

Building a Potassium MOT

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Abstract

A magneto-optical trap (MOT) was developed in order to cool and trap potassium atoms. This required construction of a mechanism for tuning and locking the frequency of a trap and repump laser in order to maintain the correct energy transitions needed to ensure trapping of the atoms. Once the lasers' frequencies were locked, the beams were combined and amplified and can now be combined with lasers from a similar system for ^{87}Rb after which the light will be passed into a vacuum chamber where a two species MOT can be achieved.

Introduction

A magneto-optical trap is a device that utilizes lasers and magnetic fields in order to cool and trap neutral atoms in a vacuum chamber. Once atoms are cooled and trapped they can be further manipulated in order to form quantum gases or in general to study the atoms and their interactions with greater precision.

The optical mechanism used to cool and trap the atoms is shown in Figure 1 as the three red lines, which represent three orthogonal laser beams passing through the center of a vacuum chamber (represented by the grey rectangle). Each of these beams is then reflected back upon itself so that there are actually six laser beams passing through the center of said vacuum chamber. These laser beams are slightly red-detuned of the frequency required for absorption by the atoms present in the vacuum chamber. Because of the Doppler shift of the atoms moving with respect to the laser beams, only atoms that are moving in a direction opposite to that of the

laser beams are able to absorb a photon. Since the atom then reemits a photon in a random direction, the net momentum transfer to the atom is in the direction opposite that of its motion. Though the momentum transfer from a photon is miniscule ($\sim 10^{-36}$ Nm) the absorption of many photons will lead to a net decrease in the momenta of the individual atoms, thereby cooling the atoms and trapping them in the center of the chamber.

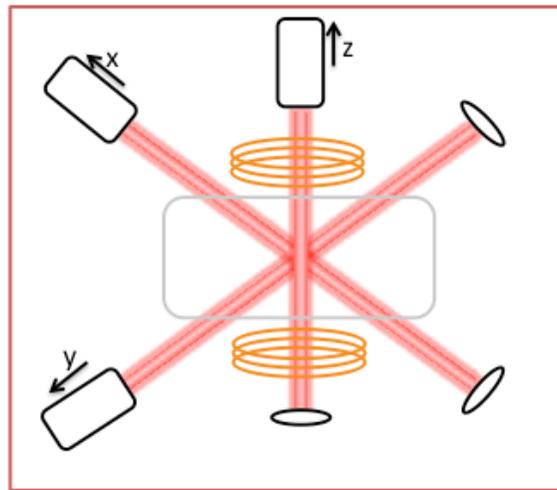


Figure 1- Simplified diagram of a MOT chamber

In addition to optical trapping and cooling, a MOT takes advantage of magnetic trapping. This is accomplished by the placement of two coils, one above and one below the chamber, in an anti-Helmholtz configuration. These coils produce a uniform magnetic field gradient within the vacuum chamber with no magnetic field at the center and increasing field with increasing distance from the center of the chamber. The presence of a magnetic field induces Zeeman splitting in the energy levels of the atoms as shown in Figure 2. Since there is no magnetic field at the center of the trap, the atoms are least likely to absorb photons because the Doppler shift needed to overcome the red detuning is at its greatest. However, as the atoms become further from the center of the vacuum chamber the Zeeman splitting decreases the velocity with which the atoms need to be moving to absorb a photon, and therefore the atoms are more likely to

receive a momentum kick back toward the center of the chamber. This leads to the atoms becoming trapped in the center of the chamber.

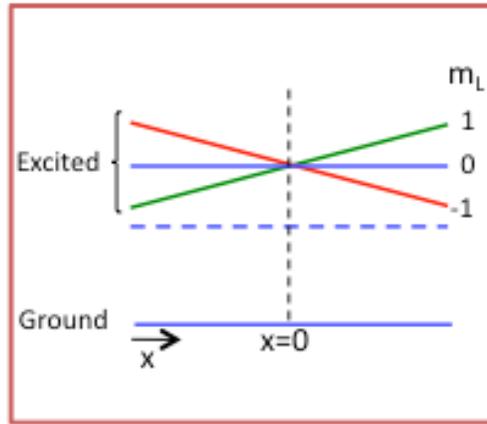


Figure 2- Diagram of Zeeman splitting in a Boson, a similar effect occurs in Fermions

The purpose of this project was to design a system to align and tune the lasers necessary to achieve a potassium-40 (^{40}K) MOT and combine them with a similar system of lasers already in place for a rubidium-87 (^{87}Rb) MOT. Combining ^{40}K and ^{87}Rb in a MOT allows for the study of two particle interactions between Fermions and Bosons and may even be used in the creation of two atom molecules. Though this two-species MOT will not be used to study these atoms it will be used as a test setup where new techniques and apparatus will be studied and tested before being implemented in other labs.

In order for a MOT to form, two lasers are necessary. The first laser is known as the trap laser and allows for cycling transitions of the atoms. This transition is seen in Figure 3 where the trap laser is set to a frequency that excites the atoms from the $F=9/2$ ground state to the $F'=11/2$ excited state. From there, by selection rules, the only transition the atoms can make is to return to the $F=9/2$ ground state. It is necessary for the trap laser to cause this cycling transition because in order to cool and trap the ^{40}K , the atoms must be able to return to the same ground state as soon

as it has absorbed a photon so that it may absorb many photons and thereby receive a non-negligible momentum transfer.

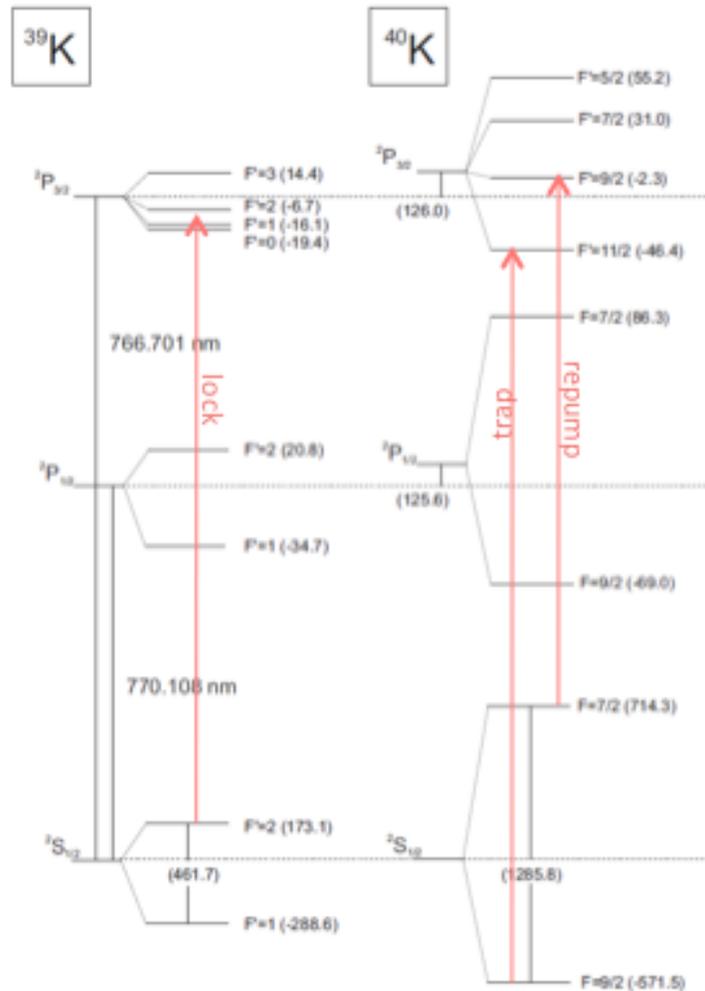


Figure 3- Fine and hyperfine structures of ^{39}K and ^{40}K including transitions utilized in creating a MOT¹

However, occasionally an atom will absorb off resonance and will jump to the incorrect excited state. In this case the atom may fall down to the $F=7/2$ ground state instead and will no longer be trapped in the cycling transition. This occurrence necessitates the use of a second laser known as the repump laser. This laser takes any atoms from the $F=7/2$ state and pumps them up to the $F'=9/2$ state from which they can fall back to the $F=9/2$ ground state and reenter the cycling transition.

Apparatus and Procedure

The frequencies of the trap and repump lasers need to be tuned to the necessary transitions and stabilized before a MOT can be achieved. The setup of the apparatus used to tune and lock the lasers to the correct frequencies is shown in Figure 4.

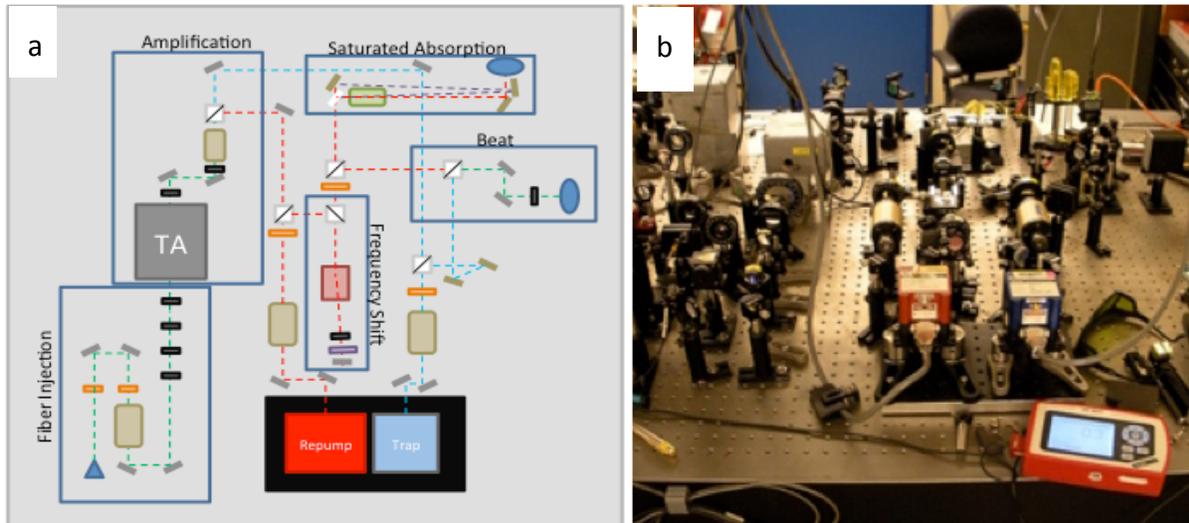


Figure 4- a) Simple diagram of laser tuning and locking configuration, b) Actual picture of lab apparatus

There are five components necessary to lock both the trap and the repump laser. The first of these components is saturated absorption spectroscopy and can be seen in the upper right hand of Figure 4a. To utilize saturated absorption spectroscopy, one beam (the probe) is sent through a cell containing potassium and is collected with a photodiode. A second beam (the pump) is passed through the same cell in the opposite direction such that the two beams overlap as much as possible within the cell (see Figure 5). The intensity of the light hitting the photodiode can then be observed as the frequency of the laser is swept over a small range centered on the frequency at which the atoms absorb. A reduction in the intensity should occur at the exact frequency at which the atoms absorb. However, because of the thermal motion of the atoms there will be absorption in a relatively wide range of frequencies due to Doppler shifting.

The presence of the pump beam propagating in the opposite direction allows for the appearance of sharper absorption for non-Doppler shifted atoms. This occurs because atoms that are moving parallel to either of the beams may Doppler shift and be absorbed for one beam, but not for the other. However, atoms that are moving perpendicular to both beams will not be Doppler shifted towards either beam and will therefore only absorb at the precise frequency where absorption is expected. Since only these non-Doppler shifted absorptions will take place in both beams, the absorption peak will be sharper and will be visible above the background of the Doppler shifted spectrum. Figure 6a shows a Doppler broadened spectrum and Figure 6b shows the same spectrum taken using saturated absorption.²

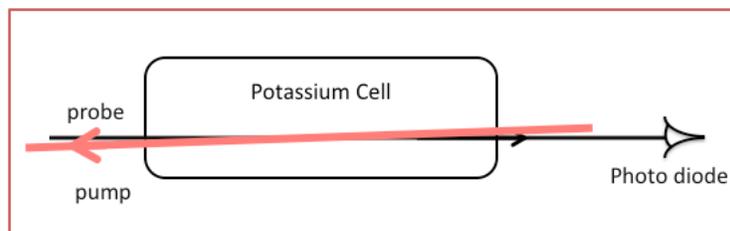


Figure 5- Simple diagram of saturated absorption spectroscopy cell

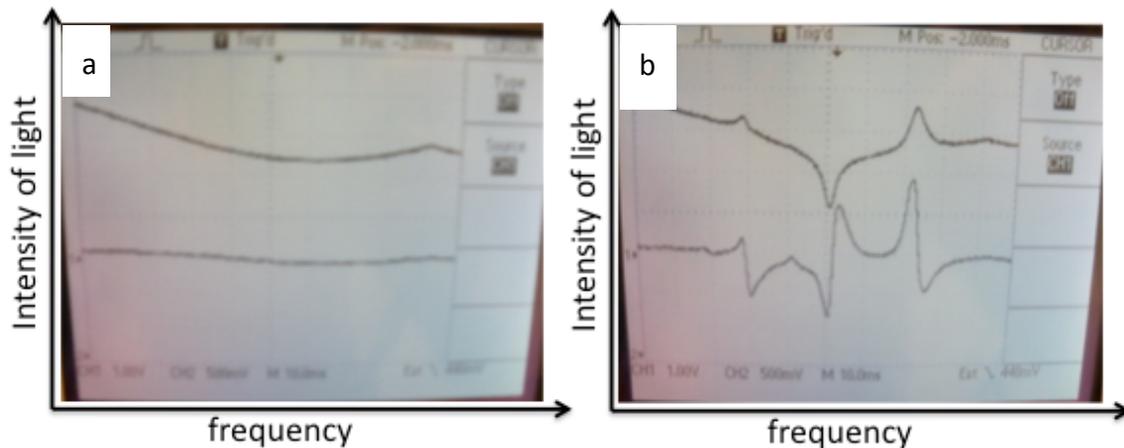


Figure 6- a) Signal from a single 767nm laser passing through a Potassium cell b) Signal from two counter propagating 767nm lasers, which overlap in the Potassium cell

^{40}K is the isotope of interest because it is Fermionic. However, this isotope has a very low natural abundance (0.01% as compared to ^{39}K at 93%) and therefore produces too weak a signal

for use in saturated absorption spectroscopy. I should here note that in the vacuum chamber used for the MOT itself the potassium source used is enriched to 4% so that this same problem does not arise. In order to still lock the repump laser using saturated absorption spectroscopy we must instead lock to a transition present in ^{39}K (see Figure 3) and then shift the frequency of the laser by the difference between the two signals before sending it to the MOT. This shift in the laser frequency is the second of the components described above and is shown as the “Frequency Shift” in Figure 4a. An Acousto-Optical Modulator (AOM) is used to shift the beam being sent to the saturated absorption spectroscopy by 411 MHz (this value was calculated using the values given in Figure 3). This is accomplished by passing a laser beam through a small segment of quartz, which has sound waves driven through it. This causes the appearance of phonons in the quartz, which then causes diffraction of the incoming laser beam such that the frequency of the transmitted beam is altered. In this apparatus a 205.5 MHz AOM was used and the light was passed through twice, creating the sought after shift of 411 MHz total. From now on, the portion of the repump beam that was shifted and sent to the saturated absorption cell will be referred to as the “lock” beam.

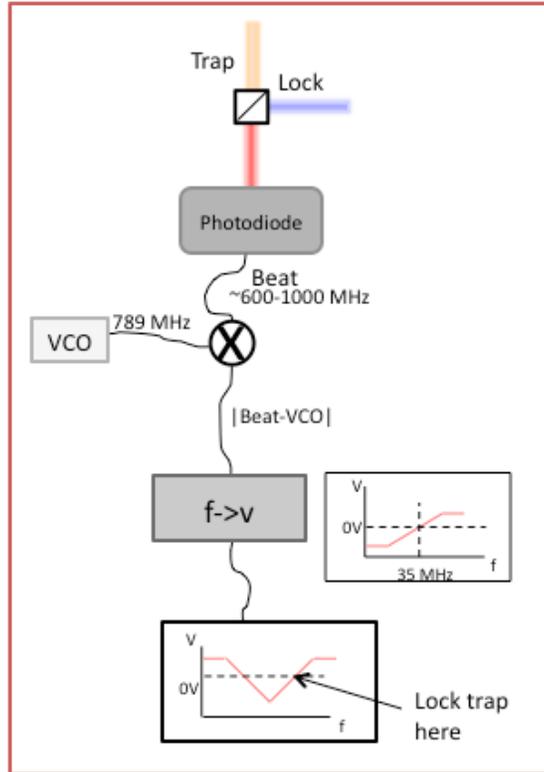


Figure 7- Diagram of beat mechanism

In order to lock the trap laser, a different component, the “beat” in Figure 4a, was used. Figure 7 shows the details of the electronics needed to achieve and lock to a beat note. To achieve a beat note the trap and “lock” lasers were combined on a polarizing beamsplitter cube. The resulting, combined laser beam was then passed into a photodiode and the resulting signal is known as the beat note and has frequency

$$f_{\text{beat}} = f_{\text{trap}} - f_{\text{lock}} \quad (1)$$

Using Figure 3, the difference between these two frequencies necessary to achieve a MOT was calculated to be 824 MHz. However, since the trap laser was not yet locked the beat frequency ranged between 600 and 1000 MHz even when the trap laser was set to near the correct frequency. The beat frequency was then sent into a frequency mixer along with signal from a

voltage-controlled oscillator (VCO). A VCO is an adjustable source of constant frequency. The signal resulting from this mixing had a combination of two frequencies

$$f_{\text{mixer}} = |f_{\text{beat}} - f_{\text{VCO}}|, f_{\text{beat}} + f_{\text{VCO}} \quad (2)$$

In order to eliminate the additive response, this signal was sent through a low pass filter so that only the subtracted signal remained. This signal was then passed into a frequency to voltage (f->v) converter, which gave a linear response on a range between about 0 and 70 MHz, and gave zero voltage at 35 MHz. Since the response of the f->v converter gave zero voltage at 35 MHz, the VCO previously mentioned was set to give a frequency of 789 MHz, 35 MHz away from the desired 824 MHz of the beat note. Therefore when the frequency of the trap laser was swept over a range of frequencies, it could be locked to the zero of voltage coming from the f->v converter.

Once the trap and repump lasers were locked to the correct frequencies they were sent to the fourth component of the system shown in Figure 4a, "Amplification," where the two laser beams were combined and sent into a tapered amplifier (TA). When the TA was run at high current (~1.8 Amps) the power of the beam was greatly intensified. This light was sent through the last component shown in Figure 4a, the "Fiber Injection." This was a series of lenses, mirrors and an isolator, which allowed for the beam to be injected into a fiber. Optimization of this injection is currently underway. Once it is optimized, the fiber will carry the light closer to the MOT chamber, where it will be combined with light from a similar Rb system using a polarizing beamsplitter cube. Once the light is combined using the cube it will be sent through a waveplate that is λ for 780nm light and $\lambda/2$ for 767nm light. This will allow the two lasers to have the same polarization as they are sent to the MOT chamber where a combined ^{87}Rb , ^{40}K MOT will be achieved.

Conclusion

The optics layout and electronics required for tuning and locking the trap and repump lasers to the frequencies necessary to achieving a ^{40}K MOT were designed and implemented. More work has yet to be done in order to combine these beams with light from a similar ^{87}Rb system and send them to the MOT chamber where a two-species MOT can be achieved.

References

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2. Author unknown, Doppler Free Saturated Absorption Spectroscopy (http://instructor.physics.lsa.umich.edu/adv-labs/Doppler_Free_Spectroscopy/DopplerFree.pdf), 3 August, 2011.