Laser Manipulation of Atomic Beam Velocities: Demonstration of Stopped Atoms and Velocity Reversal

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Atomic-beam sodium atoms were slowed to zero or negative velocities by counterpropagating laser radiation which was frequency chirped with precise electro-optic modulation techniques. The resulting "gas cloud" had a temperature below 50 mK and a density above 10^6 atoms/cm^3. We mention future possibilities in atom slowing, deflection, and storage.

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Following the first suggestion of atom cooling by Hänsch and Schawlow,[1] the literature has contained many discussions of the possibilities of modifying atomic velocities and, ultimately, confining the atoms in "traps."[2] Some proposals are bizarre, some stimulating and wild, and a few have been found to be wrong in subtle ways.[3] Early work on atom slowing by Letokhov and co-workers[4] showed interesting experimental curves, but the role of optical-pumping effects was not clarified. Phillips and co-workers[5,6] were first to address the fundamental problem of laser cooling: As atoms slow down, the changing Doppler shift moves them out of resonance with the laser field and thus limits the cooling to a few homogeneous linewidths ($\lesssim 100$ m/s). Phillips and Metcalf[5] compensated the time-dependent Doppler shift by tuning the atom's resonance frequency in a complementary way using the Zeeman effect. With the correct magnetic field spatial gradient to keep the resonance condition as the atoms slowed down, they were able to sweep nearly the whole atomic-beam velocity distribution down into a narrow peak only a few natural linewidths wide (< 50 m/s).[6] Unfortunately, to reach velocities much below ~ 400 m/s, an extreme tradeoff of signal size versus velocity was encountered. As discussed in their preceding Letter, slowing to zero velocity has now been achieved in two stages.[7]

The present authors decided to investigate atom slowing in a way which would be the most clear in its physical interpretation, with separate lasers to cool and diagnose the atomic-beam velocities. The major new technique in our work is a laser-frequency-sweep capability based on frequency shifting of the laser light with efficient, broadband electro-optic phase modulators. Our modulators, fabricated by R. T. Weppner of the Joint Institute for Laboratory Astrophysics, use a single $LiTaO_3$ crystal ($0.6\times0.5\times25$ mm^3) in a microwave traveling-wave configuration.[8] With 4–6 W of rf power, they operate near the theoretical maximum efficiency, with 34% of the input laser power being transferred into each of the two first-order phase-modulation sidebands, roughly 10% of the power in each second-order sideband, and 12% left in the carrier. The first phase-mismatch null is at 3.8 GHz with good performance to ~ 3.5 GHz. With these modulators we can frequency sweep the laser in an inertia-free and completely versatile way. If a different frequency versus time sweep is needed, we need only supply another electronic wave form into the voltage-controlled frequency source (which is a heterodyne device based on available 2.5–3.5-GHz voltage-tuned microwave integrated-circuit oscillators). Time-dependent cooling intensity is also controllable electronically to investigate the interesting domain of subnatural velocity widths produced in the final cooling stages.

For comparison with other experimental results, we are also working with sodium. While it is convenient for atomic-beam experiments, the nuclear spin of $\frac{3}{2}$ and electron spin of $\frac{1}{2}$ give an unneeded wealth of hyperfine structure. As we must repeatedly scatter photons from each atom to slow it down, it is essential to be careful about optical-pumping effects. The relevant energy levels of ^{23}Na are shown in Fig. 1. With circularly polarized light, the $3s\,^2S_{1/2}(F=2)$–$3p\,^2P_{3/2}(F'=3)$ transition approximates a (leakage-free) two-level system. However, since we need to scatter about $MV/\hbar k \simeq 20\,000$ photons in order to slow down an atom completely, even a little leakage is serious. So, a second modulator driven at 1772 MHz adds weak sidebands to "tickle" the atoms that leaked into the level $3s\,^2S_{1/2}(F=1)$, thus bringing them back into the main two-level system. This frequency also has to track the always changing velocity, so that it is actually the

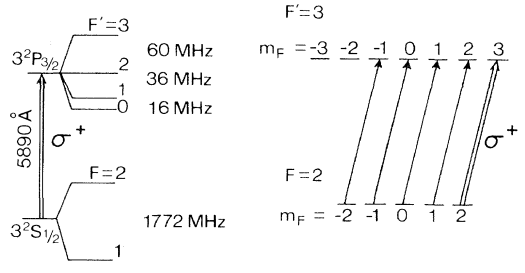

FIG. 1. Level scheme of Na with the cooling transitions.

swept sideband of the 1772-MHz sideband that works.[9]

The experimental schematic (Fig. 2) shows the utilized frequency components as the double arrows in the spectral input and output of electro-optic modulator number 2. Our configuration puts nearly all the strong, unused laser intensity at frequencies to the red side of the resonance. In this case, the atom's induced optical dipole interacts with the transverse gradient of the laser field to produce a converging force. For our conditions this term does not dominate, but the sign is right.

The atomic beam originates from a $\frac{1}{2}$-mm aperture in an effusive oven heated to 250 °C (2 mT), giving 620 m/s as the most probable velocity. The beam is collimated to a full angle of 3 mrad as it enters the high-vacuum flight tube. The laser field from the cooling laser is slowly converging toward the atomic-beam source, so that for each point in the interaction region the laser k vector is essentially antiparallel to the atomic velocity. Each absorbed quantum transfers $v = \hbar k/M = 3$ cm/s equivalent velocity decrement in an organized, accumulating manner to slow the atom's velocity. Every atomic excitation produced by this absorption leads to a spontaneously emitted photon, emitted into a random direction. As the cooling process continues, velocity is systematically removed from the longitudinal motion. Fluctuations in the fluorescence direction give rise to a random walk in the transverse velocity. After N absorption/emission events a transverse velocity of about $\sqrt{N}\,v$ is produced, where $v = 3$ cm/s is the recoil velocity for a single event. After $N = (600\text{ m/s})/(3\text{ cm/s}) = 20\,000$ events, the atoms are essentially stopped longitudinally and have a transverse random velocity of $(20\,000)^{1/2} \times 3$ cm/s $= 4.2$ m/s.[10] The longitudinal energy spread is controlled by the effective frequency resolution of the interaction: Atoms continue cooling until the linewidth of the interaction prevents Doppler identification of the fast and slow parts of the velocity distribution. The sodium 10-MHz natural linewidth is equivalent to a velocity resolution of about 6 m/s. Of course, saturation broadens this width. We have arranged to weaken the laser cooling sideband just before it is switched off to provide the optimum velocity sharpness of the cooled distribution.[11] Our probing laser crosses the atomic beam at 56° from perpendicular incidence to minimize the light scattered from the chamber windows. Thus, our velocity readout scale is compressed by the factor $\cos 34° = 0.829$. Figure 3 shows our results. We measure the final velocity peaks to be 25 MHz full width. Since the natural width is again convolved in the measurement, this corresponds to a 15-MHz or 9-m/s projected velocity width. Assuming a transverse velocity of about 5 m/s, we estimate the final longitudinal velocity full width to be $\Delta v_{\text{final}}^{\text{long}} \leq 7.5$ m/s. Thus interaction with the swept laser has converted (part of) our thermal atomic beam into a stationary gas sample, slowly expanding at ~ 6 m/s equivalent to a kinetic temperature of $\simeq 50$ mK. From knowledge of the oven temperature and beam

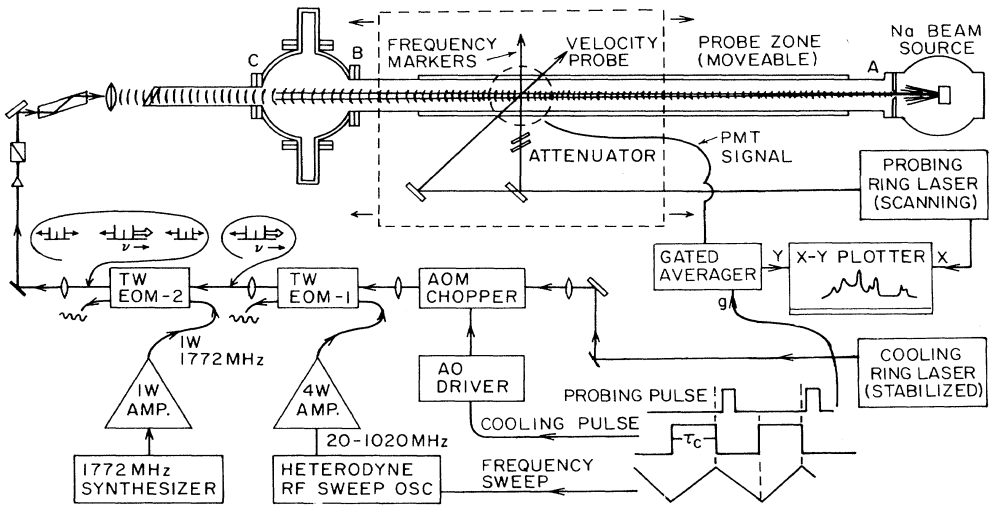

FIG. 2. Schematic of two-laser–atom-beam cooling experiment. The cooling-laser output is fed through an acousto-optic shutter, a $LiTaO_3$ traveling-wave electro-optic modulator (TW EOM) which puts on the frequency-swept sidebands, and an additional TW EOM to provide the $F = 1$ atom recovery sideband. The sigma-polarized 35-mW cooling-laser beam is carefully "mode matched" to the weakly diverging atomic beam (3 mrad full angle). After the sweep, the cooling-laser beam is cut off and we briefly sample the fluorescence induced by the slowly scanning weak (100 μW) probe laser, thus measuring the resultant velocity distribution as a function of time (and axial position). A 3.5-μW transverse probe beam provides frequency markers for the probe scan.

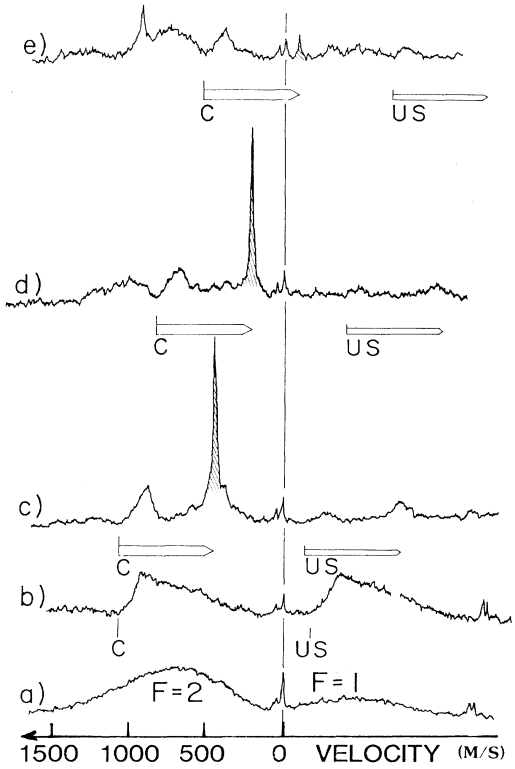

FIG. 3. Sodium-atomic-beam cooling using a frequency-chirped laser. Trace *a*, cooling laser off. The D_2 transition shows the velocity distribution of the two ground states as well as the two sets of frequency markers from the perpendicular probe. The vertical line marks position of the $F'=3$ resonance with zero-velocity atoms. Trace *b*, cooling laser and its 1772-MHz sidebands are present without sweeping. In this case, the laser carrier (C) transfers momentum to all atoms that it can resonantly reach until they slow down out of the resonance region. Traces *c*–*e*, cooling-laser sidebands (US) are swept (indicated by arrows), carrying atoms to lower velocities where they are left (shaded peaks) when the cooling laser is cut off and the velocity distribution is measured. The 1-GHz sweep corresponds to a velocity decrease of ~ 630 m/s and takes 2 ms. Trace *c*, the starting velocity ~ 1080 m/s, final velocity ~ 460 m/s. Trace *d*, start at 840 m/s, end at 210 m/s. Trace *e*, start at 530 m/s, end at -90 m/s! The apparent weakening of the slow-atom peak is partly because fewer atoms are available when the sweep starts below the velocity distribution maximum and partly because the lower velocity more slowly replenishes the atoms lost by hyperfine pumping by the probe beam. This figure also shows fast atoms cooled to 920 m/s by "unused" lower 1772-MHz swept sideband.

geometry, we estimate the density to be $\gtrsim 10^6$ atoms/cm^3. Our cooling sideband power (~ 10 mW) was marginal in these experiments and a significant fraction of the atoms dropped out of resonance. With slightly more laser power and a new trick to double the effective frequency sweep it will be possible to decelerate essentially the entire atomic beam to a narrow ~ 6-m/s velocity window[11] that may be placed at any slow velocity that we like, including zero.

This capability opens the way for many interesting new experiments. For example much sharper velocity peaks will result if a second stage of cooling is done with another, longer-lived and therefore spectrally narrower transition. It is a factor of 200 from the Na resonance linewidth of 6 m/s to the 3 cm/sec ultimate velocity noise due to individual recoil events. Another interesting measurement would be two-pulse sequences to establish a stationary target and then a well-defined "collider" packet to study velocity-sensitive collisions.

At the low velocities $\lesssim 50$ m/s the Doppler effect essentially disappears for resonance line interactions. Thus spectacular deflection and collimation effects can be expected. For example our slow atomic beam may be deflected through 90° with a dipole magnet or an extended transverse laser field. The resulting "Zacharias fountain" atomic beam would give an ideal opportunity for two-zone Ramsey excitation. The falling atoms may be "reflected" upward again by a resonant laser pulse. Position detectors (with image intensifiers) could trigger appropriate horizontal laser pulses to stabilize transverse motion in this "bounce trap." For short bounce times, probably concave-upward reflector wave fronts could provide transverse stabilization more simply. Multiple-reflector atom "racetrack" rings should be possible. A number of atomic transitions of interest for slow-atom and bound-trap atomic frequency standards are considered in our article in Ref. 2. Even Cs and Rb hfs clock transitions offer a remarkable new promise with diode lasers replacing our bulky, balky, and expensive dye lasers.

Thus we do not see an optical atom trap and zero motion as the only attractive possibility for interesting spectroscopy: The bounce trap has the same essential advantage of atom storage and buildup—without the high fields to perturb the energy levels. We expect that the near future will offer some delicious and bizarre advances in the art of manipulating atoms.

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[1]T. W. Hänsch and A. L. Schawlow, Opt. Commun. **13**, 68 (1975). See also D. J. Wineland and H. G. Dehmelt, Bull. Am. Phys. Soc. **20**, 637 (1975).

[2]See, e.g., *Proceedings of the Workshop on Spectroscopic Application of Slow Atomic Beams, Gaithersburg, 1983,* edited by W. D. Phillips, U.S. National Bureau of Standards Special Publication No. 653 (U.S. GPO, Washington, D.C., 1983).

[3]J. Dalibard, S. Reynaud, and C. Cohen-Tannoudji, Opt. Commun. **47**, 395 (1983).

[4]V. I. Balykin, V. S. Letokhov, and V. I. Mishin, Pis'ma Zh. Eksp Teor. Fiz. **29**, 614 (1979) [JETP Lett. **29**, 560 (1979)]; V. S. Letokhov and V. G. Minogin, Phys. Rep. **73**, 1 (1981).

[5]W. D. Phillips and H. Metcalf, Phys. Rev. Lett. **48**, 596 (1982).

[6]J. V. Prodan, W. D. Phillips, and H. Metcalf, Phys. Rev. Lett. **49**, 1149 (1982).

[7]J. Prodan, A. Migdall, W. D. Phillips, I. So, H. Metcalf, and J. Dalibard, preceding Letter [Phys. Rev. Lett. **54**, 992 (1985)].

[8]This device was inspired by the work of R. G. DeVoe and R. G. Brewer, Phys. Rev. A **20**, 2449 (1979).

[9]Actually 1772–60 MHz is the proper frequency for this excitation. However, because of reflections in our microwave setup we got more sideband power at 1772 than at 1712 MHz and good results were obtained with this choice.

[10]This overestimates the transverse heating since the fluorescence pattern is peaked forward and backward along the propagation axis. The axial direction of motion is under effective "feedback" control by the laser cooling process.

[11]R. Blatt, W. Ertmer, P. Zoller, and J. L. Hall, to be published. Both Monte Carlo and differential equation treatments show additional velocity narrowing with continued low-level irradiation.