Physics 4261: Lectures for week 11

Prof. Colin V. Parker (cparker@gatech.edu)
Georgia Institute of Technology

11.0.1 Light shift

Finally, we consider the evolution of the system with no dissipation, and compute a quantity we call the "light shift". This is how much the addition of the radiation field causes the atomic levels to shift. Classically, it is analogous to the refractive index of the atoms. Recall that the addition of the field to the equations lead things to oscillate at the frequency $W/2 = \sqrt{(\delta/2)^2 + (\Omega/2)^2}$. Now, if $\Omega \to 0$ this oscillates at $\delta/2$ as expected from being off resonance. Therefore the difference

$$\frac{W-\delta}{2} = \frac{1}{2}\left(\delta^2 - \sqrt{\delta^2+\Omega^2}\right) \approx \frac{\Omega^2}{4\delta} = \frac{\Gamma^2}{8\delta}\frac{I}{I_{\text{sat}}},$$

represents the amount that the "dressed atoms" have different energy levels from the atoms ordinarily.

11.1 Spectroscopy

In this section we are going to cover the basics of actual physically realized spectrscopy, having a good understanding of single atoms in radiation fields under our belts. So far, our atomic theory has told us that intrinsic properties of the atoms determine the center wavelength and the width of our transitions. The main question that we want to ask here is: what effects can lead to broadening or shifts in experiments. We begin with the Doppler effect

11.2 Doppler broadening

Doppler broadening is typically the most significant source of broadening, but fortunately it can be overcome. From your homework, you derived that the Doppler effect leads to an additional broadening

$$g_D(\omega) = \frac{c}{u\omega_0\sqrt{\pi}} \exp\left\{-\frac{c^2}{u^2}\frac{\delta^2}{\omega_0^2}\right\},$$

where $u = \sqrt{2k_BT/M}$. The book gives a useful rule of thumb for the Doppler width. For a 600 nm transition at 300 K, the linewidth is 6 GHz$/\sqrt{M}$, with M in atomic mass units. Note that this exceeds natural linewidths (and many hyperfine splittings) for most atomic transitions. This broadening is undesriable for two reasons.

1. A broader line makes it harder to find the center.

2. Measuring the experimental natural linewidth is important for comparisons.

11.2.1 The crossed-beam method

Here we summarize what happens in the crossed-beam method. The atoms leave the oven with a thermal velocity distribution, but then only certain angles are allowed into the chamber. Thus the transverse velocity is reduced by the spread angle α (or $\sin\alpha$) from the expected value of the thermal velocity (plus some prefactors, which we will ignore). By putting the beam in the direction perpendicular to the atomic beam, the transverse velocity will be small, and therefore the Doppler broadening reduced. A consideration here is the transit-time broadening, although in these experiments this is typically small. This is the frequency time uncertainty relation $\Delta f_{\text{tt}} = 1/T = v/d$.

11.2.2 Saturated absorption spectroscopy (Foot 8.3)

I would call this the workhorse of modern spectroscopy. Note that here we will use the notation $N(v)$ to denoted the density of atoms with velocity v (relative to the beam). Our starting point is the number of atoms in the ground state (i.e. $|c_1|^2 = (1+w)/2$), which is given by

$$N_1(v) - N_2(v) = Nf(v) \times \frac{1}{1 + (I/I_{\text{sat}})\,\frac{x^2}{x^2+\Gamma/4}},$$

where x is the Doppler-included detuning $x = \omega - \omega_0 + kv$. Let us sketch out what $N(v)$ looks like with no intensity. But here is where things get tricky: when the intensity is significant compared to the saturation value, the atoms which are on-resonant with the laser beam will exist in the upper state with significant probability and absorption will be saturated. Now, let me take another beam (weak beam, probe beam), and run it in the opposite direction. Note the Doppler shift of this beam is in the opposite direction! Now, if the beam is at true resonance, then both beams will be resonant with stopped atoms, and there will be low absorption of the probe, as the transition is saturated by the pump. That being said however, if the laser if within the Doppler profile, but not exactly on resonance, the pump and probe will see different velocity groups, and hence the probe will be absorbed at the normal amount. So the net effect is to carve a hole in the distribution. On your homework you will work out how wide this "hole" is.

When there are multiple excited states (for example, multiple hyperfine levels) another phenomenon can happen when the frequency is exactly halfway between two transitions. In this case, one transition from the pump beam will be resonant with a velocity class which is resonant with the *other* transition for the probe beam. This is called a "crossover".

Note that a few more things can happen if there are multiple hyperfine or fine structure levels in the ground state. In this case, in addition to saturating transitions by populating the upper level of the optical transition, the population can also be "depumped" into another ground state level which is off-resonant, and this is similarly reduces the absorption on resonance. However, if two transitions involving different ground states are on resonance (this requires large Doppler width and small hyperfine splitting in the ground state), then the population can be "repumped" into the original state, reducing the natural depumping effect and *increasing* the absorption strength.

11.3 The radiation force (Foot 9.1)

We are briefly going to discuss the transfer of momentum to atoms as they absorb and emit light. In a uniform incident field, the emission will have no significant direction. It will not be purely isotropic, as it must follow the dipole antenna pattern appropriate the polarization of the source. However, as many photons will be kicked out "forward" as "backward" (along any direction), so the net effect on the atomic momentum is zero. The absorbed photon, on the other hand, may have significant directional information (e.g. if the beam comes at the atoms from only one direction). As each photon carries momentum $\hbar k$, the total force is given by

$$F = \hbar k R_{\text{scat}} = \frac{\hbar k \Gamma}{2} \frac{I/I_{\text{sat}}}{1 + I/I_{\text{sat}} + \frac{4\delta^2}{\Gamma^2}}.$$

In particular, the maximum possible force (when $I/I_{\text{sat}} \to 1$) is given by

$$F_{\text{max}} = \frac{\hbar k \Gamma}{2}.$$

In this case the acceleration is

$$\begin{aligned} a_{\text{max}} &= \frac{\hbar k \Gamma}{2m} = \frac{\Gamma}{2} v_{\text{rec}}, \\ v_{\text{rec}} &= \frac{\hbar k}{m}. \end{aligned}$$

11.4 Using radiation to slow an atomic beam

Here we are going to investigate the use of laser radiation to slow an atomic beam from an oven. Assume the atoms are in the thermal velocity range, which in practice means about $100 \sim 1000$ m/s. (How did I calculate this?) Call the initial velocity v_0. In principle, the (negative) acceleration could be as much as a_{max}, but in practice typically a "safety factor" α is employed, for various reasons (the intensity is not truly infinite, there may be weak spots in the beam, etc.). Furthermore as we will see, the atoms cannot always be kept on resonance. Thus $a = \alpha a_{\text{max}}$ is the acceleration. Basic physics tells us a few things about the velocity, position and time:

$$\begin{aligned} v(t) &= v_0 - at, \\ t(v) &= \frac{v_0 - v}{a}, \\ z(t) &= v_0 t - \frac{1}{2} a t^2, \\ z(v) &= \frac{v_0 - v}{2a} \left[2v_0 - (v_0 - v) \right], \\ z(v) &= \frac{v_0^2 - v^2}{2a}, \\ v(z) &= \sqrt{v_0^2 - 2az}. \end{aligned}$$

So, why did we want the velocity? Because we need to calculate the detuning. Remember, including Doppler shift, the detuning is given by

$$\delta = \omega - \omega_0 + kv.$$

Therefore, if ω and ω_0 are fixed, the detuning will grow as the atoms slow down, and then we will not be capable of reaching anywhere close to the maximum acceleration.

11.4.1 Chirped slowing

The first scheme to combat the Doppler shift is called the chirped slower. In this case, the frequency $\omega(t)$ is set such that δ is constant, that is

$$\begin{aligned}\omega(t) - \omega_0 + kv(t) &= \delta, \\ \omega(t) &= \omega_0 + \delta - kv_0 + akt.\end{aligned}$$

So the detuning is initially red by kv_0, and this is steadily reduced as the atoms slow down. This is called chirping because the frequency increases with time, which is how some birds sing.

11.4.2 Zeeman slowing

For a Zeeman slower, the frequency of lasers is fixed, but the magnetic field varies spatially, so that the frequency ω_0 depends on position. The Zeeman effect in the linear regime gives $\omega_0(z) = \bar{\omega_0} + \mu_B B(z)/\hbar$. Then, for fixed detuning,

$$\begin{aligned}\omega - \omega_0(z) + kv(z) &= \delta, \\ \omega - \bar{\omega_0} - \mu_B B(z)/\hbar + k\sqrt{v_0^2 - 2az} &= \delta, \\ B(z) &= \frac{\hbar}{\mu_B}\left[\omega - \bar{\omega_0} - \delta + kv_0\sqrt{1 - \frac{2az}{v_0^2}}\right], \\ B(z) &= B_{\text{bias}} + B_0\sqrt{1 - \frac{z}{L_0}}, \\ B_0 &= \frac{\hbar k v_0}{\mu_B}, \\ L_0 &= \frac{v_0^2}{2a}.\end{aligned}$$

Notice that we can change B_{bias} by changing ω. I will plot for you the magnetic field profile of the Zeeman slower.