Characterization of a Rubidium Magneto-Optical Trap

Final Report

Gregory Carson, Tyler McCleery, Dwana King, Randall Dannemann
Faculty Advisor: Dr. Alina Gearba

Society of Physics Students Chapter #6626
University of Southern Mississippi
Dept. of Physics & Astronomy
118 College Dr. #5046
Hattiesburg, MS 39406-5046

December 15, 2007

I. Introduction

Recently, at the University of Southern Mississippi, rubidium atoms were cooled and trapped in a standard magneto-optical trap, to temperatures 1/10,000 of a degree above absolute zero. The purpose of this research program was to perform a systematic study of the total number of trapped atoms versus several laser intensities, laser detunings, and magnetic field gradients, with the ultimate goal of finding the best experimental conditions in which the number of trapped atoms is the highest. Low temperatures and high atomic numbers are the crucial factors in a series of novel and exciting applications such as Bose-Einstein condensation, cold molecules, atomic lithography, atom optics, quantum computing and many others. Other measurements characterizing the behavior of the cold atoms in the magneto-optical trap such as size, atomic density and lifetime were also performed.

II. Experimental setup

Our magneto-optical trap is built in a standard configuration [1], consisting of three pairs of counter-propagating, red-detuned laser beams having opposite circular polarizations and a pair of coils in anti-Helmholtz configuration. The force experienced by the neutral atom in this configuration is both velocity and position dependent, providing both cooling and trapping. Cooling and trapping of ^{87}Rb is achieved using commercial 50 mW diode lasers operating at 780 nm. With a nuclear spin of 3/2, the ground state $5^2S_{1/2}$ splits into two hyperfine sublevels, $F = 1$ and 2, while the excited state $5^2P_{3/2}$ splits into four hyperfine sublevels $F = 0$, 1, 2 and 3. Since the difference in energy between the two hyperfine levels is big, two separate laser frequencies are needed, one for the cycling transition (trapping), and another one to prevent optical pumping into the other hyperfine ground state (repump).

In order to minimize the drift in the laser frequency that is usually related to changes in the laser cavity caused by mechanical vibrations and temperature variations, both lasers must be locked onto the desired hyperfine transitions. The lasers are locked using the so-called Doppler-free saturated absorption spectroscopy method [2]. This technique overcomes the problem of Doppler broadening, resulting in narrow lines with linewidths that can approach the natural linewidth of the transitions, and thus improving the resolution by a few orders of magnitude. The biggest advantage of using a "peak-lock" method is that it provides an absolute value for the laser frequency, which results in a precise knowledge of the laser detuning from resonance. The trapping laser is locked onto the crossover transition which lies 133 MHz below the $5^2S_{1/2}$ ($F = 2$) → $5^2P_{3/2}$ ($F = 3$) transition, while the repump laser is locked on the $5^2S_{1/2}$ ($F = 1$) → $5^2P_{3/2}$ ($F = 2$) transition using a separate Doppler-free saturated absorption setup. The required electronics for locking the lasers were built in house.

The frequency of the trapping laser is then shifted onto the desired one by an acousto-optical modulator (AOM). Another specialty electronic device built in house drives the AOM. This device allows the AOM to operate on variable frequencies. For the present study we set the AOM at 113 MHz, which brings the trapping laser 20 MHz below resonance. The first order output of the AOM is combined with the repump laser beam. The combined laser beam is then split into three equal power beams using polarization optics. The three laser beams are made circularly polarized with the appropriate handedness using quarter wave plates and then sent into the chamber. After exiting the chamber the three beams pass again through quarter wave plates, before being retroreflected onto themselves. Two beams are in the horizontal plane, while the third one is in the vertical plane. Under typical experimental conditions, for measured laser power of 4.5 mW, and laser beam diameter of 7.5 mm, the intensity in one beam is calculated to be 10.2 mW/cm^2. The two anti-Helmholtz coils, with current traveling in opposite directions, are attached to the chamber with their axis collinear with the vertical beam axis, producing the quadrupole field required for the MOT operation. The magnetic field strength produced by the anti-Helmholtz coils in the z direction, which coincides with the axis of the coils, is twice as compared to that in the x and y direction. The magnetic field gradient in the z direction is approx. 10 Gauss/cm. The trapping chamber is held at ultra-high vacuum, about $2 \cdot 10^{-10}$ torr. The rubidium vapor is provided by a commercial dispenser source placed inside the vacuum chamber. The cold rubidium cloud is monitored with a high-speed video camera connected through a computer via an image acquisition card. The fluorescence emitted by the cold atoms, which is proportional to the number of atoms in the excited state, is monitored with a calibrated photodetector subtending a known solid angle.

III. Results

a. Cold cloud size

Figure 1 shows a picture of the cold atomic cloud taken with the high-speed video camera. Figure 2 shows a longitudinal cross-section through the cold cloud. It can be observed that the intensity distribution in the MOT is gaussian and from the fit, the MOT size (FWHM) is estimated to be 0.96 mm.

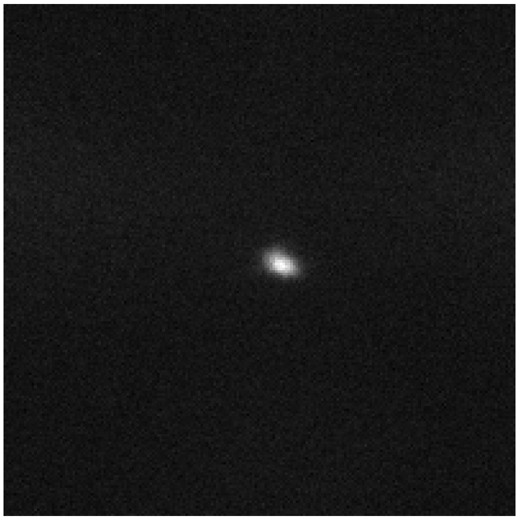

Fig. 1. Cooled and trapped Rubidium atoms

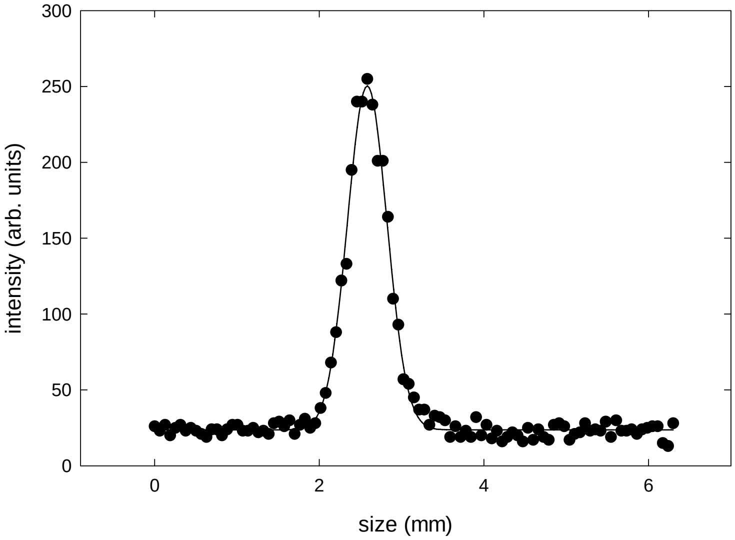

Fig. 2. Longitudinal cross-section through the cold atomic cloud

b. Total number of trapped atoms

To determine the number of trapped atoms, the fluorescence emitted by the cold atoms was measured with a calibrated photodetector. The photodetector, with an active detection diameter of 2.5 cm was placed outside the trapping chamber. A convex lens with a diameter of 2.5 cm was placed between the MOT and the photodetector, 50 cm away from the center of the trap to produce a parallel beam. A pin-hole was placed in front of the detector to minimize the background light (due to non-trapped rubidium atoms, laser light scattered through the chamber and any room light). Our detection geometry gives us a factor of 1890 to multiply the fluorescence measured with the photodetector, in units of photon per second. In order to determine the contribution from the MOT only, the trap was turned on and off by switching the magnetic field on and off. The difference between the two readings was then taken. A total of 10 measurements of the fluorescence measured with the trap on and off were taken, at a given intensity and detuning, and the differences were averaged.

The number of trapped atoms is determined from the equation

$$N = \frac{F}{R}$$

where F is the total amount of light scattered by the trapped rubidium atoms (in units of photons/sec) and R (in units of photons/sec) is the total amount of light scattered by one atom. The rate R at which one atom scatters photons is given by [3]

$$R = \frac{\left(I/I_s\right)\pi\Gamma}{1+\left(I/I_s\right)+4\left(\Delta/\Gamma\right)^2}$$

where Γ = 5.98 MHz is the natural linewidth of the atomic transition and I_s = 3.28 mW/cm^2 is the saturation intensity. For our setup, I = 61.2 mW/cm^2 is the total intensity in the six trapping laser beams and Δ = 20 MHz is the trapping laser detuning from resonance. Under these experimental conditions, the total number of trapped rubidium atoms is calculated to be $8.4 \cdot 10^7$ atoms.

c. Atomic Density

To calculate the atomic density in the MOT, the volume of cloud of trapped rubidium atoms must first be determined. In three dimensions, the volume appears to be spherical, but actually has an ellipsoidal shape due to the quadrupole magnetic field configuration. The MOT volume is calculated to be 3.7 mm^2, which gives an atomic density on the order of $2.2 \cdot 10^{10}$ atoms/cm^3.

d. MOT lifetime

The MOT lifetime is defined as the average time an atom remains in the trap before it is removed (or escapes) from the trap by collisions with other atoms. This quantity is obtained by measuring the time it takes to unload the MOT from the steady-state number of atoms (trap on) to zero (trap off). Figures 3 shows an unloading curve, obtained by switching off the current through the rubidium dispenser after 5 seconds of steady state operation. From the data, the MOT lifetime is determined to be 2.56 seconds.

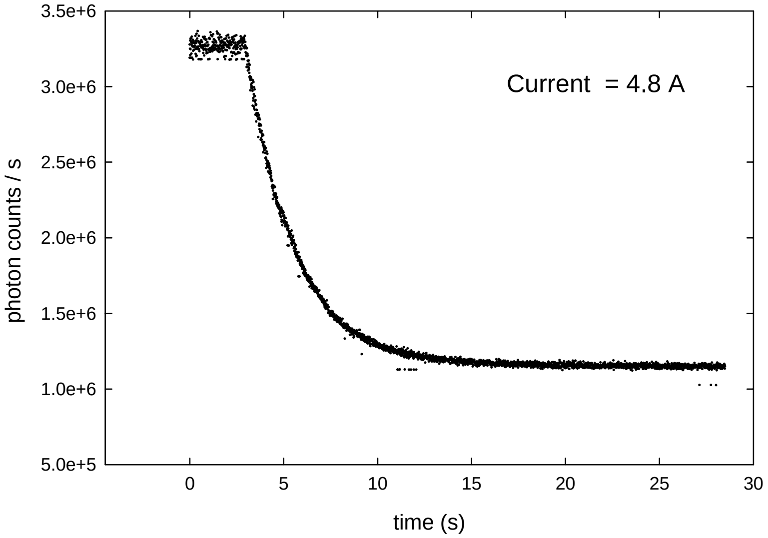

Fig. 3. MOT unloading by switching off the current through the Rb dispenser

Figure 4 shows a loading curve obtained by turning on the current through the rubidium dispenser. The loading time is much higher since it takes time for the dispenser to provide the necessary background vapor from which the atoms will be trapped.

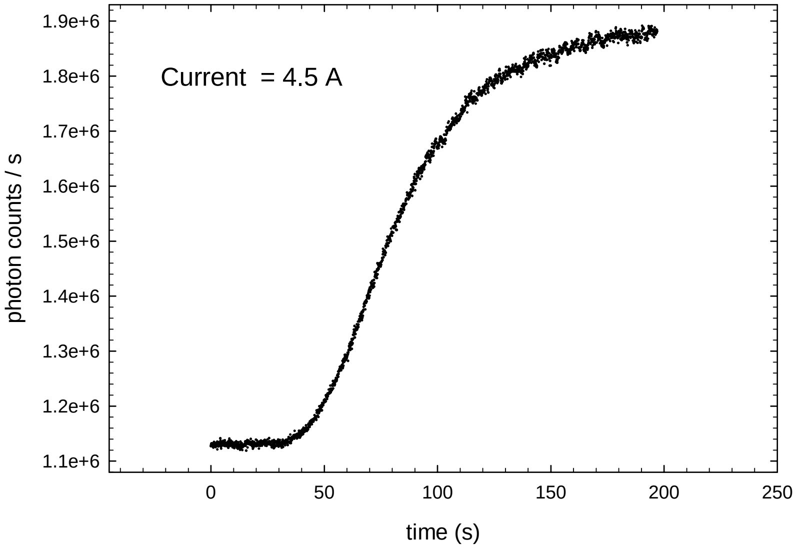

Fig. 4. MOT loading by switching on the current through the Rb dispenser

The behavior of the cold and trapped rubidium atoms can be described by the rate equation [4]

$$\frac{dN(t)}{dt} = L - \gamma N(t) - \beta n N(t)$$

where N is the number of trapped rubidium atoms at time *t*, L is the loading rate, γ is the loss rate due to collisions between cold rubidium atoms with hot background gas, β represents the loss rate due to collisions between two cold rubidium atoms, and n is the rubidium density in the trap. If the density is assumed to be constant, this equation can be easily integrated and the loading rate as well as the two loss rates can be extracted.

A study of the total number of trapped atoms versus rubidium background pressure will be performed in the near future and the above-mentioned parameters will be determined.

e. Total number of trapped atoms versus laser intensity at fixed laser detuning

In performing this study, the laser detuning was kept constant at 20 MHz below resonance, while the intensity of the trapping laser beams was varied using neutral density filters. This way, the trapping volume was unaltered. The data are presented in Fig. 5, where the total number of trapped atoms is plotted versus the laser intensity in a single beam. The data shows the expected trend, the number of trapped atoms increasing with laser intensity. One interesting study that will be performed in the near future will be to increase the laser intensity by reducing the beam size and observe radiation-trapping effects [5].

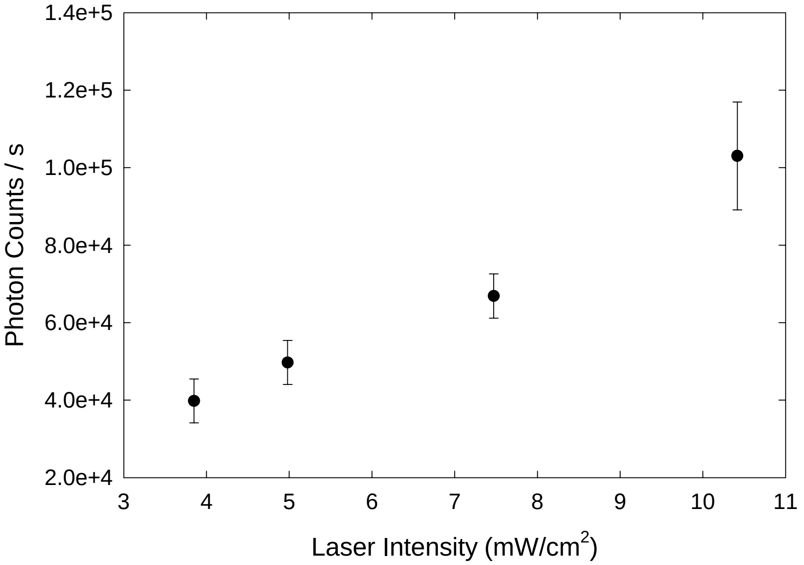

Fig. 5. Total number of trapped atoms vs. laser intensity

Another study that was performed consisted in measuring the total number of trapped atoms for several values of the trapping laser detuning from resonance while keeping the intensity constant. Unfortunately, changing the laser detuning by changing the RF frequency on the acousto-optical modulator altered the volume of the trap. The data analysis requires some normalization to account for the change in the volume of the trap. A more precise study will require a modification of the current experimental setup, by double-passing the trapping laser beam through the acousto-optical modulator. This will ensure that the trapping volume will not be altered when changing the laser detuning from resonance, but unfortunately will result in a decrease of the total laser power available for trapping.

References

1. E. L. Raab, M. G. Prentiss, A. E. Cable, S. Chu, and D. E. Pritchard, "Trapping of Neutral Sodium Atoms with Radiation Pressure," Phys. Rev. Lett. **59**, 2631 (1987).

2. D. W. Preston, "Doppler-free Saturated Absorption: Laser Spectroscopy," Am. J. Phys. **64**, 1432 (1996).

3. C. Wieman, G. Flowers, and S. Gilbert, "Inexpensive Laser Cooling and Trapping Experiment for Undergraduate Laboratories," Am. J. Phys. **63**, 317 (1995).

4. S. Bartalini, I. Herrera, L. Consolino, L. Pappalardo, N. Marino, G. D. Arrigo, and F. S. Cataliotti, "Full Characterization of the Loading of the Magneto-Optical Trap from an Alkali Metal Dispenser", Eur. Phys. J. D **36**, 101 (2005).

5. T. Walker, D. Sesko, and C. Wieman, "Collective Behavior of Optically Trapped Neutral Atoms", Phys. Rev. Lett. **64**, 408 (1990).

Financial Report

Photodetector Package (Electron Tubes, P25232-05)	$1,703
Matched Achromatic Pair (Thorlabs, Inc., MAP 1075150-A1)	$180.00
Rotating Adjustable Focusing Element (Thorlabs, Inc., SM1V10)	$32.60
Mounted Absorptive Neutral Density Filter (Thorlabs, Inc., NE20A)	$54.00
Total	$1,969.60