Measurement of the Temperature of Rubidium Atoms in a Magneto-Optical Trap

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ABSTRACT

We have performed measurements that can be used to determine the temperature of rubidium atoms in a magneto-optical trap. The expansion of the atomic cloud after switching off the current through the anti-Helmholtz coils was recorded with a CCD camera. Analysis of the measurements revealed that the cloud of atoms in optical molasses expands at a velocity of 4 cm/s.

INTRODUCTION

Laser cooling and trapping of neutral atoms is a rapidly expanding field of research. The theory for laser cooling and trapping was firmly established in 1975 (Hänsch & Schawlow, 1975). However, it was only in 1985 that the very first laser-cooled and trapped atoms were experimentally observed (Chu, 1998). The magneto-optical trap (MOT) was first realized in 1987 (Raab et al., 1987). In 1997, the Nobel Prize in Physics was awarded to Chu, Cohen-Tannoudji, and Phillips for pioneering research in the field of laser cooling and trapping of neutral atoms (Phillips, 1998).

At the Optoelectronics Laboratory of the Department of Physics, University of San Carlos in Cebu City, an MOT for rubidium atoms in a vapor cell using diode lasers has been in operation since 1998 (Liwag, 1999). So far, we have exerted considerable efforts to obtain high vacuum in the trapping cell to maximize the number of trapped atoms, and to increase the lifetime of the atoms in the MOT. At a pressure of 10^{-8} mbar, we measured up to 10^{8} trapped atoms with lifetime as long as 3 seconds. These experiments were necessary to pave the way for Bose-Einstein condensation (BEC), which remains the ultimate goal of this research (Ketterle, 1999).

The measurement of the temperature of trapped atoms in an MOT is one of the most exciting and challenging experiments in the field of laser cooling. We performed experiments using the time-of-flight (TOF) method for measuring temperature wherein we measured the arrival times of the atoms on a probe laser beam passing directly under the atomic cloud when the MOT is switched off. Because the time scales involved here require sub-millisecond accuracy, we set up a computer-based system to block the trapping laser beams using an electronically-controlled relay switch (Liwag et al., 2000). However, small timing problems in switching off the current and the laser beams might be the reasons we failed to record the TOF signal.

In this paper, we present the results of our experiments in determining temperature by measuring the expansion velocity of the atomic cloud in optical molasses. In molasses, the light-atom interaction is used to create a strong damping force which reduces the average velocity considerably. Due to these lower velocities and the corresponding longer time scales, TOF measurements in molasses are less difficult. The temperature, an important parameter in the process of realizing BEC, is the only parameter lacking in the

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Fig. 1. The formation of optical molasses in one dimension using two laser beams. To account for the Doppler shift of resonance frequency, red-detuned laser beams are used.

characterization of our MOT. From this point, we hope to proceed towards the realization of BEC in the future.

Laser cooling and trapping

The interaction between light (photons) and matter (atoms) involves a transfer of momentum from photons to atoms. The net momentum transfer from the beam of photons to the atoms results in an optical force which can be used to decelerate the atoms. Since the kinetic energy of atoms is a direct measure of their temperature, a reduction of this kinetic energy means a reduction of the atomic temperature, or “cooling” of the atoms.

The optical force can be used to create optical molasses, which can be understood using a one-dimensional description shown in Fig. 1.

Consider an atom with a resonance frequency ω_0 moving with a velocity v along a trajectory of two counterpropagating laser beams of frequency ω_L and wave vector k. Due to the Doppler effect, the moving atom will “see” each of the lasers to be shifted in frequency ω_A given by (Petra, 1998)

$$\omega_A = \omega_L - k \cdot v \qquad (1)$$

where $k \cdot v$ is the Doppler shift. Since both lasers are red-detuned (i.e., tuned to a frequency slightly below resonance ($\omega_L < \omega_0$)), the atom moving towards the laser beam will “see” a frequency closer to resonance, while an atom moving in the same direction will experience a frequency farther from resonance. Therefore, the atom absorbs more photons from the counterpropagating laser beam. As a result, there is a net force on the atom causing it to slow down. This force is proportional to the atom’s velocity and causes a viscous damping of the atom, as if the atom were moving in a thick fluid.

Optical molasses in three dimensions were observed in 1985 and was achieved using three pairs of counterpropagating laser beams along the three mutually orthogonal axes. An atom situated in the mutual intersection of the six laser beams experiences strong three-dimensional viscous damping, and its average velocity is rapidly reduced close to zero. The atoms do not actually come to rest, but execute a random walk motion which leads to atoms disappearing from the optical molasses.

The minimum temperature in optical molasses is given by the Doppler limit (Cohen-Tannoudji, 1998)

$$T_D = \frac{h\Delta\nu_N}{2k_B} \qquad (2)$$

where h is Planck’s constant, $\Delta\nu_N$ is the natural linewidth (in frequency units) of the atomic transition, and k_B is Boltzmann’s constant. For Rb, the Doppler limit is 144 μK.

Optical molasses, or 3-D Doppler cooling, is not an optical trap for atoms. The force that is required to trap a Doppler-cooled atom must be a position-dependent force which pushes the atom to a defined center of the optical trap.

The optical trap is constructed by superimposing a quadrupole magnetic field on an optical molasses formed by using circularly polarized laser beams. The magnetic field induces spatially dependent Zeeman shifts of the atomic energy levels, while the circular polarizations stimulate transitions in these Zeeman-shifted levels. This produces a restoring force on the atom that is proportional to the its position from the origin of the trap defined by the magnetic field.

The restoring force F in the MOT is given by the relation (Liwag, 1999)

$$F(z) = 4kg_F\mu_B B_0 z \frac{I}{I_s}\left(\frac{\frac{2\Delta}{\Gamma}}{\left(\frac{2\Delta}{\Gamma}\right)^2 + \left(1+\frac{I}{I_s}\right)}\right) \qquad (3)$$

where g_F is the Landé factor for the atomic transition, μ_B is the Bohr magneton, Γ is the natural linewidth of the transition, $\Delta = \omega_L - \omega_0$ is the detuning of the laser, I is the intensity of the laser beam, and I_s is the saturation intensity. For a "red" detuning of the laser ($\Delta < 0$), this force is opposite the sign of the z-coordinate.

An inhomogeneous quadrupole magnetic field is produced by reversing the current in one of the two coils, which are separated by a distance equal to their radii, known as Helmholtz coils. The characteristic of this magnetic field is that it is zero at the center of the coil separation and increases linearly along the x-, y-, and z-axes.

Hence, the term $B_0 z$ in Eq. (3) represents the magnetic field strength at position z. This optical trap is commonly referred to as the magneto-optical trap or the MOT.

Experimental setup

The MOT setup consists of a glass cell maintained at low pressure by an ion pump. Rb atoms are loaded into the cell by heating the Rb reservoir in the system. The laser used for trapping the atoms is tuned to a frequency slightly lower than the resonance frequency. The rest of this beam is shaped into a circular beam and divided into three pairs of counterpropagating beams, which intersect the center of the MOT in three mutually orthogonal directions. Because of the hyperfine splitting of the ground states of Rb, a second diode laser is needed. This so-called "repumper" laser is tuned to the hyperfine transition of ^{87}Rb to insure continuous absorption-spontaneous emission cycles. It pumps electrons which end up in the lower (F = 1) hyperfine ground state into the F = 2 ground state, via the F = 1 → F' = 2 transition. The "repumper" laser is simply directed into the center of the MOT to overlap the center of the six trapping laser beams.

A pair of anti-Helmholtz coils is set up such that the center of the coils coincides with the center of the glass cell. The experimental setup of the MOT is shown in Fig. 2.

Temperature of trapped atoms in the MOT

The time-of-flight (TOF) method is a standard experiment for measuring atomic temperatures (Phillips, 1998). Using this method, a probe laser beam is sent through the trapping cell at a distance of 1 cm below the atomic cloud. The probe beam enters a photodetector connected via an image acquisition (NI-IMAQ™) card to a computer. The expansion of the cloud when the trapping laser beams and the current are switched off simultaneously was monitored. Since this simultaneous switching requires sub-millisecond accuracy, a fast relay switch with a razor blade was designed to block the trapping laser beam electronically using LabVIEW™. A program that switches on the relay to block the trapping beams and at the same time switches off the current through the anti-Helmholtz coils was designed. Switching times of less than 1 ms have been obtained for our relay, which makes it an inexpensive alternative to an optomechanical shutter. However, we have not achieved a temperature measurement using a photodetector.

Instead of measuring the TOF signal after blocking the trapping laser beams, we measured the expansion in optical molasses of the atomic cloud. In this method, the expansion of the cloud is monitored when the current, through the anti-Helmholtz coils, is switched off while

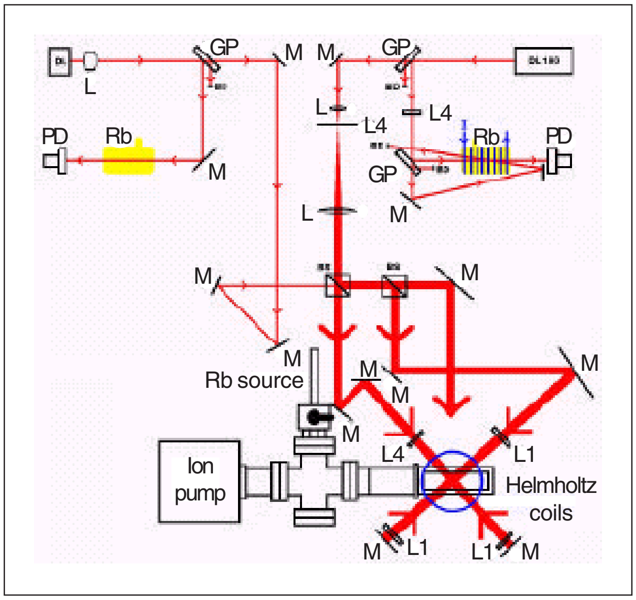

Fig. 2. Experimental setup for laser cooling and trapping of Rb atoms. The upper right part shows the saturation spectroscopy setup for the trapping laser. A current running through a coil wrapped around the Rb vapor cell produces a magnetic field to induce a Zeeman shift of the cooling transition. The upper left part shows the saturation spectroscopy setup for the repumper laser. The lower part shows the trapping cell with the anti-Helmholtz coils.

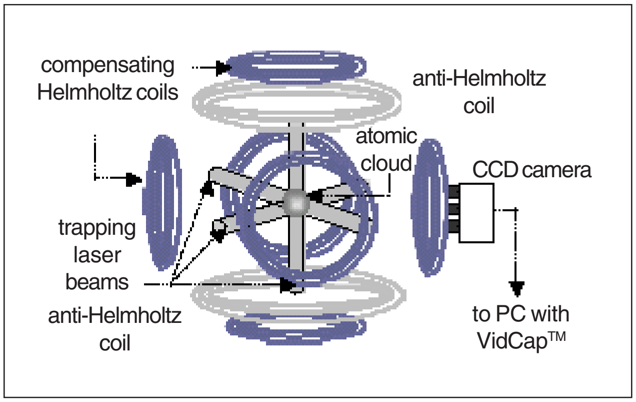

Fig. 3. Experimental setup for the measurement of temperature for atoms expanding in optical molasses when the current through the anti-Helmholtz coils is switched off.

the trapping and repumper lasers are kept on. When the atomic cloud expands in optical molasses, the velocities decrease due to damping. Therefore, the time scales involved are much longer than for standard TOF signals. The longer time scales make it possible to use a CCD camera for our experiment.

Images of the expanding cloud were captured by a CCD camera connected to a computer with the video capture software VidCap™. Using a LabVIEW program to electronically switch off the current through the anti-Helmholtz coils, it was observed that the cloud proceeded in a direction to the upper left side of the CCD camera's field of view. This upward motion has been attributed to a residual magnetic field, including that of the earth's magnetic field. To compensate for this residual magnetic field, three pairs of Helmholtz coils were set up around the MOT, with their minimum separations limited by the MOT dimensions. For each Helmholtz pair, the current flows in the same direction to produce a 1-D magnetic field that is uniform at the center of the MOT. The current through each of the three pairs was adjusted until the optimum compensation, which shows the atomic cloud expanding uniformly in all directions, was observed. The experimental setup for the measurement of temperature is shown in Fig. 3.

A typical set of images of the cloud expansion was obtained at a capture rate of 26 frames/second, and covered a total of 6 frames as shown in Fig. 4.

The total time elapsed since the current was switched off until the atomic cloud disappeared completely in the molasses was about 230 ms, from which a maximum velocity of 4 cm/s was calculated. The temperature T of the atoms is given by the relation (Petra, 1998)

$$\frac{1}{2}mv^2 = k_B T \qquad (4)$$

where $m = 144 \times 10^{-27}$ kg is the mass of a Rb atom and v is the average thermal velocity of the atoms.

Using Eq. (4), a temperature of 8 μK would be obtained for Rb atoms–a value that is way below the Doppler limit of 144 μK for ^{87}Rb. This shows that we cannot use this simple model to measure the temperature in molasses. In this case, the properties of our molasses have to be known in order to calculate the atomic velocity without damping.

We are currently working on a model which will enable us to describe the expansion of an atomic cloud in optical molasses. We expect that from this analysis we can determine the value of the temperature.

CONCLUSIONS

We calculated a maximum velocity of 4 cm/s for our Rb atoms in optical molasses–more than 4 orders of magnitude lower than the most probable velocity of

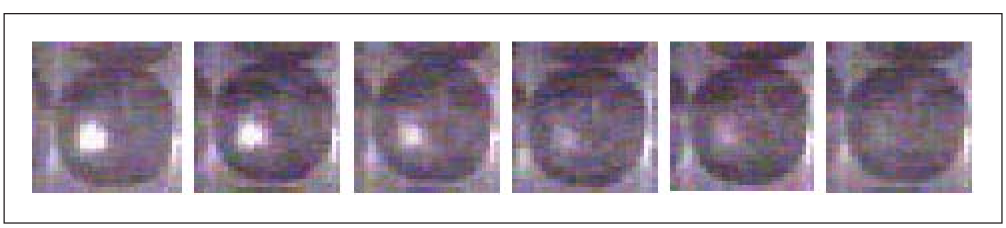

Fig. 4. Frame-by-frame image at 26 frames/ second of the cloud of trapped Rb atoms after switching off the current in the anti-Helmholtz coils, with compensation for residual magnetic fields.

237 m/s for Rb atoms at room temperature. The calculated temperature of 8 μK is way below the Doppler limit for Rb, and therefore we need to complete our analysis of the cloud expansion in optical molasses to come up with a more realistic value of the temperature.

We hope that our analysis will yield a temperature that is reasonably of the order of magnitude of the Doppler limit for Rb. We now look forward to the realization of BEC in our MOT.

REFERENCES

Cohen-Tannoudji, C.N., 1998. Manipulating atoms with photons. *Rev. Mod. Phys*. 70: 707-719.

Chu, S., 1998. The manipulation of neutral particles. *Rev. Mod. Phys*. 70: 685-706.

Hänsch, T. & A. Schawlow, 1975. Cooling of gases by laser radiation. *Opt. Comm*. 13: 68-69.

Ketterle, W., 1999. Experimental studies of Bose-Einstein condensation. *Phys. Today*. 30-35.

Liwag, J.W.F., et al., 2000. Characterization of the magneto-optical trap for Rb atoms. *Proc. 18th SPP Congress*. 214-216.

Liwag, J.W.F., 1999. Cooling and trapping of ^{87}Rb atoms in a magneto-optical trap using low-power diode lasers. M.S. thesis. University of the Philippines Diliman, Quezon City.

Petra, S.J.H., 1998. Development of frequency-stabilized laser diodes for building a magneto-optical trap. M.S. thesis. Universiteit van Amsterdam, The Netherlands.

Phillips, W.D., 1998. Laser cooling and trapping of neutral atoms. *Rev. Mod. Phys*. 70: 721-741.

Raab, E.L., et al., 1987. Trapping of neutral sodium atoms with radiation pressure. *Phys. Rev. Lett*. 59: 2631-2634.