Optical Pumping

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In 1966, French physicist Alfred Kastler won the Nobel Prize in Physics for his discovery of optical pumping, something that he theorized about in the 1950s.[1] But what is optical pumping, and what can it teach us about the nature of the universe? Before we can unpack the method Kastler developed, we must understand what it was that he developed it for.

The Zeeman Effect, named after Nobel laureate Pieter Zeeman,[2] has to do with shifts in atomic energy, which are the possible energy levels of atoms. Most readers will likely be familiar with the Bohr model of the atom as seen in Figure 1, and it has a few points of interest. First and foremost, the model is wrong – well, at least for any atom that isn't hydrogen. The second thing to note is that the rings electrons supposedly use to orbit the nucleus can be thought of as different energy levels, with rings closer to the nucleus having lower energy. From this, an energy "well" can be constructed with the ground state energy at the bottom and consecutively higher energy levels above it. The aforementioned Zeeman Effect creates *additional* energy shifts between the already existing levels when the atom is under the influence of a magnetic field, the separation distances of which are directly proportional to the strength of the magnetic field with 1 stronger field creating wider gaps. This is the effect for which Kastler developed optical pumping.

But how did Kastler "optically pump" the atoms? Using a circular polarizer, you can give light an angular momentum, and it's this light that "pumps" the electrons. Normally, electrons absorb light jump to a higher level, and jump back down after emitting light. These basic levels are generally labeled with the letter F. However, considering the Zeeman Effect and its additional shifts, usually labeled mf, where precisely do the electrons land? When this circularly polarized light hits the electrons, there are selection rules that determine which specific mf-level electrons can land on when jumping up and down. While going up, as in absorbing the light with angular momentum, the change in mf must be +1. While going down, as in emitting light, the change in mf can be +1, 0, or -1. A consequence of these rules is that electrons repeatedly pump up and down, but trend toward always going to a higher and higher mf level until they land on a level at which the selection rules no longer allow them to transition, as seen in Figure 2.

With an understanding of the phenomena that optical pumping aims to examine, we can develop an experiment to find the "Landé G Factor" which relates the magnetic field strength and resonant frequency of different energy transitions of particles, which in our case was a certain transition known as the "D emission line" in rubidium-85 and rubidium-87. In a setup where light passes through a circular polarizer and into a cell with atoms in a controlled magnetic field with a detector on the other end, signal strength can be measured from the light going through the system. As per theory, the electrons get quickly pumped up after absorbing the light and having reached their capacity, allow the rest of the light to pass through freely into the detector.

However, if the frequency of the coil placed around the cell containing the atoms reaches a "resonance" equaling the frequency at which electrons may be emitted, the 3 electrons are stimulated and end up emitting light, and so get knocked down a level and can once again absorb light. When taking a record of the signal through the system at the detector, the pumped-up electrons simply let all light through. But as the frequency of the coils approaches the resonant frequency, the electrons get pushed back down and can absorb more light. As a result, there is a dip in the signal through the system since less light is coming out at the other end.

When we experimented, we began by finding how our magnetic field strength is impacted by the current that we ran through it. As we have no way of measuring the field strength directly when the cell with atoms is in place, this relationship will give us crucial insight into the magnetic field strength during the experiment. We set out to find resonant frequencies for particular magnetic fields using a frequency generator, and

then repeatedly tested for different field strengths until we had enough points to create a reasonably accurate relationship between the resonant frequencies and field strengths. From the slopes of those relationships, we could ultimately derive the sought-after g factors, and the derived g factors ended up agreeing with the expected values from the theory.

So, what then? The idea of a connection between the energy gaps of particles in a magnetic field and its resonant frequency may be exciting to a physicist as it gives insight into a fundamental property of particles through quantum mechanics, but why would a member of the general public care? This effect is crucial for magnetometers to function, which can be used to calibrate magnets or just measure the magnetic field of the Earth.[3] An application outside of general science would be MRI, where a magnetic field is used for imaging by doctors.[4] Lasers also make use of optical pumping to have energized light output, and although they may not be able to measure a magnetic field or diagnose a medical problem, the average person can at the very least agree that lasers are cool.[5]

References

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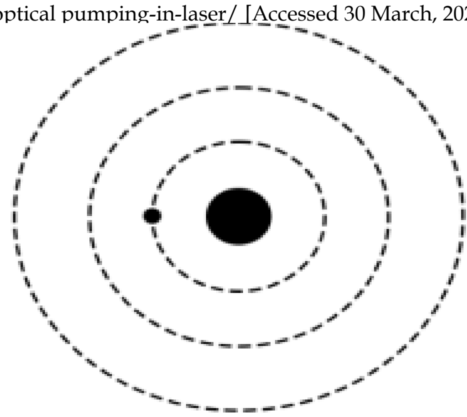

Figure 1: In the Bohr model of the atom, there is a central nucleus composed of protons and neutrons as well as rings which electrons use to orbit the nucleus.

*This author wrote this paper for Physics 480: Experimental Methods taught by Dr. Scott Schappe.

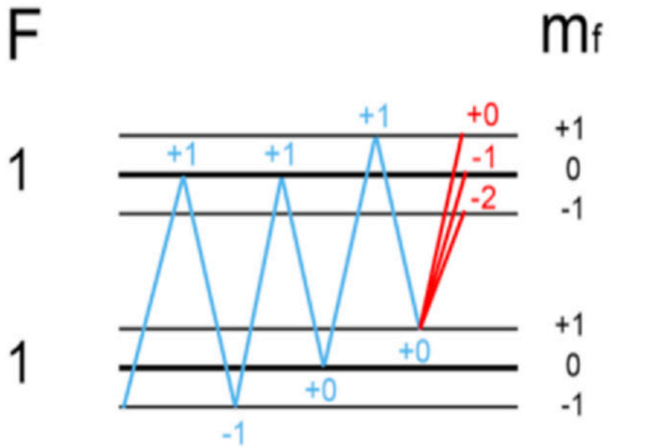

Figure 2: This diagram shows a possible path an electron may take while being pumped. It eventually reaches a point where no transition is possible, as going up must be +1.

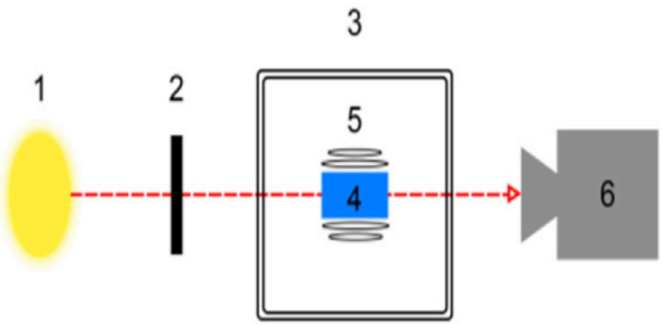

Figure 3: This is a basic version of the apparatus, light goes from the source (1), to the circular polarizer (2), into the magnetic chamber (3), through the atom cell with RF coils around it (4, 5), and finally into the detector (6).

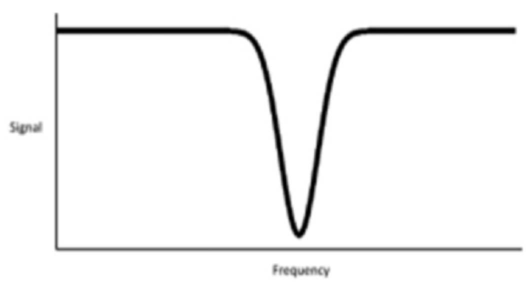

Figure 4: This figure shows an example of what the signal as a function of frequency for a particular magnetic field strength could look like. At the point of the dip, a resonant frequency is reached, and less light goes through the system.