1 MOT Characterization: Week 7

This week, the focus is on characterizing the MOT. This includes direct detection of the MOT fluorescence, the loading curve, and measuring the number of atoms that are trapped.

1.1 Background

The number of atoms in a sample, N, is one of the most useful parameters for AMO experiments. On top of being a basic figure of merit to diagnose the well-functioning of the lasers and quantifying signals, it also allows us to estimate densities and collision rates in the sample, which become crucial when using a MOT as a starting point for processes such as evaporative cooling.

In general there are three main imaging methods for probing atomic samples:

1. **Fluorescence imaging (FI):** measuring the amount of spontaneously emitted light (fluorescence) from a sample directly after it has absorbed a pulse of near-resonant light. A larger signal is indicative of a larger amount of atoms in the sample.
2. **Absorption imaging (ABS):** measuring the amount of attenuation in the light profile (absorption) after the sample was illuminated with a pulse of resonant light. The darker the "shadow" that the sample casts, the more atoms it should be composed of.
3. **Polarization phase-contrast imaging (PHC):** analyzing the intensity , phase and polarization profiles of a far-detuned light that has gone through the atomic sample (dispersion). The density profile of the gas can then be extracted by modeling the interaction between the light and the cloud.

Both ABS and PHC require a more involved analysis and modeling of the interaction between the probing beam and the cloud of atoms. Thus, they usually require the sample to be cold, dense and small. Although our MOT has a remarkably low temperature, it is still not a feasible sample for either of these methods. Thus, we will rely on FI for characterizing our MOT.

1.2 Basic FI picture

We will model our atomic sample as a uniform, spherical sample composed of N_a atoms in total. Then, we would like to answer the question: how many photons, N_γ will this sample spontaneously emit after it has been pumped with a brief pulse of near-resonant light?

If we assume a simplified picture of a two-level system undergoing spontaneous emission (associated with the Einstein coefficient A_{eg}), then N_γ will be given by:

$$N_\gamma = \frac{t_p}{\tau}\,\rho_{ee}\,N_a \tag{1}$$

where t_p is the pulse duration, $\tau = 1/\Gamma$ is the excited state lifetime, and ρ_{ee} is the fraction of the atoms in the excited state. For our case, ^{85}Rb, $\tau = 26.2348$ ns and $\Gamma = 2\pi \times 6.066$ MHz. The quantity $N_e = \rho_{ee}N_a$ corresponds to the total amount of atoms that are in the excited state, and ρ_{ee} can be evaluated by solving the optical Bloch equations for an ensemble of atoms (see Foot):

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

Here Δ is the detuning of the pulse with respect to the resonant frequency, I is the intensity of the beam, and I_s is the saturation intensity, which is given by:

$$I_s = \frac{\pi}{3}\frac{hc}{\lambda^3}\Gamma$$

where for our case $\lambda = 780$ nm and thus $I_s = 1.671$ mW/cm^2. The factor $\frac{t_p}{\tau}$ estimates the number of emission events that will occur during the probing pulse. Note that it would be one if the pulse duration exactly matched the lifetime of the excited state, but in general the pulse will be much longer.

Eq. (1) takes care of all the physics of the system, and now we need to take into account experimental conditions and constraints. These photons will be emitted uniformly in 3D space, but we will only be able to collect a small fraction η of these photons with our camera/photodetector. We estimate this "collection efficiency" by $\eta \sim \Omega/4\pi$, where Ω is the collection solid angle subtended by our measuring device, compared to the total 4π steradians available for a spherically-symmetric emission. Ω can be evaluated exactly using calculus, but for a sensor that is sufficiently far from the sample, and is also sufficiently small such that the small-angle approximation is valid, it can be approximated as

$$\Omega \sim \frac{\pi r^2}{d^2}$$

where r is the radius of the light-collecting optic (most probably a lens), and d the distance between the sample and the optic.

Then, the number of detected photons, N_p will be given by:

$$N_p = \eta \, \frac{t_p}{\tau} \, \rho_{ee} \, N_a \tag{3}$$

The signal that we will measure, assuming we use either a CCD or a CMOS sensor, will not be in terms of number of photons but in the number "counts" of photoelectrons (times whatever multiplicative gain the device has). This is characterized by the *quantum efficiency*, ξ of the sensor, which measures the number of counts per every incoming photon. ξ is usually reported as a percentage. For example, if $\xi = 33\%$, the sensor will report 1 count per every 3 photons. Conversely, for every "count" event, we would expect to have received 3 photons.

We can measure ξ for a sensor with area A by exposing it to a pulse with a fixed duration t_e and a known intensity I. Then, assuming every photon was detected, we can write the total received energy in different forms:

$$\varepsilon = I \, A \, t_e = N_c \, Q = N_p \, \frac{hc}{\lambda} \tag{4}$$

where N_c is the number of measured counts after such pulse and Q is the device quantum efficiency relating energy (Joules) with respect to counts. Q is experimentally useful in terms of units, but for our purposes we can evaluate a "per photon" equivalent of Q:

$$\overline{Q} = \frac{Q\lambda}{hc}$$

such that $\overline{Q} = 1/\xi$. Finally, we are ready to write down a relationship between the number of measured counts/photons after a FI pulse and the number of atoms in the sample:

$$N_p = N_c\ \overline{Q} = \eta\ \frac{t_p}{\tau}\ \rho_{ee}\ N_a \tag{5}$$

and we can solve for N_a in terms of the experimentally relevant quantities:

$$N_a = \frac{N_c \overline{Q}}{\eta\ \frac{t_p}{\tau}\ \rho_{ee}} \tag{6}$$

1.3 Re-create MOT

In the first week, you aligned the beam into the MiniMOT kit, balanced the powers in the different arms, checked the polarization and retro-reflection before turning on the coils and getting your cold atom gas. This week, the setup should already aligned, balanced and properly retro-reflected. As a result, putting you should be able to quickly create your MOT using the frequency and power on the RF generator that you used last week. Once you have a MOT, we can move on to characterizing the MOT properties.

1.4 Detecting MOT using fluorescence

Before we setup the CMOS camera we will be using to image the MOT, we can measure its quantum efficiency using the procedure described in section 7.2. Introduce the camera in one of the arms of the MOT and see what kind of image is recorded. If the sensor is saturated, you will need to make use of a ND filter to reduce the overall power of the beam, and take this attenuation factor into account. Take a picture and use it to estimate ξ.

We now should set the lens with which we'll be collecting light for the sensor. Remove the bullet cam and replace it with a provided mini-flashlight. You will most likely need to use the ND filter again to prevent the sensor from saturating. Install the lens right in front of the camera at a distance that roughly corresponds to the focal length and then proceed to adjust it until you observe a sharp image of the flashlight. The LED should look like a square with sharp edges. Once you finish this step, we will no longer be adjusting the separation between the lens and the CMOS, and we'll be moving them together using the provided breadboard.

Once this step is done, reset the bullet cam and the MOT. Make sure you can observe the atoms in the bullet them, and then proceed to adjust the CMOS + lens assembly until you are able to clearly observe the MOT in the camera. Verify that you are observing the atoms by slightly displacing them with a magnet and seeing them move in the CMOS. The signal should also disappear when the light is blocked or the coils are turned off.

Adjust the snapshot duration such that the image of the MOT in the CMOS is not saturated. Then try to optimize the MOT by adjusting the parameters of the lock such as the overall offset of the lock and the amplitude of the current modulation.

After this, use the camera to record a background image of the field of view when there is no IR light passing through the setup, and another background image when the IR is passing through, but the coils are turned off. Let the MOT load until it reaches a steady state and take another picture. We will use those pictures to estimate the number of atoms in the sample and its size.

After this step, use the recording feature of the camera to try to take a video of the MOT loading until it reaches a steady state. We will analyze this video to characterize the loading of the MOT in terms of its overall size and the number of atoms as a function of time.

Record a video of the atoms leaking from the MOT after you block each of the arms of the MOT.

Finally, record a video of the MOT as you turn off the coils, and try to see if you can observe the explosion of the MOT. For this step, use as many frames per second (FPS) as the camera allows.

1.5 Analysis Questions for the report

1. What is the quantum efficiency ξ you measured? How does it compare to the nominal value of $\xi = 33.7\%$?
2. What was the distance between the light-collecting lens and the CMOS? How does it compare to the reported focal length of the lens?
3. Use your recorded pictures of the MOT to isolate the MOT fluorescence by subtracting the background image you recorded (with light, no magnetic field gradient). Then, estimate the number of atoms in your sample. From your picture, measure the radius of the cloud and estimate its overall volume assuming a spherical/ellipsoidal shape. What is the density of the cloud? How does it compare to the density of rubidium at STP conditions?
4. Briefly discuss how do the atoms leak from the MOT after blocking each of the beams. Is there any difference between any of the arms?
5. Analyze the frames of the recorded video of the MOT loading, and prepare a plot of atom number and cloud radius as a function of loading time.
6. Were you able to observe the MOT exploding? What change in the setup could you do to try to better observe the explosion?