Laser Collimation of a Chromium Beam Using Doppler Force

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We report on the collimation of a chromium atomic beam by one-dimensional transverse Doppler laser cooling. Operated on the cycling 7S3 → 7P4 transition at 425.55 nm, the optical molasses laser power was 60 mW, which was detuned 2.5 MHz below the resonant frequency. The angular divergence of the atomic beam was reduced from 4.5 mrad to 0.48 mrad, corresponding to a transverse velocity of ±0.46 m/s, and the relevant transverse temperature is 265 µK.

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I. INTRODUCTION

The remarkable capabilities of laser cooling and trapping techniques for the precise handling of atoms has led to great advances in the field of atom optics. One of the most promising applications of finely controlled neutral atom beams is direct-write atom lithography of nanometer-scale features, which is called “atom lithography”. This technique typically uses a series of cylindrical atomic lenses formed by an optical standing wave (SW) to focus or manipulate atoms and deposit an atomic beam onto a substrate [1]. The collimation of the atomic beams plays an important role in atom lithography technology for two main reasons: the structure width (SW) deteriorates fast with an increasing divergence of the atomic beam. Moreover, the SW optical potential is extremely shallow, and so the atomic velocities along the SW direction must be low for the atoms to be “trapped” in SW nodes (or antinodes). For these two reasons, a high degree of collimation, typically less than 1 mrad, of the atomic beam is required. While collimation can be achieved in a very straightforward way using nozzles and/or collimating apertures, these approaches generally result in a great loss of flux. Recently, laser cooling techniques, which utilize dissipative forces to increase the brightness of atomic beams, have arisen as an alternative that provides high degrees of collimation without a significant loss of flux [2, 3].

Compared with Reference [6], which described the collimation of an atomic gallium beam by using polarization gradient cooling, this paper describes the collimation of an atomic chromium beam by using optical molasses. Doppler cooling by optical molasses is effective for the atoms within the capture velocity region, but polarization gradient cooling is effective only for the atoms with a very narrow transverse velocity. In this paper, the results on laser collimation of a thermal 52Cr beam using one-dimensional transverse Doppler laser cooling are reported. We have analyzed the optical molasses force on atoms and
the distribution of atoms for a range of laser detunings. We have also produced a $^{52}\text{Cr}$ beam and measured its fluorescence, by which we can determine the angular distribution of atoms on the beam axis. $^{52}\text{Cr}$ is particularly interesting because it has some advantages in atom lithography. First, $^{52}\text{Cr}$ has the largest abundance (84%) in isotopes, and $^{52}\text{Cr}$ is free of hyperfine structure and nucleon spin. Second, $^{52}\text{Cr}$ has an optical transition from the ground state to an excited state, it is $^7S_3 \rightarrow ^7P_0^4$, with a wavelength of $\lambda = 425.55$ nm in vacuum, the coherent laser light that is necessary for manipulating $^{52}\text{Cr}$ can be obtained from a frequency-doubled Ti:Sapphire laser. Third, the deposited structure of $^{52}\text{Cr}$ atoms can be removed directly from the vacuum for direct examination with some microscopy techniques [4].

II. DOPPLER FORCES ON ATOMS

The spontaneous force is experienced by the neutral atoms in a process of subsequent directed absorption from a laser beam and isotropic spontaneous emission of photons. Owing to the random direction of the spontaneous emission, there is on average a net momentum transfer in the direction of the absorbed photons. Two low-intensity laser beams of the same frequency, the same intensity, and the same polarization are directed opposite to one another (i.e., by retroreflection of a single beam from a mirror), the net force from the two beams obviously vanishes for atoms at rest. However, atoms moving slowly along the light beam experience a net force proportional to their velocity whose sign depends on the laser frequency. If the laser is tuned below the atomic resonance, the frequency of the light in the beam opposing the atomic motion is Doppler shifted toward the blue in the atomic rest frame, and is therefore closer to resonance; similarly, the light in the beam moving parallel to the atom will be shifted toward to the red, further out of resonance. Atoms will therefore interact more strongly with the laser beam that opposes their velocity and they will slow down [5, 6].

It is straightforward to estimate the force on atoms from the process of absorption followed by spontaneous emission. Since the population in the excited state decays at a rate $\gamma$, and in the steady state the excitation rate and the decay rate are equal, so the total scattering rate $\gamma_p$ of light from the laser field is given by

$$\gamma_p = \frac{s_o \gamma}{1 + s_o + (2\delta/\gamma)^2},$$

where $s_o$ is the saturation parameter which is defined by $s_o = I/I_s$, $I_s$ is the saturation intensity, for chromium $I_s = 85W/m^2$, and $\delta$ is the detuning of the laser frequency from resonance. From equation (1), the force resulting from absorption followed by spontaneous emission becomes

$$F_{sp} = \frac{\hbar k s_o/2}{1 + s_o + (2\delta/\gamma)^2}.$$  

It is straightforward to estimate the force on atoms from equation (2). The discussion here is limited to the case where the light intensity is low enough so that stimulated emission
FIG. 1: Optical forces vs atomic velocity. The two dotted traces show the force from each beam, and the solid curve is their sum. The straight line shows how this force mimics a pure damping force over a restricted velocity range. $\nu_c$ is the capture velocity, these are calculated for $s_o = 1$ and $\delta = -\gamma$.

is not important. This eliminates any consideration of the excitation of an atom by light from one beam and stimulated emission by light from the other. In the low intensity case the forces from the two light beams are simply added to give $\vec{F} = \vec{F}_+ + \vec{F}_-$, where

$$\vec{F}_\pm = \pm \frac{\hbar k \gamma}{2} \frac{s_o}{1 + s_o + [2(\delta \mp |\omega_D|)/\gamma]^2};$$  \tag{3}$$

then the sum of the two forces is

$$\vec{F} \approx \vec{F}_+ + \vec{F}_- = \frac{8\hbar k^2 \delta s_o \vec{v}}{\gamma(1 + s_o + (2\delta/\gamma)^2)^2} = -\beta \vec{v},$$  \tag{4}$$

where terms of order $(kv/\gamma)^4$ and higher have been neglected. Figure 1 shows the optical force dependence on the velocity, and Figure 2 shows the damping force as a function of velocity at opposite detuning. From them we can see that for $\delta < 0$ ($\delta = -\gamma$), this force opposes the velocity and therefore viscously damps the atomic motion. $\vec{F}$ has its maxima near $v = \pm (\gamma'/2k)(X/\sqrt{3})$ and decreases rapidly for larger velocities, here $\gamma' = \gamma \sqrt{s_o + 1}$ is the power broadened line-width, $X$ is a numerical factor given by $\sqrt{x - 1 + 2\sqrt{x^2 + x + 1}}$, and $x = (2\delta/\gamma')^2$. For $x \gg 1$, these maxima appear at $v = \pm \delta/k$ as expected, so $v_c = \pm \delta/k$ was defined as the capture velocity [7–11]. From Figure 1, the damping force is efficient when the velocity of the atoms is smaller than $v_c$, the capture velocity. Figure 3 shows the force as a function of velocity for an atom in a gradient cooling configuration, which was used in reference [6]; the inset shows an enlargement of the curve around $v = 0$. Note the strong increase in the damping rate over a narrow velocity range that arises from the sub-Doppler process. In Figure 4 the damping coefficient $\beta$ for chromium atoms as a function of the detuning for different values of the saturation parameter $s_o$ is given. From it we can
FIG. 2: The damping force as a function of velocity at opposite detuning.

FIG. 3: The force as a function of velocity for an atom in a gradient cooling configuration with $s_0 = 1$ and $\delta = -\gamma$. The inset shows an enlargement of the curve around $\nu = 0$. Note that the strong increase in the damping rate over a narrow velocity range that arises from the sub-Doppler process.

see that for small detuning and low intensity the damping coefficient $\beta$ is linear in both parameters. However, for detuning much larger than $\gamma$ and intensities much larger than $I_s$, $\beta$ saturates and even decreases as a result of the dominance of $\delta$. The decrease of $\beta$ for large detuning and intensities is caused by saturation of the transition, in which case the absorption rate becomes only weakly dependent on the velocity. From this simulation, we can see that the damping coefficient is maximum at $s_0 = 2$ and $\delta = -0.5\gamma$. 
FIG. 4: The damping coefficient for an atom in a traveling wave as a function of the detuning for different values of the saturation parameter \( s_0 \). The damping coefficient is maximum at \( s_0 = 2 \) and \( \delta = -0.5\gamma \).

FIG. 5: Simulative transverse distribution of atoms with cooling laser on and off.

Considering again the example of a chromium atom: we have a \( ^7S_3 \rightarrow ^7P^0_0 \) transition at \( \lambda = 425.55 \) nm, so \( \hbar k = 15.6 \times 10^{-28} \) kgm/s. The spontaneous life of this transition is 31.77 ns, so the force can be as high as \( 2.46 \times 10^{-20} \) N, if 50% of the atoms are in the excited state, this corresponds to an acceleration of \( 2.8 \times 10^5 \) m/s\(^2\) – much larger than what is observed with electrostatic or magnetostatic fields.

We consider a simulation of the collimation process that is based on Doppler laser cooling. The chromium atoms obey a Gaussian distribution at a transversal orientation and a Maxwell-Boltzmann distribution at longitudinal orientation. Figure 5 shows the simulated...
distribution of atoms along the transverse direction with and without laser cooling. From this simulation, we can see that the distribution becomes narrower and the central intensity becomes stronger with the laser on. Figure 6 shows the simulated spatial distribution of chromium atoms for different frequency detunings of the cooling laser. For a red-detuned laser frequency ($\delta < 0$), the atomic beam was collimated and collimation was achieved most effectively at the detuning of $\delta = -\Gamma/2 = -2.5 \text{ MHz}$ for chromium atoms, but for a blue-detuned laser ($\delta > 0$), the atomic beam diverged, this is in good agreement with Figure 2. So in our experiment, we detuned the laser frequency 2.5 MHz below the chromium atomic resonant frequency. Figure 7 shows the transverse velocity of atoms versus detuning of the cooling laser. For chromium atoms with the Doppler cooling mechanism, the limit
FIG. 8: Experimental arrangement. Showing effusive chromium source (at 1650 °C) with 1-mm-diam. aperture, split photodiode for frequency locking, precollimating aperture (3 mm × 1 mm), collimation region, and fluorescence imaging detector. The optical elements shown are the mirror (M), beam splitter (PBS), cylindrical lens (CL), and acousto-optic modulator (AOM).

The chromium beam was produced using a radiatively heated tungsten crucible with a 1-mm circular aperture. Typical operating temperatures at 1650 °C produce a most probable longitudinal velocity of \( (2k_B T/M)^{1/2} = 960 \text{ m/s} \). The longitudinal velocity distribution was a thermal distribution characterized by the crucible temperature. The beam was further defined with a 3 mm × 1 mm square aperture 450 mm from the crucible. The atomic beam was then collimated by one-dimensional optical molasses located 20 mm downstream from the square aperture. For chromium atoms, the \( ^7S_3 \rightarrow ^7P_4 \) dipole transition was used for cooling at a wavelength of \( \lambda = 425.55 \text{ nm} \) (in vacuum), with a line-width of \( \Gamma = 5 \text{ MHz} \) and saturation intensity \( I_0 = 85 \text{ W/m}^2 \). The initial angular distribution entering the molasses, determined by the 3 mm × 1 mm rectangular aperture, had a base width of approximately 4.5 mrad, for a nominal transverse velocity of ±4.37 m/s. Figure 9 shows the image of the chromium beam, it indicates that here we have a high quality chromium atomic beam to be used in experiments.

A frequency-doubled single-mode Ti:Sapphire laser system (MBR–100 and MBD–200), pumped with 8.5 W by a solid state laser (Verdi–10), typically produced 200 mW–260 mW of blue light at 425.55 nm. The laser was locked to the atomic transition using a split photodiode technique. An acousto-optic modulator (AOM) was used to detune 2.5 MHz below the chromium atomic resonant frequency. Another weak beam was chosen as the
probe beam, to measure the amount of collimation. In this experiment both the cooling beam and the probe beam had the same frequency. The cooling laser beam was expanded using cylindrical lenses to a $1/e^2$ width of 24 mm along the atom beam and a $1/e^2$ width of 3 mm transverse to the atom beam. This laser profile produced our best atomic beam collimation. Typical powers in the cooling beam ranged from 60 mW to 70 mW, and the probe beam, also linearly polarized, was circular in cross section with a $1/e^2$ diameter of 2 mm and had 3 mW power. As Figure 8 shows, the cooling laser beam intersected the atoms perpendicularly and was retroreflected to form a standing wave. The atoms traveled 660 mm downstream, where they were illuminated transversely by the probe laser. The probe laser-induced fluorescence from the atoms was collected with a lens and imaged onto a charged-coupled device (CCD) camera.

The cooling laser was aligned perpendicular to the atomic beam by observing the fluorescence due to the incident and retroreflected beams with a photomultiplier located above the cooling region. The cooling laser frequency was scanned over the transition. If the cooling beam was not perpendicular to the atomic beam, a double peaked fluorescence signal or a shift in the peak center was observed when the retroreflected beam was on. Iterative adjustments of the cooling laser direction were made to overlap the two fluorescence peaks. In this way the cooling laser was aligned perpendicular to the atomic beam to about 1 mrad.

The effect of Doppler laser cooling is presented in Figure 10. CCD images of the atom beam illuminated by the probe laser are shown. The cooling laser was 60 mW and detuned $-2.5$ MHz from resonance. Figure 10 (a) shows the fluorescence of the images of the uncollimated and collimated atomic beams. A slight asymmetry in the fluorescence line shape due to the probe detuning is evident, and the measured full width at half maximum (FWHM) was 7.2 mm and 2.4 mm, respectively. The divergence of the cooled atomic beam was found to be about 4.5 mrad and 0.48 mrad, the corresponding nominal transverse velocity was 4.3 m/s and 0.46 m/s, respectively. Figure 10 (b) shows the profile of the fluorescence intensity with Doppler cooling off and on. It was in good agreement with the simulation, as shown in Figure 5.
FIG. 10: CCD images of laser-induced fluorescence from an atomic chromium beam. (a) the fluorescence of images with laser off and on (b) the profile of fluorescence intensity with Doppler cooling off and on. Cooling laser 60 mW power, $\delta = -2.5 \text{ MHz}$.

IV. CONCLUSIONS

We have achieved the collimation of a beam of chromium atoms by Doppler laser cooling. The atomic beam FWHM was reduced from 7.2 mm to 2.4 mm, and the atomic beam divergence was reduced from 4.5 mrad to 0.48 mrad.

References

Chap. 4.