I propose to introduce an inexpensive laser cooling and trapping experiment to be done at Purdue. This will introduce students to a growing area of physics with some fun observables. The equipment required to do this is inexpensive and will cost less then $3000. There are a lot of parts to this experiment including designing tunable lasers and saturated absorption spectrometers. Along the way students will learn a great deal of physics and gain much experience in the lab. The results of this lab are also highly visible and rewarding making it more interesting for the students. Included is the information needed to set up and run this experiment along with some information on the components needed for it.

I. Introduction

Laser cooling and trapping is something that students should be introduced to during their duration at a university. It is a growing area of interest and is widely studied. Atom trapping comes in various degrees of complexity. Atoms have been cooled to temperatures as low as 1μK. They can then be held in a confined area in a vacuum chamber for long periods of time, allowing for more in-depth detailed studies of the behavior of atoms. Once the atoms are trapped, the motion is highly visible stirring much excitement and appeal to this type of work.

This paper is a proposal to setup and perform an atom trapping experiment in a graduate/undergraduate level lab course at Purdue University. It will be based on the work of Carl Wieman and Gwenn Flowers who have set up an inexpensive undergraduate atom-trapping lab. The experiment has been performed successfully at the undergraduate level and the cost was kept under $3000. These factors coupled with the need to introduce students to new and expanding areas of research demonstrates the need for such an experiment to be included in the lab course description.

The format of this paper is to introduce this topic and discuss some theory about atom trapping. Rb gas and some of its atomic properties will also be discussed because that is the atom that will be used in the trap. Some information on the equipment needed for the lab and how to set it up will also be included. At the
end I will discuss obtaining this equipment and discussing costs of these components.

The instructions for this experiment will assume that you are using a tunable laser diodes created as explained in reference 2. About 10% of the beam will be sent into the saturated absorption spectrometer to control the frequency as discussed in reference 3.

II. Theory of Laser Cooling and a Rb Cell Trap

The main force involved in the laser cooling is created from the recoil when momentum is transferred from the photons scattering off the atoms. A good analogy would be a bowling ball being hit with a barrage of ping pong balls or using the water stream from a high pressure hose to push a rubber ball around\(^1\).

The change in velocity for a single photon scattering is approximately 1 cm/s. This is quite small but if a strong atomic transition is excited roughly more then 10\(^7\) photons are scattered per second creating an acceleration of 10\(^4\) times the acceleration of gravity\(^1\). This effect is referred to as radiation pressure, which slows or cools the atoms and traps them in a local position in a vacuum cell.

To make this work you need to be able to control how the force is exerted on the atom. Using Doppler shift for moving observers you can influence the behavior of these forces. Each atomic transition corresponds to a photon with a particular frequency. Adjusting the frequency of the photon just below the atomic transition causes the atom to absorb the photon only when moving in the opposite direction along the beam as shown in figure 1. Using six beams incident at right angles along a 3-dimensional access you can create a damping force that opposes the motion of the atom slowing it and confining it to the trap\(^1\).

This process will cool the atoms but the atoms will still diffuse out of the region if there is no position dependence to the optical force.

One way to introduce this is done in the “magneto-optical trap” (MOT). The position dependence will be from appropriately polarized laser beams and by applying an inhomogeneous magnetic field to the trapping region.

The details of how this works are left up to the student to understand and write up. The purpose of this paper is to propose this experiment and guide the students.

Now I will discuss Rb and its use in the atom trap. One laser essentially does the trapping. The frequency is tuned to the low side of the \(5S_{1/2}F=2 \rightarrow 5P_{3/2}F'=3\) transition of Rb\(^{87}\). This transition has a one in a 1000 chance of decaying into the F=1 state. This state does not absorb the incident photons so it essentially removes the atom from the cooling effect. After a short while all of the atoms will be in this state and the cooling laser will have no cooling affect on the Rb. To solve this problem a second laser is set below the
5S\textsubscript{F}=1→5P\textsubscript{F'}=1 or 2 state. This transition will decay back into the 5S\textsubscript{F}=2 state and you are back in business\textsuperscript{1}.

The trapping is done in a low-pressure cell that contains small amounts of Rb vapor. Low energy atoms with a velocity less then \(V_{\text{max}} = 20\) m/s are captured. As time progresses the number of atoms increases in a similar fashion to the charging of a capacitor described by the following equation in figure 2.

In the equation in figure 2, \(\tau\), is the time constant. It is the time it takes for the trap to fill until it is in a steady state with \(N_0\) atoms. This is also the average length of time an atom stays in the trap before being knocked out by colliding with other atoms.

### III. The Trapping Apparatus

A schematic diagram for the atom trap is provided in figure 3. The components needed for the trap are two tunable laser diodes, two saturated absorption spectrometers, a trapping cell and optical components.

The optical components include lenses for expanding the laser beam, mirrors, beam splitters and wave plates to control the polarization of the beam.

The trapping cell is created by a UHV vacuum system pumped down with an ion pump. The cell will have an Rb source and windows for the laser light to enter through. A glass vacuum cell can be used as an alternative in the system for easier alignment of the laser with shorter beam paths of equal length as shown in figure 4.

\[ N(t) = N_0 \left(1 - e^{-\frac{t}{\tau}}\right) \]

Equation for number of atoms \(N\), trapped as a function of \(t\).

### IV. Optical System for Laser Cooling

The first thing necessary is to have the cooling laser set to the needed frequency. The beam then needs to be sent into the trap in such a way so that the radiation pressure acts along all 6 axes.

In larger more professional setup, the beam is sent through an optical isolator and reshaped circularly with a diameter of 1 to 1.5 cm using beam-shaping optics. The beam is then split into three equally intense beams using dielectric beam splitters. After this, the beam is then...
circularly polarized by a quarter wave plate and sent into the trap so that the beams intersect at the center orthogonal. The beams then exit the trap going through another quarter wave plate and reflected back directly on the incident path. This ensures that the 6 directions are covered.

In this proposed experiment based on the work in reference 1, we will eliminate some of the expensive components such as the optical isolator, dielectric beam splitters and high quality quarter wave plates.

The beam will be expanded into an elliptical shape of 4.5 cm by 1.5 cm. This will then be split into 3 equal beams. Instead of a fancy system of beam splitters, we will use staggered mirrors to cut the beam into three equal beams 1.5 cm by 1.5 cm. The actual relative power is not as crucial in this less complex experiment but this set up should ensure the 3 beams are of similar powers.

Two of the beams are kept in the horizontal plane and the third is deflected up and over the trap to drop down through the z-axis. They must intersect orthogonal. The path lengths of the beam should be as close to equal length as possible because the laser is not perfectly collimated. Beam polarization should be kept linear until reaching the quarter wave plates. This is shown in figure 5.

Once exiting the trap the beams will be reflected back onto themselves and return through the trap. The orientation will not be exact but the trap will work if there is a large enough overlap so you wont have to worry about them coinciding exactly on the same path.

V. Hyperfine Pumping

The second laser does not involve a complex optical setup, it is merely there to pump up the atoms that decay into the 5SF=1 state. This beam should be expanded to roughly 2-3 cm along the major axis and sent directly through the point where the cooling beams intersect. This will keep the atoms in a state that can be cooled by the main beam. The hyperfine beam should be sent in such a way as to not scatter into the observing photodiodes.

VI. The Trapping Cell

The cell described in reference 1 can be used, however there is an alternate method. Using an elongated cylindrical tube in the vacuum system you can modify the original design to help keep optical path-lengths equal. The schematic of the system is shown in figure 5. The vacuum setup and pump down procedure I will
leave out of this document. It will be up to the students to learn how to put together, pump down and bake out a UHV vacuum system. The trap will work at pressures of $10^{-5}$ Pa but is optimum in a range from $10^{-6}$ to $10^{-7}$ Pa.

Along with making the optical path lengths more equivalent, the Rb source can be installed in one end of the tube as shown in figure 4.

**VI. Rb source**

I will discuss some properties of Rb vapor that make it somewhat hard to use. A good solution to this problem was introduced by Weiman and his collaborators for the undergraduate experiment that will be used in this experiment.

One would think that the ion pump for the UHV system would take Rb out of the trap making it unstable. This is not the major problem. Due to chemical and physisorption the walls of the cell will remove far more Rb than the ion pump. The absorption rate depends on how much Rb is already coating the walls of the cell. In a stainless steel pipe the Rb vapor would slowly creep down the pipe coating the walls. This causes a pressure drop down the pipe. Materials other than stainless steel, such as glass, also absorb large amounts of Rb.

A recommended solution is to use a commercial "getter" that was designed for the undergraduate lab. This consists of a Rb compound in a stainless steel oven. Two of these ovens are spot welded together and wired to a UHV feed through. This feed through can be attached at the end of the cylindrical tube as shown in figure 4. When a current between 3 and 5 A is applied Rb vapor is released. Increases in current will increase the amount of Rb vapor released. This system will release enough Rb into the cell that you will not have to coat the walls.

**VII. Optical Access**

Using this altered design as shown in figures 4 and 5, it will not be a complicated process for setting up the optics. The entire UHV system, as shown in figure 4, is rather small as can be seen with the scale in the figure.

One way to set up the optics is to first align all of the beams without the trapping cell in place. Use a visible laser to align all of the optical components so that the beam intersects orthogonal in all 6 directions. Once you are confident with this setup you should be able to insert the trapping cell into the path of the beams. The cylindrical shape of the cell will bend some of the light, but it will preserve the geometry well enough to perform the experiment.

**VIII. Trap Observation**

It is possible to observe the trap with the naked eye but you must look carefully in a dark room. It is recommended that you obtain an inexpensive CCD video camera and a monitor to use observing the trap. The trapped atoms will show up like a little glowing cloud in the center of the cell. A properly positioned photodiode can be used to detect the fluorescence also being careful that it is not picking up scattered light from the glass cylinder.

The trap can be obscured from view by background fluorescence of Rb that is free in the cell. The lower pressures will reduce the amount of background Rb in the cell making the trap more visible.
IX. Trap Operation

The first thing to do is to activate the Rb source. By monitoring a weak probe beam, you can determine the Rb pressure. When you can see dim lines of Rb florescence from the trapping beams you should be at an adequate pressure to begin.

After adequate Rb pressure is detected the magnetic field gradient is turned on and the lasers are set to the appropriate transitions. If this is the first time running the experiment it will be necessary to try both directions of current through the coils to determine the correct sign for trapping.

X. Components Availability

All of the components required for this lab are relatively inexpensive and can be found in various supply catalogs. Substitutions and minor changes in components can be made to save costs and will not have a large impact on the outcome of the experiment.

Reference 1 is a good source of information regarding components and the pricing of components. Using that as reference, the cost of an entire system would be less than $3000.

If using inexpensive ¼ wave retarders you will find that the bulk of the optical cost is in the mirrors. It is recommended that you use kinematic mounts that run between $50 and $100 each. It is not necessary to use these and less expensive mounts should be adequate.

The mirrors should be gold plated and highly reflecting for the infrared light. The Weiman experiment used gold dielectric mirrors.

UHV components are readily available. The glass cylinder can be purchased with various dimensions. Small modifications to these components will not affect the experiment.

The university has ion pumps available in various labs and equipment required for a bake out. If desired a new ion pump could be priced and purchased for this experiment. The use of a pump already owned alleviates the costs greatly.


2 J. Millspaw, “A narrow-band tunable diode laser with optical feedback control,” Phys. 670F, Purdue University, Physics Department, West Lafayette, IN, 47906

3 J. Millspaw, “Saturation spectroscopy of Rb using a tunable diode laser,” Phys. 670F, Purdue University, Physics Department, West Lafayette, IN, 47906