A Conceptual Tour of TeachSpin's 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 rubidium gas, Rb^{85} and Rb^{87} buffered with neon. Light given off by a rubidium lamp is first collimated into a beam by a 50 cm focal length lens and then passed through a filter which transmits only the wavelength which excites an atom from the $S_{1/2}$ to the $P_{1/2}$ energy level. This light has a wave length of 794.8nm and carries an energy of 1.56eV . The beam proceeds through a 45 degree linear polarizer followed by a ¼ wave plate. This creates circularly polarized light each photon of which carries one unit of angular momentum. The circularly polarized light is sent through a cell containing the two isotopes of rubidium gas. The cell is heated to keep the rubidium vaporized and the temperature can be both monitored and varied. The usual operating temperature is 50° C. (Of course, the effect of temperature on optical pumping can be examined.)

The light that has passed through the sample cell is again collimated 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 $S_{1/2}$ to $P_{1/2}$ 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 significantly less than the intensity of the beam that entered.

If, however, the sample cell is in a magnetic field, interesting things happen. The $S_{1/2}$ and $P_{1/2}$ energy levels subdivide, each into 8 sublevels characterized by, among other things, a distinct quantum of angular momentum. Because the circularly polarized light entering the gas contains one unit of angular momentum, the selection rules demand that any transition from the $S_{1/2}$ to the $P_{1/2}$ level be to an energy state with one more unit of angular momentum than the state it left.

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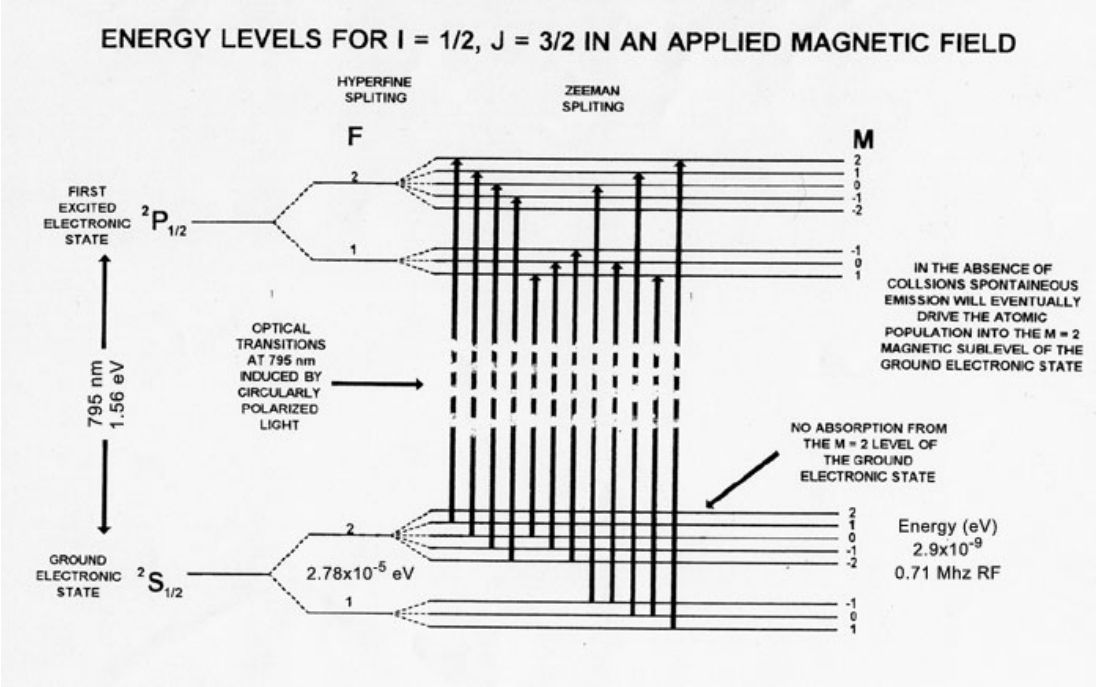

If you examine the energy diagram shown in Figure 1, you can see that this constraint means that atoms from the F=2 M=2 level of the $S_{1/2}$ energy level cannot move into any of the $P_{1/2}$ energy states. Atoms that have moved from the 7 available $S_{1/2}$ to the various $P_{1/2}$ levels reradiate their absorbed energy and return equally to all 8 ground level $S_{1/2}$ states. Because the atoms in the 7 available $S_{1/2}$ states are continually being exited into the $P_{1/2}$ and then, in returning, are spread amongst all of the $S_{1/2}$ levels, the atoms in the gas quickly become "pumped," into that eighth $S_{1/2}$ level. With disproportionate number of the atoms in the $S_{1/2}$, F=2, M=2 state, the gas is no longer in the thermal equilibrium. Atoms in that state are not capable of absorbing subsequent photons. The number of atoms of gas which are in $S_{1/2}$ levels capable of absorbing the rubidium light has greatly decreased. The entire sample becomes significantly more transparent. The light beam emerging from the cell actually becomes brighter.

We could actually observe this pumping process by turning the on beam entering the gas very suddenly. Initially, the light reaching the photo-detector would be relatively dim as the rubidium atoms of the gas absorbed the 794.8 nm light. In times on the order of milliseconds, however, the atoms would reach their non-thermal equilibrium state. The gas would become transparent and the intensity of the light at the photo-detector would increase significantly.

To begin our experiment, the light beam through the Optical Pumping apparatus 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 only the horizontal component will be of interest. The large set of Helmholtz coils with its axis along the light path creates a horizontal field opposite to that of the earth. We start our examination of the brightness of the light emerging from the sample cell with the

horizontal magnetic field produced by the Optical Pumping coils opposite to but smaller than that of the earth leaving a net horizontal field around the cell in the same direction as that of the earth's field. Figure 2 shows the oscilloscope trace as the magnetic field is swept through zero and increases in the direction of the earth's magnetic field.

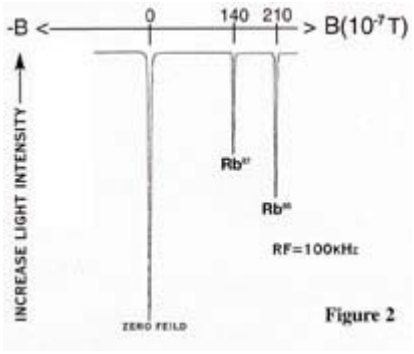

Figure 2

Initially, because of the splitting caused by the magnetic field, a large proportion of the atoms have been "pumped" into the $S_{1/2}$, F=1, M=2 state and the gas is transparent, Minimal light is being absorbed. The signal from the photo-detector is put into the y axis of an oscilloscope used in the xy mode. The x axis indicates the current in the Helmholtz coils producing the horizontal magnetic field. At first, as the applied horizontal magnetic field is slowly increased and the net field shrinks, the oscilloscope shows a flat line. As long as there is a net magnetic field, the gas remains transparent. At some point, the applied field and the earth's field are the equal and opposite and the gas is in a zero magnetic field. The Zeeman levels collapse. The atoms "escape" from the $S_{1/2}$, F=1, M=2 state and are again available to absorb and reradiate the light passing through. We see a distinct dip in the line on the oscilloscope indicating that light is being absorbed.

Once the applied field is greater than the Earth's magnetic field the Zeeman levels again begin to separate. The atoms are again "pumped" into a non-thermal equilibrium distribution with an inordinate proportion in the $S_{1/2}$, F=1, M=2 state. The gas again is unable to absorb the light coming through. The Zeeman levels separate further and further as we increase the magnetic field.

In addition to the magnetic field we are changing, we have also created a small rf field across the cell. It bathes the cell in photons with an energy in the10^{-9} eV range, the energy range of the difference between the Zeeman levels. (The accompanying diagram is for a 1.0 gauss magnetic field in which the energy splitting between the Zeeman levels is 2.9 x 10^{-9}eV, requiring an rf signal of .71 MHz).
As the Zeeman levels separate due to the increasing magnetic field, we reach a moment when the particular rf energy we are supplying is exactly the same as the difference between the Zeeman levels. This "resonant" energy allows the atoms in the pumped level to make transitions and the system is again able to absorb light. There is a dip in the light the intensity of the light coming out of the sample cell. The dip is not as great as that at our zero field transition. This is because there are two isotopes of rubidium, each with its own characteristic way of spreading out its Zeeman levels. The first dip is

caused when the rf energy is just right to "depump" the Rb^{87} isotope. We see a second dip in the light when the separation of the Rb^{85} levels matches that of the applied rf field.

If we repeat the experiment with a higher energy (higher frequency) applied rf, we find a similar pattern. However, although the 0 field dip is exactly the same, the dips due to resonance occur at a higher field. The "depumping" does not occur until the separation of the Zeeman levels reaches a point where they are in resonance with the new higher rf value.