Laser Cooling and Trapping for Advanced Teaching Laboratories

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1. Introduction

A considerable number of modern atomic physics experiments rely on laser cooling and trapping of neutral atomic samples. Cutting edge work with Bose-Einstein Condensates, degenerate Fermi gases, dipolar gases, optical lattices, atomic clocks and quantum computation all start with the trapping of atoms in a magneto-optical trap(or MOT). In an educational environment the MOT offers a fertile landscape for teaching a wide variety of theoretical concepts, such as atomic structure including fine and hyperfine structure, the Zeeman effect, scattering, laser cooling, and polarization states of light; as well as relevant experimental techniques, such as spectroscopy, optics, feedback control systems and measurement techniques. Commercial equipment has recently become available to bring this exciting and important class of techniques into the teaching laboratory environment, making laser cooling experiments possible even at institutions without substantial atomic physics infrastructure or expertise.

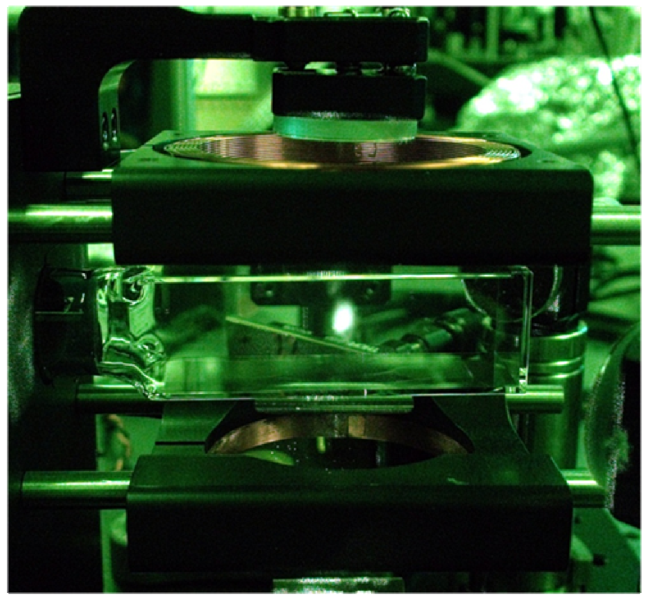

Figure 1: Picture of a MOT in a miniMOT cell

In this workshop we will present and work with a system that enables the production of cold atoms in a MOT, such as the one shown in Figure 1, in an advanced undergraduate teaching environment. Participants in the workshop will:

- Receive a brief introduction into laser cooling and trapping of atoms,
- Learn to align optics into the correct configuration for producing a MOT,
- Produce a MOT,
- Measure the number of trapped atoms in the cloud.

This document is meant to serve as a primer to workshop attendees, and to provide both a theoretical and experimental foundation for the workshop activities.

2. Theoretical background

In this section we outline the basic concepts required to understand the operation of a MOT. For the interested reader, there are many excellent resources available that will enable a more solid theoretical and experimental background on laser cooling and trapping of neutral atoms [1-4].

In the context of a dilute vapor of neutral atoms temperature may be thought of as corresponding to the average velocity of the atoms in the ensemble. The higher the average velocity is, the higher the corresponding temperature of the atom ensemble is. Therefore, to cool the atoms we must slow them down. This is done by applying a non-conservative force that, on average, removes energy from the atoms in the ensemble. The primary force used in laser cooling and trapping is radiation pressure from a source of near-resonant light which transfers momentum from photons scattering off atoms.

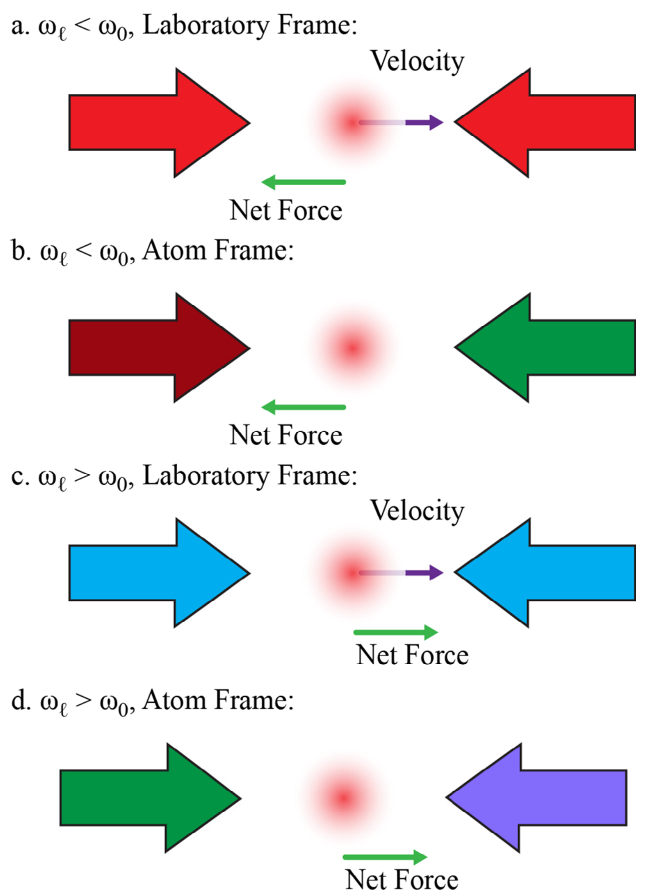

Figure 2: Laser cooling cases: (a) Red detuning in the laboratory frame. (b) Red detuning in the atom's rest frame. (c) Blue detuning in the laboratory frame. (d) Blue detuning in the atom's rest frame

Consider a simple 2 level atom with energy spacing $\hbar\omega_0$ which has a J=0 ground state and J=1 excited state. If we shine a laser with frequency $\omega_l = \omega_0$ at the atom the atom will absorb a photon from the beam and receive a momentum kick in the direction of the laser beam with a magnitude of $\frac{\hbar\omega}{c} = \hbar k$ (where $k = \frac{2\pi}{\lambda}$). After a small amount of time the atom will decay to the ground state and emit a photon with a momentum of $\hbar k$ in a *random* direction. Repeating the process the atom will experience a series of kicks from the laser beam, each giving an average momentum kick of $\frac{\hbar k}{2}$ in the direction of the laser beam.The momentum kick that the atom receives from each scattered photon is quite small, but by exciting a strong atomic transition it is possible to scatter more than 10^7 photons per second, corresponding to an acceleration of ~10^4 g. The radiation-pressure force is controlled in two ways, such that it brings the atoms in a sample to a velocity near zero ("cooling"), and holds them at a particular point in space ("trapping").

2.1. Doppler Cooling

Cooling is achieved by making the photon scattering rate of the atoms velocity-dependent by exploiting the Doppler effect [5]. Consider the diagrams shown in Figure 2: We now have the case of two counter-propagating laser beams, both tuned to the same laser frequency $\omega_l \neq \omega_0$. If $\omega_l < \omega_0$ (red detuning) as shown in Figure 2a the atom experiences a net force from the two laser beams that opposes its motion, resulting in cooling of the atom. This easy to understand the problem in the atoms rest frame, shown in Figure 2b. From the perspective of the atom, the light that is counter-propagating its lab frame motion appears to be Doppler shifted to the blue, bringing it closer to atomic resonance, and increasing the scattering rate from that beam. The light which is co-propagating the atoms motion in the lab frame appears to be Doppler shifted further to the red in the atom's frame, thus reducing the scattering rate of photons from that beam.

In contrast to the red-detuned case just described, if $\omega_l > \omega_0$ the atoms will experience a net force that is aligned with the motion of the atom. Counter propagating light appears to be further blue-detuned from resonance, while the co-propagating light appears to be closer to resonance. This results in heating of the atom.

We have at this point described a force on the atoms which can be expressed to lowest order as $\vec{F} = -\alpha\vec{v}$, where α is a damping constant that depends on optical field and the scattering parameters of the atom. This can be extended into three dimensions by shining six laser beams along three orthogonal directions, which provides strong damping of any atomic motion and cools the atomic vapor. This arrangement of laser fields is often known as "optical molasses"[6].

2.2. Magneto-Optical trapping

Although optical molasses will cool atoms, the atoms will not be trapped unless there is some position dependence to the optical force. Position dependence can be introduced by exploiting the Zeeman shifts of the atomic energy levels. Consider the diagram shown in Figure 3. By applying a linear magnetic field which passes through zero the degeneracy of the J=1 excited state is broken, and the energy splitting is divided by the sign of the magnetic field. In this case, if an atom moves to the left, where the direction of the magnetic field is negative, the energy of the $m = 1$ sublevel is raised, while the energy of the $m = -1$ sublevel is depressed. The situation is reversed if the atom moves to right where the magnetic field is in the positive direction: the $m = 1$ energy level is lowered and the $m = -1$ level is raised.

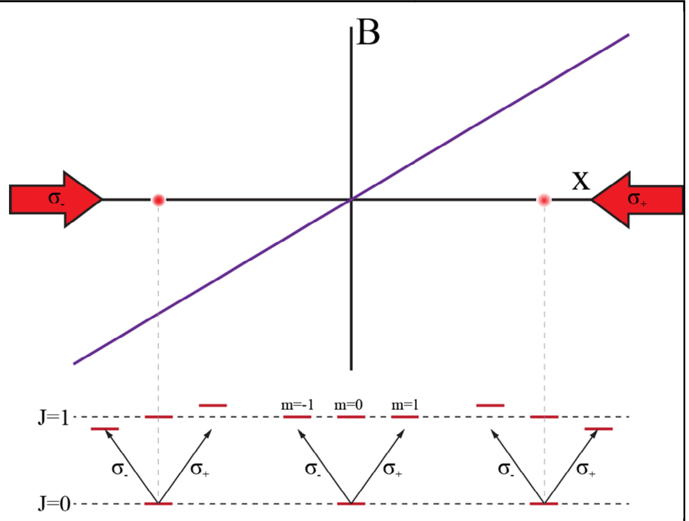

Figure 3: One dimensional diagram showing the positional dependence of the MOT. By applying a linear magnetic field which passes through zero the degeneracy of the J=1 excited state is broken, and the atoms will preferentially absorb light from their side of the magnetic field zero, resulting in a position dependent force that pushes the atoms to the field minimum.

Next consider what happens if we illuminate the atom with light (which is still red-detuned from the atomic transition as described in section 2.1) but is now circularly polarized as shown in the diagram (fig. 4). In order to conserve both angular momentum and the energy of the transition the atom on the left side will preferentially absorb light from the σ_+ beam, and the atom on the right will tend to absorb light from the σ_- beam. The net result is a force on the atoms with positional dependence (i.e. $\vec{F} = -\beta\vec{x}$). Combining this force with the effects of the Doppler cooling described above (section 2.1) the total force on the atom will be, to lowest order, of the form $\overrightarrow{F_{total}} = -\alpha\vec{v} - \beta\vec{x}$.

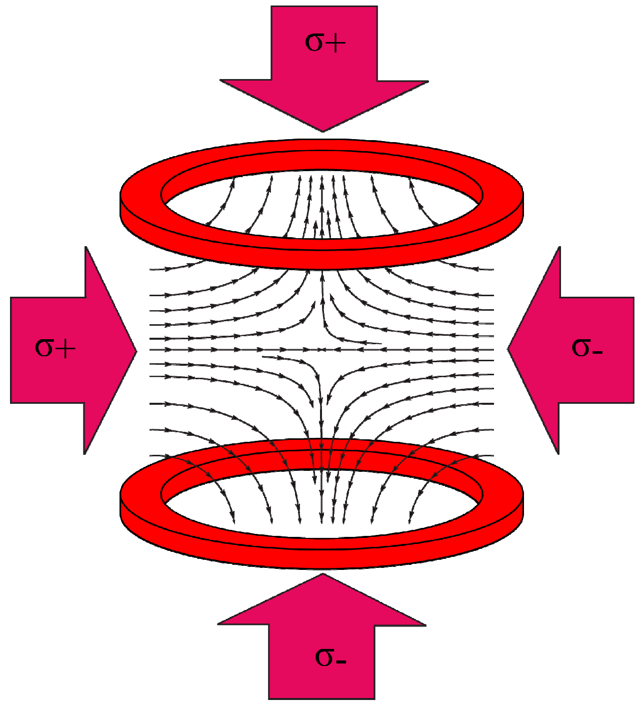

Figure 4: A typical MOT coil configuration showing the magnetic field directions and the polarization states of the MOT beams. Two beams, in and out of the page, are not shown.

This is relatively straightforward to extend to three dimensions, and is also simple to implement experimentally with appropriate polarization optics and a pair of magnetic coils in an anti-Helmholtz configuration as shown in Figure 4.

In this workshop we will be cooling ^{85}Rb on the D2 $5S_{1/2}F = 3 \rightarrow 5P_{3/2}F' = 4$ cycling transition, and using RF sideband modulation to generate repump light on the nearby $5S_{1/2}F = 2 \rightarrow 5P_{3/2}F' = 3$ transition. Since the purpose of this workshop is to give attendees a flavor of laser cooling and trapping experiments in the context of an advanced teaching laboratory, further details of the theoretical description of laser cooling will be omitted. Additionally, we will not cover in great depth the details of the experiment, including the detailed requirements of the laser system, the optical system, the magnetic field and the vacuum system. The interested reader will find a wealth of information available on the subject in the references listed below.

References:

1. Harold J. Metcalf and Peter van der Straten, "Laser Cooling and Trapping," Springer-Verlag, Graduate texts in Contemporary Physics (1999).
2. Christopher Foot, "Atomic Physics," Oxford series on Atomic, Optical and Laser Physics, Oxford University Press (2005), Chapter 9.
3. C.J. Pethick and H. Smith, "Bose-Einstein condensation in Dilute Gases," Cambridge University Press, Second edition (2008), Chapter 4.
4. http://en.wikipedia.org/wiki/Laser_cooling
5. T.W. Hansch and A.L. Schawlow "cooling of gases by laser radiation," Opt. commun. 13, 68-69 (1975)
6. S. Chu, L. Hollberg, J. ZBjorholm, A. Cable, and A. Ashkin, "Three-dimensional viscous confinement and cooling of atoms by resonance radiation pressure," Phys. rev. Lett. 55, 48-51 (1985)
7. http://faculty.ithaca.edu/bthompso/docs/Neophytes_2012_07_13.pdf

3. Parts of the system

The experimental setup for laser cooling with the ColdQuanta miniMOT system is shown in Figure 5.

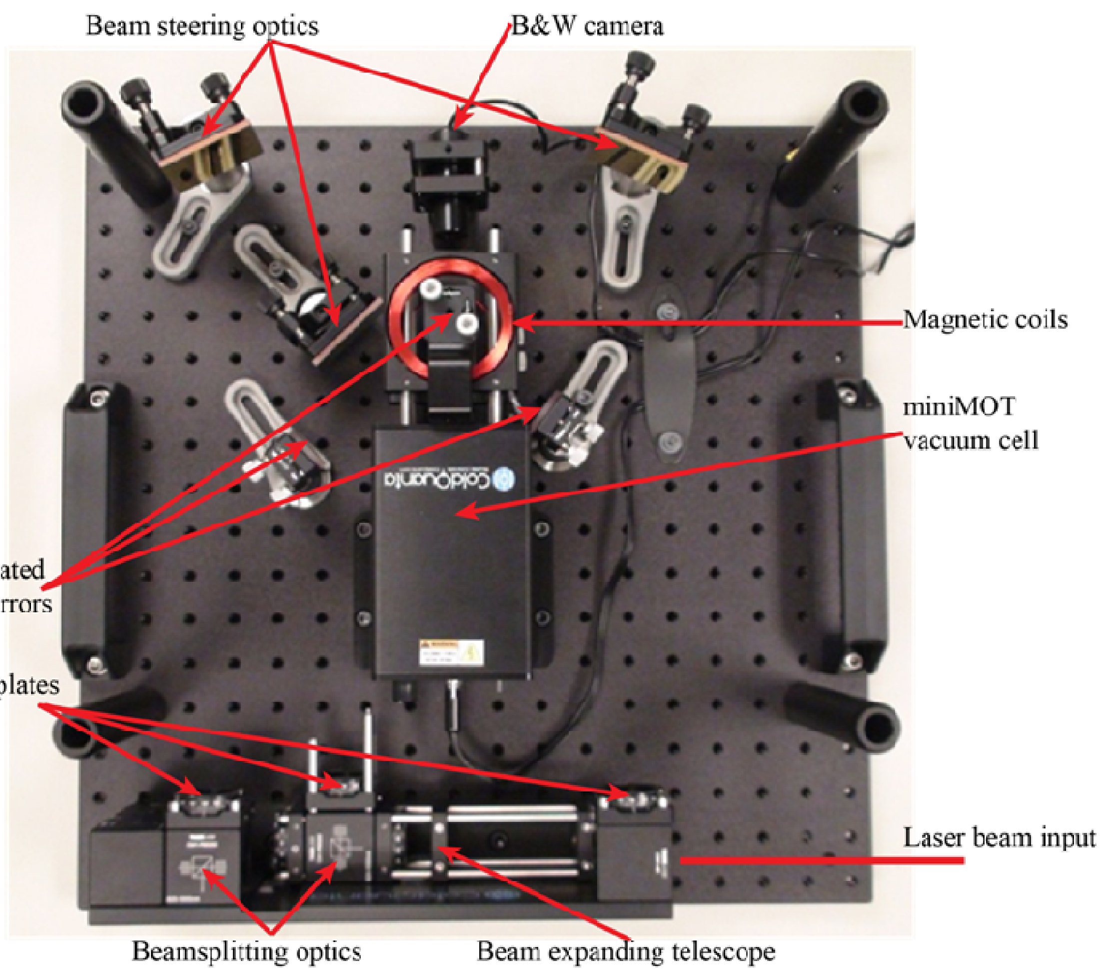

Figure 5: The miniMOT kit, showing all of the optics hardware needed to produce a MOT. miniMOT vacuum chamber is shown in the middle of the chamber, with magnetic coils. Not shown is the laser system and the number measurement setup.

Parts list:

- 1x miniMOT vacuum chamber with coils
- 1x miniMOT Kit, including:
  - 1x Beam expanding telescopes
  - 2x Polarizing beamsplitting cubes
  - 2x λ/2 waveplates
  - 3x λ/4 waveplates
  - 3x λ/4 laminated waveplate-mirrors
  - 5x Beam steering mirrors
- 1x Diode laser system at 780nm including:

Option a:

2x Tunable diode laser

2x Rubidium Spectroscopy modules

1x Beam combining optics

Option b:

1x Tunable diode laser

1x Rubidium Spectroscopy module

1x 3.2 GHz RF source for sideband modulation

1x Oscilloscope

1x imaging lens

1x amplified photodiode

All of the components for this experiment are readily available from commercial vendors.

4. Workshop Agenda

Due to the limited time frame of this workshop we will not be able to cover in detail the wealth of experimental possibilities that are available in a classroom environment for a MOT experiment. It is useful to keep in mind what is possible to cover in a teaching lab, which will largely be driven by how much time is available, and how advanced the students are. Some of the major teaching concepts are listed in Table 1

Theoretical Concepts	Experimental concepts and techniqies
Atomic structure and spectra	Laser technology
Scattering	Spectroscopy
Zeeman effect	Optics and optical techniques
Doppler effect	Optical measurement techniques
Polarization states of light	Error analysis
	Feedback and control systems

Table 1: Key concepts to be taught in the laser cool and trapping advanced lab experiment

The goal in this workshop is to give attendees a sample of types of experimental tasks that are available in a teaching lab. The agenda for the workshop will be:

I. A brief introduction.
II. Alignment of light into the optics package.
III. Alignment of MOT beams and waveplates.
IV. Demonstrating a MOT.
V. Measurement of the atom number in the MOT.