A Conceptual Tour of Optical Pumping

Optical Pumping allows us to examine the phenomenon of Zeeman Splitting, a spreading of atomic energy sublevels in the presence of a magnetic field. This experiment uses two isotopes of atoms of rubidium vapor, ^{85}Rb and ^{87}Rb. Light given off by a rubidium lamp is first collimated into a beam by a 50 mm focal length lens and then passed through an interference filter which transmits only the wavelength range that will excite atoms from the $^2S_{1/2}$ to the $^2P_{1/2}$ lowest excited energy level. This light has a wave length of 794.8 nm and carries an energy of 1.56 eV. After proceeding through a properly aligned combination of a linear polarizer and ¼ wave plate, the light emerges as a beam of right hand circularly polarized photons.

The beam now enters a temperature-controlled cell containing a vapor of both isotopes buffered by low-pressure neon gas. The cell is heated to keep the rubidium vaporized and the temperature can be both monitored and varied. The temperature of the cell is usually kept at 50° C. (Of course, the effect of temperature on optical pumping can be examined.)

The light that has passed through the sample cell is focused by a lens and aimed into a photo-detector. The intensity of the light reaching the detector is transformed into a voltage which can be displayed on an oscilloscope.

As the photons in the beam of light pass through the gas, they are absorbed by the rubidium atoms causing transitions in the atoms from the $^2S_{1/2}$ to $^2P_{1/2}$ levels. As the atoms return to the lower energy state, the light is reradiated in all directions, not just in the direction of the beam. The intensity of the beam emerging from the sample cell is, therefore, less than the intensity of the incident beam. If, however, the sample cell is in a magnetic field collinear with the direction of the beam of light, interesting things happen.

To begin our experiment, the entire Optical Pumping apparatus is oriented so that the light beam passing through the rubidium vapor cell is aligned along the north–south axis of the local Earth's magnetic field. The set of Helmholtz coils above and below the rubidium cell are used to cancel the vertical component of the Earth's field across the sample cell. This means that only the horizontal component of the magnetic field will remain. The direction of the current in the large set of Helmholtz coils (with its axis along the light path) is set so that any horizontal field produced will be opposite to that of the Earth.

In the presence of a magnetic field, the two hyperfine states of the $^2S_{1/2}$ and $^2P_{1/2}$ energy levels divide into sublevels characterized by distinct values of the 'magnetic quantum number' M, the z-axis projection of atomic angular momentum. Figure 1 depicts the quantum options available to the atoms of ^{87}Rb when the gas is in a magnetic field. Both isotopes of rubidium are present in our lamp and sample cell, each with its own total spin and magnetic moment. Our discussion will focus on the ^{87}Rb because, having a smaller total spin, it also has the smallest number of available states. (After all, this is a "conceptual" tour.)

In addition to energy, the circularly polarized light entering the gas carries one unit of angular momentum along the direction of propagation, the z-axis, which is also the direction of the magnetic field. Selection rules which dictate what transitions are allowed include a rule demanding that any transition from the $^2S_{1/2}$ to the $^2P_{1/2}$ level be to a final magnetic state with one more unit of z-axis angular momentum than the initial state. ($\Delta M = +1$)

The ^{87}Rb energy diagram in Figure 1 shows no M=3 state in the $^2P_{1/2}$ level. Thus, the constraint that $\Delta M = +1$ means that atoms from the F=2, M=2 level of the $^2S_{1/2}$ energy level cannot move into any of the $^2P_{1/2}$ energy states and therefore cannot absorb any of the photons in the beam. Atoms in other $^2S_{1/2}$ states are able to absorb at least some portion of the incident photons, at the relative absorption probabilities shown.

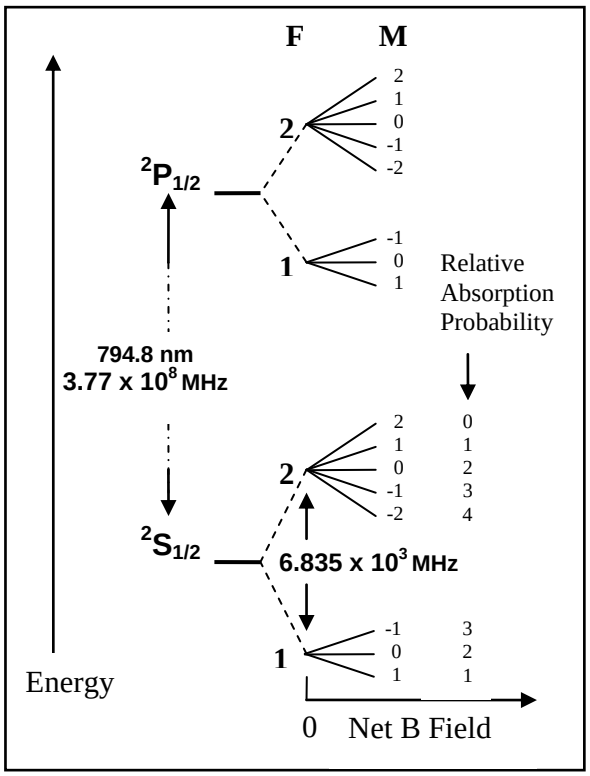

Fig.1: Energy Levels for ^{87}Rb, showing Zeeman differentiation dependence on ambient magnetic field. At B = 0.1 mT = 1.0 gauss, Δ Energy = 0.71 MHz.

Atoms that have been excited from the seven available $^2S_{1/2}$ energy states to the various $^2P_{1/2}$ levels quickly reradiate their absorbed energy. Because the selection rules for the reradiated photons include $\Delta M = 0, +1, -1$, atoms can return to all eight ground level $^2S_{1/2}$ states. The atoms in the seven differentially absorbing $^2S_{1/2}$ states are continually excited into $^2P_{1/2}$ energy levels, and then, after reradiating, spread among all eight of the $^2S_{1/2}$ levels equally. As a result, in the presence of a magnetic field, atoms in the gas are soon "pumped," into states less likely to absorb, especially that "non-absorbing" F=2, M=2 energy level of $^2S_{1/2}$.

Based on this discussion, when our sample cell is in a magnetic field, there will be a disproportionate number of the rubidium atoms in $^2S_{1/2}$ states with lower absorption probabilities, and the intensity of the light beam emerging from the cell should be greater than that at zero magnetic field.

We start our examination of the intensity of the light emerging from the sample cell with the horizontal magnetic field produced by the Optical Pumping coils essentially zero. This means that the cell is in a net magnetic field which is just the horizontal component of the local Earth's field. As the current in the Helmholtz coils is increased, the magnetic field created by the coils increases in the direction opposite the Earth's. The net magnetic field at the cell first drops to zero and then increases in the opposite direction. We monitor the event with an oscilloscope in the x-y mode. The x axis indicates the current in the Helmholtz coil and thus is proportional to the net magnetic field at the cell. The y axis records the voltage from the photo-detector, which is directly proportional to the amount of light reaching the detector. Figure 2 shows the oscilloscope trace as the net magnetic field is swept through zero and then increases in the direction opposite to the Earth's magnetic field.

With no current in the Helmholtz coils, the Zeeman splitting, caused by the horizontal component of the Earth's magnetic field, has allowed the atoms to be "pumped" into the less absorbent states. And, although the increasing current in the Helmholtz coils is actually decreasing the net field at the cell, the oscilloscope shows a flat line, indicating a constant intensity in the light reaching the photo-detector. Regardless of the size of the net magnetic field, it seems that the same disproportionate number of atoms of the gas are being be "pumped," into the less absorbing states.

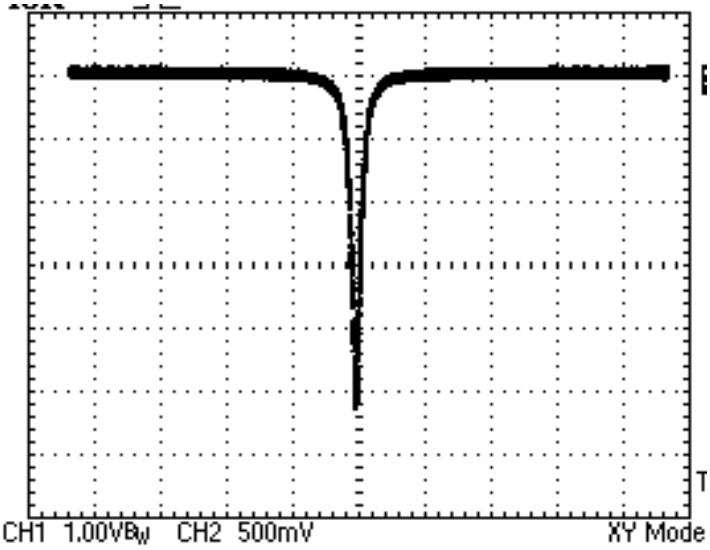

Figure 2: Transmitted Intensity vs. Magnetic Field

When the applied field and the Earth's field are the equal and opposite, the gas is in a zero magnetic field. The Zeeman levels become "degenerate;" there is no longer any distinction between the states. We can no longer "pump" the atoms into less absorbing states – there aren't any! We see a distinct dip in the line on the oscilloscope indicating that, as expected, more light is being absorbed by the gas. Although our electronics make the dip seem quite significant, the actual change in absorption is only about 1 %.

Once the applied field is greater than the Earth's magnetic field, the Zeeman levels again separate. The atoms are again "pumped" into the less absorbing states. The gas is again less able to absorb the light coming through and the photo-detector signal returns to its original level.

Although our energy diagram indicates that, as the net magnetic field increases, the Zeeman levels are separating further and further, the photo-detector signal remains constant. We need a way to "see" this spreading of the Zeeman levels.

To study the relationship between the Zeeman splitting and the magnetic field, we will introduce a small constant rf field across the cell, perpendicular to the direction of propagation of the light beam. The energy provided by the photons in our rf field will be in the 10^{-9} eV range, the same energy range as the difference between the Zeeman levels. (In fact, when the ^{87}Rb atoms are in a 0.1 mT = 1.0 gauss magnetic field, the energy splitting between the Zeeman levels is 2.9 x 10^{-9}eV, equivalent to an rf frequency of 0.71 MHz or 710 kHz).

For this next experiment, the rf signal is set at a frequency of 100 kHz. Starting with enough current in the Helmholtz coils to make the net magnetic field at the cell very close to zero, we again "sweep" through the *zero-field transition*.

As shown in Figure 3, when the magnetic field passes through zero, the signal from the receiver dips, as before. And once the magnetic field is reestablished, the trace, again, returns to its pre-zero level. This time, however, as the magnetic field increases, we reach a moment when the rf photons we are supplying have just the energy to match the energy difference between the Zeeman levels. This "resonant" energy allows atoms in the pumped levels to make transitions to the more absorbent states. The system now has more atoms able to absorb light, and there is a corresponding dip in the light intensity coming out of the sample cell

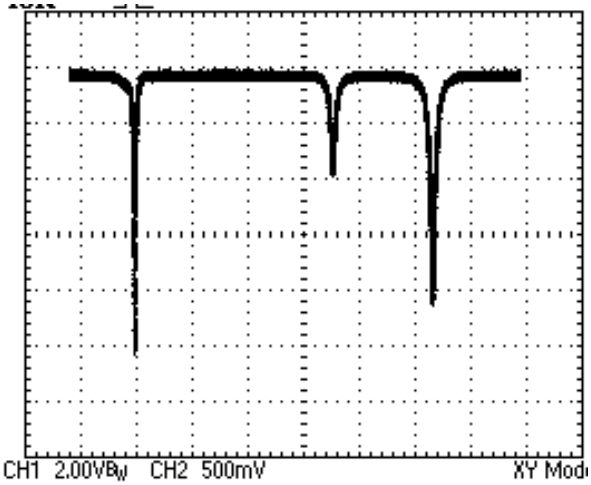

Figure 3: Transmitted Intensity vs. Magnetic Field with a 100 kHz rf field applied.

We actually see two extra dips in the Figure 3 trace, neither of which is as great as that of the zero field transition. There are two extra dips because there are two isotopes of rubidium, each with its own characteristic way of spreading out its Zeeman levels. At zero field the Zeeman levels are collapsed; *all* of the atoms participate in the creating the deep first dip. The second dip is caused when the rf energy is just right to "depump" the ^{87}Rb isotope. The last dip occurs when the energy separation of the ^{85}Rb levels matches the energy of the applied rf field

Interestingly, the absolute magnitude of the Zeeman splitting depends only on the magnitude of the magnetic field, not the direction. This becomes evident if we start with a relatively large net horizontal magnetic field in the same direction as the Earth's magnetic field before sweeping through zero field. Figure 4 shows the symmetric pattern on either side of the zero field transition. It seems that depumping occurs at the same magnitude of the magnetic field, regardless of whether its direction is the same as or opposite to the propagation direction of the pumping light beam.

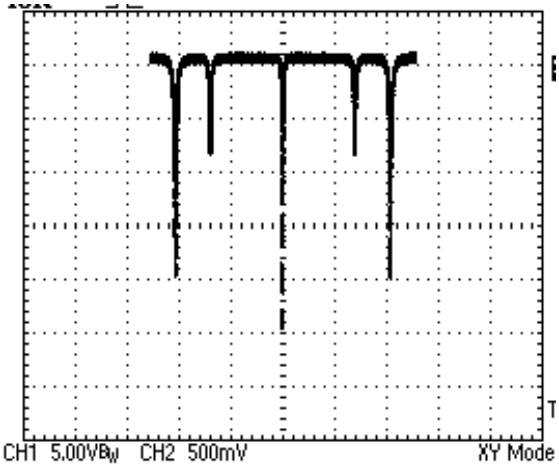

Figure 4: Intensity vs. B with 100 kHz rf

We can also investigate, quantitatively, the way the separation of the Zeeman levels depends on the magnitude of the ambient magnetic field. The same sweep of the magnetic field was used for each of the two traces shown in Figure 5. For the first (upper) trace, the rf was set at 100 kHz. The second trace was made with the rf set at 120 kHz.

As expected, the zero-field dip is exactly the same for both sweeps. There is no doubt, however, that in the lower trace, made using higher rf frequency, the dips due to resonant depumping occur at higher magnetic fields. Since the depumping marks the point at which rf photon energy matches the energy difference between the Zeeman levels, it is clear that this Zeeman energy splitting must be larger at higher magnetic fields.

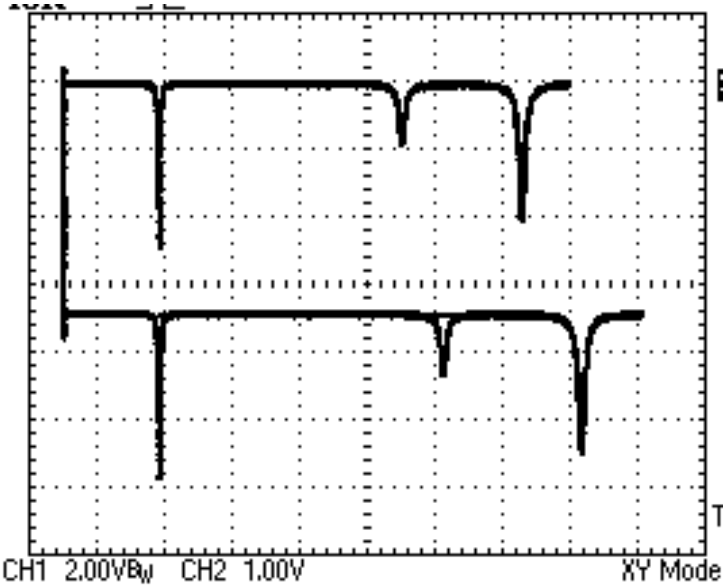

Figure 5: Intensity vs. B with 100 and 120 kHz rf.

If we take the zero transition as our reference, then the x value of the trace is proportional to the ambient magnetic field at the cell. Calculating the ratio of the x-values of the upper to the lower trace, for either the ^{87}Rb dip or the ^{85}Rb dip, shows that they are in the same 1.0:1.2 ratio as the rf frequencies used to produce them

This discussion is just an introduction to the TeachSpin apparatus and the concept of optical pumping. The laundry list of experiments that we have done with this reliable, versatile, high-precision instrument include, among others, high field quadratic Zeeman splitting, a study of transient effects as the rf is switched on and off, field reversal experiments, and optical observation of spin precession. We are sure you will discover many more, and hope that you will share them with us so that we can pass them on to other people who enjoy "playing" with TeachSpin's Optical Pumping Apparatus.

The Role of Optical Pumping in an Advanced Lab

Optical pumping is a non-laser way to use light, interacting with atoms in the vapor phase, to 'pump' the atoms into states that permit the observation of radio-frequency quantum transitions between energy levels of the atoms' ground states. This experiment is also an excellent illustration of the polarization properties of light, the energy-level structure of atoms' ground states, and the Zeeman effect of external magnetic fields on these atomic energy levels.

In addition to providing insights into quantum transitions for undergraduate students, Optical Pumping is also an important tool in many areas of modern physics research.

Explorations of Atomic Physics Using Optical Pumping	**Modern Physics Research Topics Related to Optical Pumping**
1. Transient Effects Rabi Oscillations Optical Pumping Times Field Reversal Adiabatic Transients 2. High-Field Spectroscopy Determination of Ground State Hyperfine splitting using Quadratic Zeeman Splitting data 3. Pressure Dependence 4. Effects of other Buffer Gases 5. Coherent Population Trapping 6. Pump with both D1 & D2 lines	Hyperpolarization – MRI Frequency Standards – Atomic Clocks Polarized Nuclear Physics Targets Precision Magnetometers Overhauser Polarization Coherent Population Trapping Single Particle Spectroscopy Double Resonance Experiment High Stability Gas Lasers Precision Metrology to Study QED “Slow” Light