Continuous High-Flux Monovelocity Atomic Beam Based on a Broadband Laser-Cooling Technique

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We report application of Hoffnagle's broadband cooling concept to cool Na atoms in an atomic beam. The rms velocity spread of the cooled atoms is 0.75 ± 0.05 m/s (1.5 ± 0.2 mK) with a flux of $(9.5 \pm 1.0) \times 10^8$ atoms/s. 1D broadband optical molasses is also demonstrated. Potential applications of the cooling scheme are discussed.

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One of the main challenges in the cooling of an atomic beam by radiation pressure [1] results from the fact that the inhomogeneous broadening (due to the thermal velocity distribution) is usually much larger than the natural linewidth of the atomic transition used for the cooling process. This implies that there cannot be much cooling unless the atoms can be kept in resonance with the laser field throughout the cooling process. To compensate this changing Doppler shift, two methods were developed: frequency chirping, which tunes the laser frequency rapidly [2-4], and use of a spatially varying magnetic field, which Zeeman tunes the atomic energy levels spatially as the atoms are slowed down [3]. Frequency chirping is inherently noncontinuous, so it cannot easily provide a steady stream of cooled atoms. Zeeman tuning, on the other hand, continuously cools the atoms, but for many spectroscopic purposes one cannot accept the associated magnetic fields and field gradients in the interaction region, while extraction of the slowed beam into a low-field region can cause extreme loss of atom density.

An alternative approach circumvents these limitations by using light with a broad spectrum so that there is always some portion of the light spectrum resonant with the atoms [5-7]. However, the use of only a broadband light beam, counterpropagating to the atomic beam, causes all the atoms to experience a velocity-independent radiation force (scattering force), leading only to deceleration with no velocity compression. To introduce a velocity-dependent radiation force, spectrally truncated light can be used. The optical power of this light is restricted in the spectral range $\omega < \omega_0 - \Delta_c$, where ω_0 is the resonance frequency of the atomic transition in the rest frame, and Δ_c (>0) determines the cutoff axial velocity $V_c = c\Delta_c/\omega_0$. But the scattering force due to the Lorentzian tail of the natural line shape will continue to decelerate the atoms axially (even though their velocity is less than V_c), thus limiting the velocity compression obtainable [8]. To achieve significant cooling using spectrally truncated light, Hoffnagle [9] considered the addition of a monochromatic laser beam, copropagating with the atomic beam, to balance the off-resonance scattering force. In this Letter we report an experiment based on Hoffnagle's concept, which obtains a large velocity compression for sodium atoms in an atomic beam, and we discuss potential applications of this cooling technique.

We use the $|F=2, m_F=2\rangle \rightarrow |F'=3, m_{F}'=3\rangle$ "cycling" transition of the D_2 line in sodium atoms as the cooling transition (saturation intensity 6.3 mW/cm^2) in this experiment, driven by σ^+ polarized light. Since the hyperfine splitting in the excited $3\,^2P_{3/2}$ state is less than the bandwidth of the cooling light, optical hyperfine repumping is necessary. Figure 1 shows the schematic of our experimental apparatus. A conventional sodium oven ($T \sim 540$ K) produces an atomic beam which is overlapped spatially with the copropagating monochromatic laser beam and the counterpropagating broadband laser beam. The angle between the axis of the atomic beam and the axis of the laser beams is about 4 mrad, and the total interaction length before the observation zone is about 1 m. Near the input window of the vacuum system the two collimated (10-mm-diam) laser beams are focused down so that their waists are located on the mirror (M1) ~ 1.6 m away. The cross section of the laser beams is 0.4 cm^2 in the observation zone. The magnetic field in the interaction region is compensated to less than 10 mG. We probe the velocity distribution of the atoms with a weak, tunable, single-frequency laser beam. This probing beam is combined with the copropagating cooling

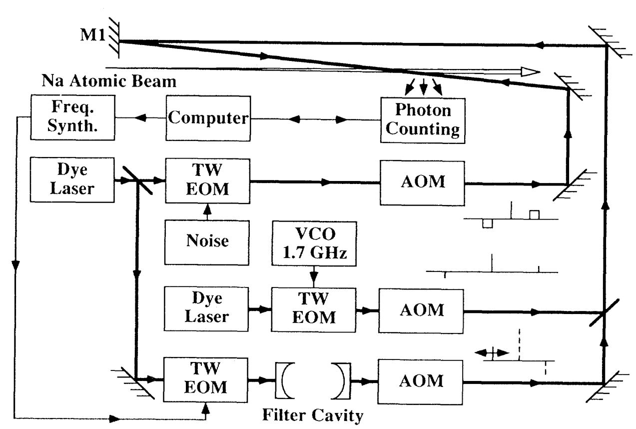

FIG. 1. Schematic of apparatus (see text for details).

beam using a beam splitter located where both beams are collimated. The induced fluorescence, which maps the velocity distribution into frequency space via the Doppler shift (5.9 m/s per 10 MHz), is detected by a gated photon-counting system. Thus the data represent the convolution of this mapped velocity distribution with the natural linewidth (10 MHz) of the probing transition.

A frequency-stabilized ring dye laser built at the Joint Institute for Laboratory Astrophysics provides the cooling and probing beams. The required spectra on the cooling beam are generated using rf phase-modulation techniques. Using a microwave noise module and rf filters, we generate electrical broadband noise having a center frequency of 856 MHz and a bandwidth of 200 MHz. The sharply filtered edges fall 20 dB within 20 MHz. This noise passes through a traveling-wave electro-optic modulator (TWEOM) [4] to produce 200-MHz-noise sidebands, with about 30% of the total optical power in each of the positive or negative first-order sidebands. The negative first-order sideband is used for cooling the atoms, while the positive first-order sideband is used for repumping atoms from the level $|F=1\rangle$ into the active $|F=2\rangle \rightarrow |F'=3\rangle$ nearly closed cooling cycle. The 200-MHz bandwidth corresponds to a velocity interval of 120 m/s. Instead of tuning the spectrally broadened light (SBL) to stop the atoms, we tuned it to cover the velocity interval 453 → 335 m/s to catch significantly more atoms. The tunable probing beam is generated as an FM sideband by another TWEOM and a computer-controlled rf frequency synthesizer. A confocal cavity filters out all but the desired sideband, whose power is then stabilized.

For convenience we use an externally frequency-stabilized [10] Coherent 699-21 dye laser system [11] to generate the monochromatic copropagating beam suggested by Hoffnagle [9]. Another TWEOM generates 1712-MHz sidebands (modulation index ≈ 0.55) on this laser beam for optical repumping. Several acousto-optic modulators (AOM) provide the necessary frequency tuning and control the intensities of the laser beams.

The cooling measurement cycle begins with a 3.5-ms cooling period, during which an equilibrium velocity distribution is established. Both cooling beams are then turned off so we can probe this distribution without perturbation. The probing beam (20 μW) is turned on for 40 μs, and we detect the fluorescence. (At this low probing power the perturbation due to the probing beam is negligible.)

All the data were taken in the frequency domain but are presented in the velocity domain for clearer interpretation. Figure 2 shows the results with 100-mW total power in the SBL cooling beam which gives 3.75 mW/cm^2 per natural linewidth (10 MHz) in the observation zone. Curve *a* is the velocity profile of the uncooled atomic beam; the flux of the atoms in the velocity range of 317–453 m/s, which is covered by the single-frequency (SF) laser beam and the edge of the SBL, is $(9.8 \pm 1.0) \times 10^8$ atoms/s through an area of ~ 0.4 cm^2.

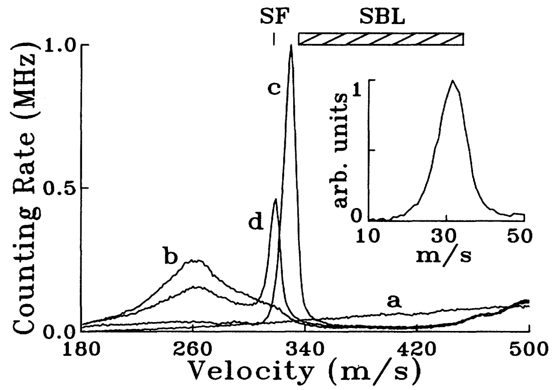

FIG 2. Part of atomic velocity distribution with, curve *a*, no cooling lasers; curve *b*, only SBL cooling (total power 100 mW); curve *c*, 100-mW SBL cooling beam and 5-mW monochromatic laser beam; curve *d*, similar to *c* but with 200-μW monochromatic laser beam. Frequency (velocity) positions of lasers are shown along top of figure. Inset: Similar velocity width obtained at ~ 30 m/s. (Note different scales used.)

Curve *b* shows the cooling effect due to the SBL laser beam with no copropagating monochromatic beam present. Atoms with an initial velocity falling within the SBL spectrum are decelerated and piled up at a lower velocity (-75 m/s relative to $V_c = 335$ m/s) with ~ 60 m/s full width. Note that SBL can slow the atoms with initial velocity > 453 m/s. These atoms contribute to the remaining counts in the range 335–453 m/s. Curves *c* and *d* show the velocity distributions with the copropagating monochromatic beam present at different power levels. Under the experimental conditions which generate curve *c*, we determined that the flux of atoms in the cold peak is $(9.5 \pm 1.0) \times 10^8$ atoms/s through an area of ~ 0.4 cm^2. Curve *d* illustrates that with a very weak single-frequency beam (200 μW) opposing it, the SBL cooling beam is able to push $\sim 50\%$ of atoms through the "thin" wall created by the monochromatic beam. Relocating the frequencies of the laser beams to cover the velocity range 153 → 35 m/s, we obtained cooled atoms centered at a much slower velocity, ~ 31 m/s (inset of Fig. 2). Since there are only $\frac{1}{40}$ the number of atoms in this (source) velocity range covered by the SBL light, the peak is much smaller, but the velocity-distribution width is the same as for the peaks at 330 m/s.

Figure 3(a) shows the atomic velocity distribution versus the frequency of the monochromatic beam, keeping the center frequency of the SBL fixed. When the cooled atoms are located within the spectrum of SBL, they see part of the light detuned to the blue. This causes heating and leads to a broader velocity distribution. Figure 3(b) shows the velocity distribution versus the total power of the SBL beam. With 10 mW in the SBL beam, the total number of the cold atoms in the peak is still about the same as with 100 mW in the SBL. This shows that the technique is feasible even with low-power sources.

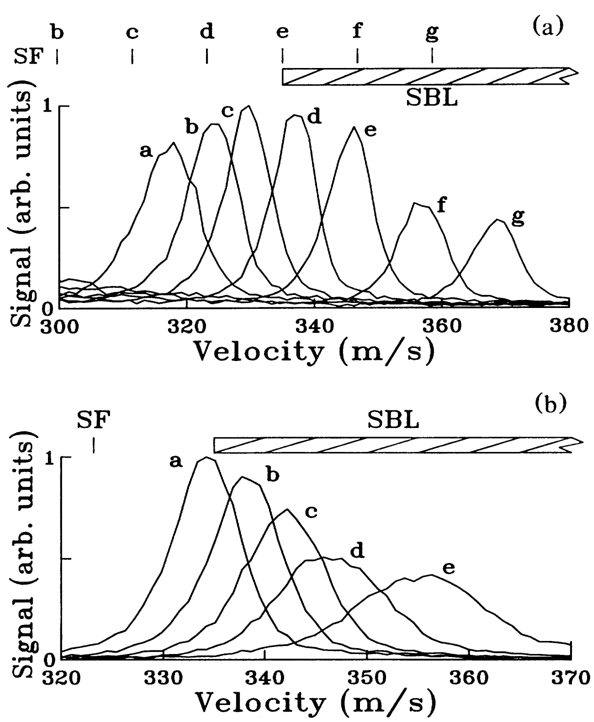

FIG. 3. (a) Atomic velocity distribution for different monochromatic laser frequencies, corresponding to velocities of 287 m/s (curve *a*) up to 359 m/s (curve *g*) in 12-m/s steps. Powers are 100 mW in SBL and 5 mW in the monochromatic laser beam. Frequency (velocity) positions of SBL and monochromatic lasers are shown for curves *b*–*g* along top of figure. (b) Velocity distribution for 5-mW monochromatic laser beam, located −12 m/s from the edge of SBL, vs different power levels in the SBL cooling beam: curve *a*, 130 mW; curve *b*, 70 mW; curve *c*, 35 mW; curve *d*, 20 mW; and curve *e*, 10 mW.

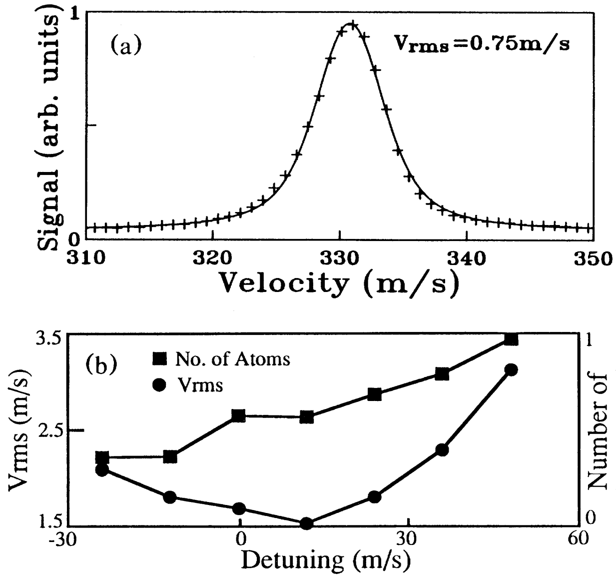

FIG. 4. (a) 1.5-mK velocity distribution produced by 100-mW SBL working against a 3-mW monochromatic laser, detuning as in Fig. 3(b). 10-MHz natural linewidth (FWHM) of probe transition corresponds to 5.9 m/s in velocity space. The slightly asymmetric feature of the velocity distribution may be due to differential power broadening by the opposing radiation forces. (b) $V_{\rm rms}$ and total number of the atoms in the cooled peak vs the detuning of the 5-mW single-frequency beam from the edge of the 100-mW SBL.

To determine the temperature of the velocity distribution of SBL-cooled atoms, we fitted a Voigt profile to the recorded data. Figure 4(a) shows the results of a fit to a typical data set. The rms spread in velocity, $V_{\rm rms}$, of this specific data set is 0.75 ± 0.05 m/s, which corresponds to 1.5 ± 0.2 mK. We found that $V_{\rm rms}$ does not change significantly as the residual magnetic field changes from $B \sim 1$ G to $B < 10$ mG, which excludes the possible polarization-gradient cooling mechanism [12] due to the imperfect σ^+ polarization of the laser beams. Figure 4(b) shows the $V_{\rm rms}$ and the number of atoms in the cooled peak versus the frequency gap between the single-frequency beam and the edge of the SBL spectrum. Note that the data in Fig. 4(b) were taken with 5-mW single-frequency power which yields larger (by about 15%), though slightly broader, peaks.

We also reversed the roles of the SBL and monochromatic beams to accelerate part of the atomic beam, thus producing a group of fast atoms with a sharp velocity distribution at 500 m/s. The temperature of the accelerated atoms is similar to that of the decelerated atoms shown in Fig. 4(a), although the number of atoms in the peak was somewhat smaller. This may be due to the divergence of the accelerating SBL beam, which increases the transverse velocity of the atoms in the beam so that some atoms leave the laser beams before they reach the detection region.

Finally, we replaced the single-frequency beam with another SBL beam to form a SBL 1D optical "molasses," which combines acceleration and deceleration of the atoms to yield a narrow velocity distribution (Fig. 5 shows a typical data set obtained under these conditions). Using less optical power one can obtain lower temperatures at the expense of collecting fewer atoms.

In summary, we have demonstrated a high-flux, continuous source of cold atoms extracted from a 118-m/s portion of an atomic velocity distribution. (With a broader noise bandwidth and higher optical power, e.g., from a current-modulated diode laser array, atoms in a larger velocity interval could be cooled using this scheme.) The temperature of these atoms is much lower than required to fill optical molasses or magneto-optical traps [13,14]. Numerous other applications would benefit from the separation of the cooled atoms from the uncooled atoms using a laser-deflection scheme [15]. Such a high-flux, monovelocity atomic beam would be useful in high-resolution spectroscopy, collision experiments, and atomic interferometry experiments.

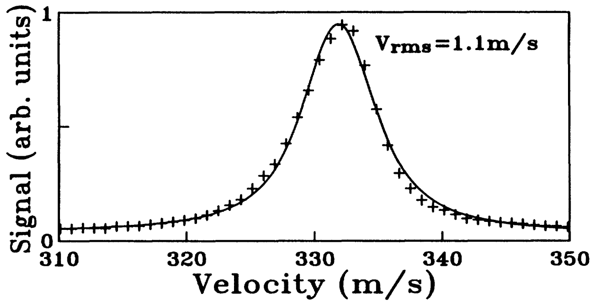

FIG. 5. Velocity distribution of 1D SBL molasses with 50 mW in each beam. V_{rms} is 1.1 ± 0.2 m/s. The velocity range covered by the SBL beams is 205–458 m/s.

We have also demonstrated the SBL optical molasses in one dimension. It is plausible to consider the use of the SBL in a 3D optical molasses or magneto-optical traps to obtain a broader velocity catching range. For the cell trap [16], this broader catching range could lead to a higher capture rate and a dramatic increase in the final number of trapped atoms. Since in a 3D optical molasses the polarization-gradient cooling may further cool atoms to a lower temperature, the combination of a faster build-up time and a colder temperature would provide an enhanced sample of cold atoms for a large number of experiments.

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Note added.—Since this work was submitted, related broadband cooling results using a modeless laser have been submitted by Littler *et al.* [17].

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