spectral brightness times $\cos\theta$, yielding an acceleration which for large velocities is asymptotically proportional to $\Gamma\delta/(kv)^2$, where Γ denotes the natural linewidth. In optical molasses, fast atoms scatter light only *off resonantly,* which results in an acceleration proportional to $\Gamma^2\delta/(kv)^3$, where a factor of Γ/kv originates from the presence of the copropagating laser beam.

Figure 3 compares the cooling rate [dE/dt = (cooling force) × (velocity)] for atoms in red-detuned isotropic light with that for six-beam optical molasses, for the same laser detunings ($\delta = \Gamma$) and photon densities (corresponding to a saturation parameter of unity per molasses beam). As can be seen from the plot, optical molasses is

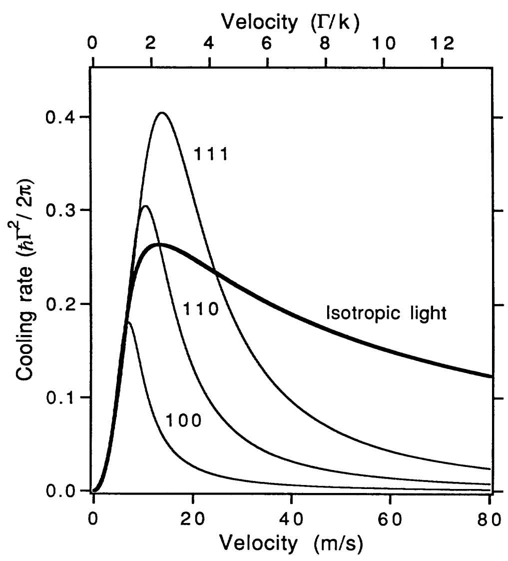

FIG. 3. Cooling rate (force times velocity) vs velocity in isotropic light (bold curve) and six-beam molasses with laser beams along the $\pm x, \pm y, \pm z$ directions and $\mathbf{v}$ along the (1,0,0), (1,1,0), and (1,1,1) directions. The curves are for a red detuning of one linewidth and a laser power corresponding to a saturation parameter of unity in each of the six molasses beams. For velocities $v > \Gamma/k$, isotropic light has a much faster cooling rate than molasses, resulting in a larger velocity capture range (see text).

only isotropic for velocities $v \ll \delta/k$. At higher velocities, the most favorable direction in optical molasses lies symmetrically between the three laser beams ("1,1,1 direction"), but is still less effective at cooling than isotropic light. This gives isotropic light a larger velocity capture range than molasses, so that if atoms are captured from the low-velocity tail of a Maxwell-Boltzmann distribution of a background gas [16], the flux of slow atoms will be increased by a factor of ~ 3 for a 2-cm-size illumination area [17], with an even greater improvement obtained for larger illumination areas.

The advantages of isotropic light over molasses are most pronounced for velocities $v \gg \Gamma/k$—the cooling rate for isotropic light is sufficient to be used to *slow* thermal atomic beams, as we have shown in our experiments. In addition, due to its wide apparent linewidth for cooling (Fig. 3), isotropic light should be superior for cooling close to the recoil limit using a very narrow linewidth transition $\Gamma \ll k v_{rec}$, where v_{rec} is the recoil velocity [11, 18–20].

In conclusion, we have demonstrated slowing and cooling of an atomic beam in red-detuned isotropic laser light by employing a simple enhancement cavity. The technique is extremely simple, and has the added advantage that the slow-atom beam is not collinear with an intense slowing laser beam, without having to use pulsing [21] or deflection techniques [22]. We also show that red-detuned isotropic light has a faster cooling rate, and consequently a larger velocity capture range, than optical molasses at higher velocities ($v > \Gamma/k$) for the same photon density. In addition, cooling in isotropic light has many interesting and novel aspects due to its apparently extended spectrum for a moving atom, and may be advantageous for cooling close to the recoil limit on narrow optical transitions.

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[1] See, for example, the special issues of J. Opt. Soc. Am. B **2**, 1706–1860 (1985), edited by P. Meystre and S. Stenholm; **6**, 2019–2278 (1989), edited by S. Chu and C. Weiman.

[2] A. Einstein, Phys. Z. **18**, 121 (1917).

[3] T. W. Hänsch and A. L. Schawlow, Opt. Commun. **13**, 68 (1975).

[4] W. D. Phillips, J. V. Prodan, and H. J. Metcalf, J. Opt. Soc. Am. B **2**, 1751 (1985).

[5] T. E. Barrett, S. W. Dapore-Schwartz, M. D. Ray, and G. P. Lafyatis, Phys. Rev. Lett. **67**, 3483 (1991).

[6] V. I. Balykin, V. S. Letokhov, and V. I. Mishin, Zh. Eksp. Teor. Fiz. **78**, 1376 (1980) [Sov. Phys. JETP **51**, 692 (1980)].

[7] W. Ertmer, R. Blatt, J. L. Hall, and M. Zhu, Phys. Rev. Lett. **54**, 996 (1985).

[8] M. Zhu, C. W. Oates, and J. L. Hall, Phys. Rev. Lett. **67**, 46 (1991).

[9] M. Prentiss and A. Cable, Phys. Rev. Lett. **62**, 1354 (1989). Although this work is on stimulated slowing, the large velocity capture range is due to power broadening of the first Doppleron resonance which corresponds to the spontaneous light force.

[10] J. Umezu and F. Shimizu, Jpn. J. Appl. Phys. **24**, 1655 (1985).

[11] M. A. Joffe, A. Martin, W. Ketterle, and D. E. Pritchard (to be published).

[12] Labsphere Inc., P.O. Box 70, North Sutton, NH 03260.

[13] V. S. Bagnato, C. Salomon, E. Marega, and S. C. Zilio, J. Opt. Soc. Am. B **497**, (1991).

[14] J. Hoffnagle, Opt. Lett. **13**, 102 (1988).

[15] S. Chu, L. Hollberg, J. E. Bjorkholm, A. Cable, and A. Ashkin, Phys. Rev. Lett. **55**, 48 (1985).

[16] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).

[17] This value was obtained by calculating the velocity capture range from the force versus velocity curves (Fig. 3) and averaging the captured flux over all directions.

[18] D. E. Pritchard, K. Helmerson, V. S. Bagnato, G. P. Lafyatis, and A. G. Martin, in *Proceedings of the Eighth International Conference on Laser Spectroscopy, Are, Sweden, 1987*, edited by W. Persson and S. Svanberg (Springer-Verlag, New York, 1987), pp. 68–72.

[19] H. Wallis and W. Ertmer, J. Opt. Soc. Am. B **6**, 2211 (1989).

[20] Y. Castin, H. Wallis, and J. Dalibard, J. Opt. Soc. Am. B **6**, 2046 (1989).

[21] S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, Phys. Rev. Lett. **57**, 314 (1986).

[22] J. Nellessen, J. H. Müller, K. Sengstock, W. Ertmer, J. Opt. Soc. Am. B **6**, 2149 (1989).