Production of a cold atomic vapor using diode-laser cooling

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Received November 30, 1987; accepted January 25, 1988

We have used the light from diode lasers (λ = 852 nm) to damp the motion of atoms in a cesium vapor. We have been able to contain more than 10^7 atoms for 0.2 sec and cool them to a temperature of 100^{+100}_{-30} μK in this viscous photon medium (the so-called optical molasses).

In the past few years there has been a flurry of work demonstrating new ways to use laser light to control the positions and velocities of atoms.[1,2] However, nearly all of this work involves rather elaborate and expensive technology. We have been working to achieve these capabilities by using technology that is simple enough to be practical for use in a wide variety of atomic- and molecular-physics experiments. In a previous paper[3] we presented a simple and inexpensive way to stop a beam of cesium atoms by using frequency-chirped diode lasers. In this paper we present the implementation of optical molasses by using diode lasers and discuss improved results on atom stopping. The cooled-vapor produced in this work was colder ($T \sim 125$ μK) and significantly denser ($\sim 10^8$ atoms/cm^3) than was previously obtained with sodium in optical molasses[2] produced by a dye laser.

The idea of cooling an atomic sample by using counterpropagating laser beams was originally proposed by Hänsch and Schawlow[4] in 1975. They pointed out that if an atom sees counterpropagating laser beams that are tuned slightly below a transition frequency, the Doppler shift will cause the atom to absorb preferentially those photons moving opposite to its velocity. The momentum imparted by these photons will cause the atom to slow down and thus be cooled. In 1985 Chu *et al.*[2] demonstrated this idea in a vapor of sodium atoms and coined the name optical molasses. They sent a beam of relatively slowly moving sodium atoms into a region where six laser beams intersected in a cross. These beams cooled the atoms to a temperature, $T = h\gamma/2k$, which is the theoretically predicted[2] minimum temperature one can achieve when exciting a resonance line of width γ. Also, they showed that the photons produced a highly viscous medium that confined the atoms for a fraction of a second before they could diffuse out of it. This production of free atoms that are far colder than anything previously obtainable opens up a rich new area for experiments, e.g., using these atoms for ultra-high-resolution spectroscopy or studying the interactions of these cold atoms with surfaces or other atoms.

Such experiments are far more practical if diode lasers can be used to cool the atoms. Tunable diode lasers have a number of important advantages over the dye lasers that were used exclusively in the early work on laser cooling. The most striking feature, of course, is their much lower cost. Other advantages, which are well known, are that they are simpler to use; because there are no optical elements to get misaligned and dirty, it is easy to change the output frequency rapidly, and they have good intensity stability. An advantage that is not well known is that it is quite easy to obtain diode-laser linewidths of much less than 1 MHz. A free-running diode laser has a typical linewidth of 30 MHz, but Dahmani and co-workers[5] have recently shown that a small amount of optical feedback from a Fabry–Perot interferometer will lock the laser frequency to that of the interferometer and can reduce the linewidth by more than a factor of 1000. In this experiment we utilized this technique; thus the laser linewidth is much smaller than the 5-MHz natural linewidth of the transition.

To produce ultracold cesium atoms we first started with a thermal atomic beam with an average velocity of 250 m/sec. These atoms were slowed to a few hundred centimeters per second by a beam of counterpropagating resonant laser light. The slowly moving atoms then drifted into a region where intersecting laser beams, which were tuned slightly below the center of the atomic resonance, formed the optical molasses. This light cooled the atoms and held them for an extended period of time. We studied the atoms by observing their fluorescence while in this region.

A schematic of the apparatus for this experiment is shown in Fig. 1. A beam of cesium effused from an oven into one end of a vacuum chamber, and the frequency-chirped laser beam entered from the opposite end. This initial slowing portion of the experiment was identical to that discussed in Ref. 3, except that the stopping laser was locked to an interferometer cavity and the stopping distance was extended to 90 cm. To lock the laser, a small portion of the output beam was sent into a 5-cm confocal cavity, which was a few centimeters from the laser. The cavity was tilted slightly so that the beam entered at an angle relative to the cavity axis. Of the order of 1% of the laser power returned to it and caused its frequency to lock to that of the external cavity. If the free-running laser frequency was within approximately 500 MHz of the cavity resonance, the optical feedback would pull the laser frequency to the cavity resonance. This allowed us to tune the laser frequency coarsely by using temperature and current in the usual manner and then to do fine

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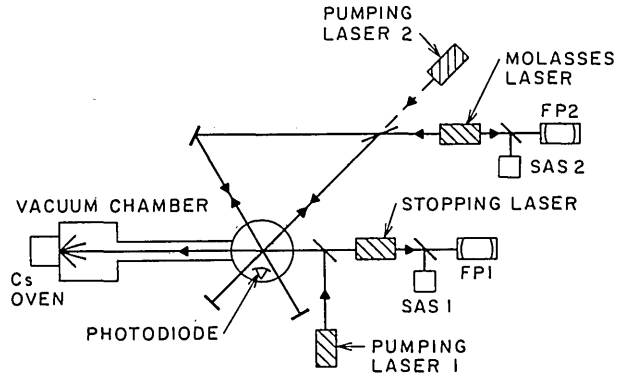

Fig. 1. Schematic of the apparatus. The third molasses beam, which was perpendicular to the other two, is not shown. FP1 and FP2 are the Fabry–Perot locking cavities. The saturated absorption spectrometers are labeled SAS1 and SAS2.

tuning by changing the resonant frequency of the cavity by using a piezoelectric transducer to translate one of the mirrors.

The stopping laser drove the $6S_{F=4} \rightarrow 6P_{3/2,F=5}$ resonance transition. A second laser, which was not locked to a cavity, was tuned to the $6S_{F=3} \rightarrow 6P_{3/2,F=4}$ transition to ensure that atoms were not lost to the $F = 3$ ground state. The frequencies of these two lasers were swept from approximately 500 MHz below the respective transition frequencies to within a few megahertz of the transition. The first half of the chirp does little slowing since the average initial velocity of the atoms is ~250 m/sec, but the additional time is needed to allow slower atoms to populate the downstream end of the beam between successive chirps. After a series of chirps, the stopping laser frequency was quickly (≈30 μsec) shifted away from the resonant frequency. The frequency of the stopping laser, just before shifting, determined the final velocity of the atoms as they entered the molasses. The $F = 3$ state depletion laser remained at the same frequency that it had at the end of the ramp and thus ensured that the $F = 3$ state also remained depleted in the molasses. The frequencies of both lasers were monitored using small cesium-saturated absorption spectrometers.

The optical molasses was produced by light from a third laser that was also locked to a cavity. The output of this laser passed through an attenuator and an optical isolator and was then split into three linearly polarized beams, each containing approximately 0.5 mW of power, that intersected each other at right angles. The intersection region was slightly less than 1 cm in diameter and overlapped the cesium beam. The three beams were reflected back onto themselves by dielectric mirrors. A small part of the output from the molasses laser was used to obtain a saturated absorption spectrum in a cesium cell. This spectrum provided an error signal that was fed back to the cavity to hold the laser frequency on the red side of the $F = 4 \rightarrow F = 5$ transition. These three lasers were sufficient to cool the atoms. However, to obtain higher densities in the molasses by multiple loading, we used a fourth (unstabilized) laser, as described below. A silicon photodiode monitored the fluorescence from the molasses region.

The cooling chirp slowed the atoms in the cesium beam to several hundred centimeters per second or less. We found that using a cavity-locked stabilized laser significantly improved the efficiency of this process. The number of stopped atoms was approximately 2.5 times larger with a stabilized laser than it was with an unstabilized laser, as was used in our previous work. The number of fast background atoms was correspondingly decreased relative to the unstabilized case. Apparently some of the laser-frequency fluctuations were large enough to cause the frequency to change more abruptly than the maximum allowable ramp rate. If this happens, some of the atoms are not decelerated enough to stay in resonance with the laser, and they are no longer slowed. In the present work we obtained approximately 5×10^6 stopped atoms/cm^3, and there were few fast-moving background atoms until a few milliseconds after the stopping chirp was finished. The narrower laser linewidth also permitted much better control over the final velocity of the atoms.

Once the atoms were slowed to low velocity they could be caught by the molasses. The fluorescence from the molasses region showed a rapid rise during the stopping laser-frequency chirp, followed by a long decay indicating slow departure of the atoms. The behavior of the atoms in the optical molasses depended quite critically on the velocity they had as they entered the molasses region. To obtain reproducible results, the end of the frequency ramp had to remain constant to within approximately 1 MHz (1 MHz corresponds to $v \approx 100$ cm/sec). If the atoms were moving too slowly they did not penetrate into the molasses, but instead they piled up on the surface and quickly diffused away. Best results were obtained when they had a final velocity of several hundred centimeters per second so that they penetrated the entire molasses region. This also produced a more dense sample since a larger volume of stopped atoms went into the molasses. In this situation the fluorescence signal from the molasses region would continue to rise for several milliseconds after the stopping laser was switched off. If the atomic velocity was increased further the atoms would fly right through the molasses.

Once the atoms were stuck in the molasses they diffused out very slowly. This is illustrated in the plot of the fluorescence as a function of time in Fig. 2. As one would expect, the diffusion time was a sensitive function of loading velocity, alignment, and molasses laser power and frequency. The longest 1/e decay time that we observed was 0.2 sec. We found that the conditions for maximum decay time were intensity per beam of approximately one half the 1 mW/cm^2

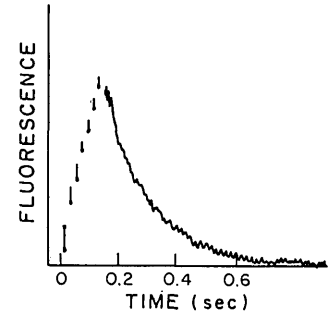

Fig. 2. Real-time trace of the fluorescence. The black dots on the left-hand side show the level after each new bunch of atoms was loaded. After eight bunches the loading was stopped, and the right-hand side shows the subsequent decay of the fluorescence as the atoms diffuse away.

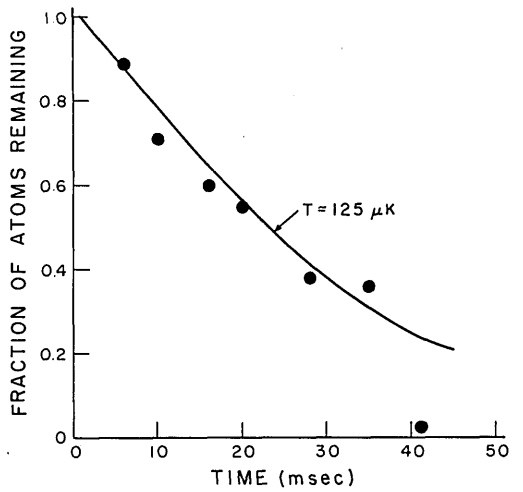

Fig. 3. The dots show the fraction of the initial fluorescence that remained after the molasses laser was blocked for the time intervals shown. The solid line is the theoretical fit. Note that the data point at 41 msec is much lower than the theoretical curve because of gravitational effects.

saturation intensity, frequency detuning between 0.5 and 1 natural linewidth, and loading velocity of a few hundred centimeters per second. These values are in reasonable agreement with what is predicted for these parameters when using the results in Ref. 6, although the intensities are a bit higher than expected.

Because the atoms remained in the molasses 20 times longer than the time for a stopping chirp (10 msec), one could obtain much higher densities by repeated loading of the molasses. However, this required a fourth laser to provide the $F = 3$ state depletion in the molasses while another batch of atoms was being stopped. In the left-hand side of Fig. 2 one can see the effects of loading eight bunches. The dots show the fluorescence level after each additional bunch was loaded. After eight bunches the loading was stopped, and there was a slow decay of the fluorescence. By using multiple loading we were able to increase the number of atoms in the molasses by more than a factor of 10. From the amount of fluorescence, we estimate the maximum number of atoms we contained in the molasses to be approximately 5×10^7. This was bright enough, when observed with an infrared viewer, that it could be seen in a well-lit room.

We determined the temperature of this vapor by measuring the spread of the atoms in the dark, as was done in Ref. 2. After the atoms had been in the molasses for approximately 25 msec, the molasses laser was quickly switched off. A brief time later the light was turned back on, and the decrease in the fluorescence was measured. In Fig. 3 we show the fluorescence as a function of the time the light was off. After more than 35 msec with the light off, the subsequent fluorescence was dramatically less (falling off rapidly with longer times without light). We believe that this was due to the gravitational acceleration of the atoms. We fitted the points in Fig. 3 with the calculated curve for the expansion of a uniform sphere of atoms with a Maxwell–Boltzmann velocity distribution. This curve will be changed somewhat by the gravitational acceleration, but this effect appears to be small for times less than 35 m/sec. From this fit we find the temperature to be 100^{+100}_{-30} μK. There is considerable uncertainty in this measurement because the decay was a strong function of the distribution of the atoms, and we could see that the distribution was only vaguely spherical and could change somewhat from one batch to the next. Nevertheless, this value is in good agreement with the predicted[2] limit, $h\gamma/2k = 125$ μK for this transition, and is colder than any cooled atoms or ions previously reported. At this temperature the rms velocity for these atoms is only approximately 15 cm/sec.

We have achieved an extremely cold and moderately dense atomic vapor by cooling atoms with light from inexpensive diode lasers. With the light on, this vapor will remain for a fraction of a second, and with the light off, the atomic motion is largely determined by gravitational acceleration. The technology required to achieve this remarkable behavior is simple enough that such atoms could be produced routinely for use in precision spectroscopy or collision studies.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation and the Office of Naval Research. We are thankful for the assistance of C. Tanner and L. Hollberg in the diode-laser development.

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