PHY 445/515 Optical Pumping and Magnetic Resonance*

This writeup gives an overview of Stony Brook University's Rubidium Optical Pumping and Magentic Resonance experiment. The experiment explores how quantum mechanics determines the energy level structure of matter and the interaction of matter with electromagnetic fields. It also allows the experimenter to make very precise measurements of atomic magnetic moments and the earth's magnetic fields. Indeed, some of the most sensitive magnetometers are based on optical pumping. Background material regarding Rb atomic structure is presented along with an overview of the apparatus and its operation.

INTRODUCTION

The Optical Pumping and Magnetic Resonance (OPMR) experiment is quantum mechanics in action! In this experiment, you will apply the quantum mechanics you have learned in the classroom to real-world observations. The apparatus is very simple and robust and the basic measurements you perform are also simple, but they allow you to probe quantum mechanics at a very fundamental level.

In this experiment you will

- Learn how quantum mechanics and angular momentum determines the energy levels of atoms.

- Learn how atoms respond to static and dynamic electromagnetic fields over a range of field strengths.

- Learn how polarized light can excite a normally opaque gas of atoms into a transparent state.

- Determine the magnetic moments of two isotopes of the Rubidium (Rb) atom, ^{85}Rb and ^{87}Rb, and compare to quantum theory.

- Use your results to make a precise magnetic field measurements.

The main thing you actually do with the experimental apparatus is measure the Zeeman splitting of the $5\ ^2S_{1/2}\ F = 2$ level for ^{87}Rb or the $5\ ^2S_{1/2}\ F = 3$ level for ^{85}Rb as you vary a magnetic field. However, before you get to this, you will likely first need to spend a little time delving into the quantum mechanics behind what all these symbols mean.

ATOMIC STRUCTURE

Coulomb Interaction

In this section we will review the atomic physics you will need to understand the experiment. An atom with atomic number Z is made up of a swarm of Z electrons, with mass m_e, charge $-e$, and spin angular momentum of $\hbar/2$ (spin 1/2), bound to an atomic nucleus with mass $M \gg m_e$, charge $+Ze$, and nuclear spin I. Since these particles are all charged, the dominant interaction between them is due to electrostatic forces. The particle-particle interactions can then be described by Coulomb potentials, giving the following Hamiltonian in a frame where the nucleus is fixed at the origin.

$$\hat{H}_0 = \sum_i \left(\frac{-\hbar^2}{2m_e}\nabla_i^2 - \frac{1}{4\pi\epsilon_0}\frac{Ze^2}{r_i} \right) + \sum_{\text{pairs } ij} \frac{1}{4\pi\epsilon_0}\frac{e^2}{|\mathbf{r}_i - \mathbf{r}_j|} \tag{1}$$

This Hamiltonian includes the kinetic energy of the electrons (first term), the interaction of the electrons with the nucleus (second term), and the interaction of the electrons with each other (third term). In your elementary quantum mechanics class, you solved the Schrödinger equation for the case of an atom of having one electron (e.g. Hydrogen)[1], to obtain the following wave functions (orbitals) and energy levels

$$\psi_{nlm}(r, \theta, \phi) = R_{nl}(r)Y_l^m(\theta, \phi) \tag{2}$$

$$E_n = \frac{-m_e c^2 \alpha^2 Z^2}{2n^2} \tag{3}$$

Where n, l, and m are integers (quantum numbers), c is the speed of light, α is the fine structure constant, $R(r)$ is the so-called radial wave function, and the spherical harmonics $Y_l^m(\theta, \phi)$ describe the electrons orbital angular momentum. In this hydrogenic atom, the energy is determined solely by the principle quantum number n, and does not depend on the other quantum numbers. For example the $2s$ state ($n = 2, l = 0$) is degenerate with the $2p$ state. The other quantum numbers, l and m, correspond to the eigenvalues of operators that commute with the Hamiltonian, the orbital angular momentum $\hat{L}^2$ and its z-component $\hat{L}_z$

$$\hat{L}^2\psi = \hbar^2 l(l + 1)\psi \tag{4}$$

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[1] If you are unfamiliar with the hydrogen atom, you should stop reading this now and first consult an elementary quantum mechanics textbook, such as *Introduction to Quantum Mechanics* by David J. Griffiths [1].

$$\hat{L}_z \psi = \hbar m \psi \qquad (5)$$

$$\left[\hat{L}^2, \hat{H}_0 \right] = \left[\hat{L}_z, \hat{H}_0 \right] = \left[\hat{L}^2, \hat{L}_z \right] = 0 \qquad (6)$$

This idea of the good quantum numbers corresponding to operators that commute with the Hamiltonian will be useful as we refine our understanding in the subsequent sections.

The hydrogenic orbitals and energy levels give us a framework to build up multi-electron atoms using *configurations*. A configuration allows us to construct the (intrinsically complicated) multi-electron wave function from the one-electron orbitals. The Pauli principle prevents us from putting more than two electrons (one spin "up" and the other spin "down") in any one orbital. A multi-electron atom is then progressively built up via the so-called *aufbau principle*, where first the lowest energy orbital $(1s)$ is filled and then progressively higher energy orbitals are filled until there are no more electrons. For example, the ground state configuration of a Lithium atom, with three electrons, is $1s^2 2s$, with 2 electrons in the $1s$ orbital $(n = 1, l = 0)$ and one electron in the $2s$ orbital $(n = 2, l = 0)$. In this experiment, we will use Rb atoms, which have 37 electrons and the ground state configuration of $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s$. This may seem very complicated, but actually the electronic structure and spectroscopy of Rb is relatively simple because it has only one valence electron outside of a closed shell of 36 core electrons that have zero net angular momentum. Thus, as we excite and de-excite our Rb atoms with electromagnetic fields in the experiment, we can conceptually just consider their action on this one valence electron. It is for this reason, along with the fact that the wavelengths at which Rb absorbs light are experimentally convenient to generate, transport, and detect, that we use Rb in the experiment.

However, although we can build up the multi-electron wave function out of a configuration of 1-electron, hydrogen-like, orbitals, the orbitals and energies are *not* exactly the same as those of the hydrogen system due to the repulsive Coloumb interaction of the other electrons. For example, in Rb, the $5s$ and $5p$ levels, which would be degenerate (have the same energy) in our elementary description of a hydrogenic atom, are not degenerate in Rb, but instead separated by an energy of about 1.6 eV (or the energy of a photon of wavelength $\lambda = 780$ nm, in the near infrared). You will use transitions between these energy levels in your experiment.

Addition of Angular Momentum

Now that we have a multi-electron atom, we label the states by the *total* spin and orbital angular momentum, which is the sum of the spin and orbital angular momenta of all the electrons. For low Z atoms, These are denoted with capital letters to form *term symbols* in the following way:

$$^{(2S+1)}L_J \qquad (7)$$

Here S denotes the total spin angular momentum, L the total orbital angular momentum, and J the total angular momentum of the electrons ($\hat{\mathbf{J}} = \hat{\mathbf{L}} + \hat{\mathbf{S}}$). The L values are denoted with letters: "S" for $L = 0$, "P" for $L = 1$, "D" for $L = 2$, and so on [1]. You can look up these term symbols for ground and excited states of atoms on the NIST atomic database [2]. The term symbols are particularly simple to construct for the two extremes of the periodic table: the alkali atoms with one valence electron and the noble gases with a closed shell. The noble gases all have the ground state term symbol corresponding to zero total spin angular momentum, zero total orbital angular momentum, and zero total angular momentum: $^1S_0$ (pronounced "singlet-S-zero"). The alkali atoms consist of a closed shell + one valence electron, which carries all the angular momentum. So for Rb, the ground and first excited states of Rb are written as:

$$\text{Ground State: } 5\,^2S_{1/2} \qquad (8)$$

$$\text{Excited State: } 5\,^2P_{1/2} \text{ or } 5\,^2P_{3/2} \qquad (9)$$

Pay attention here to how the angular momenta add up and recall your elementary quantum mechanics! When we add the angular momenta of two systems with J_1 and J_2, respectively, the possible values for the total angular momentum range between $|J_1 - J_2|$ and $|J_1 + J_2|$ with a step size of one. So for the ground state, we have $S = 1/2$ (the spin of the unpaired electron), and $L = 0$, so the only option for J is $1/2 \pm 0 = 1/2$. However, for the excited state, with $L = 1$, there are two options for J, *viz.* $J = 1 - 1/2 = 1/2$ and $J = 1 + 1/2 = 3/2$. We will use these rules for adding angular momentum again when we consider the nuclear spin.

Spin-Orbit Coupling

Since the Coulomb interaction is the strongest between the electrons and nucleii that make up matter, it is responsible for the gross energy level structure of matter at the eV energy scale. The Hamiltonian $\hat{H}_0$ of equation (1) and the corresponding non-relativistic Schrödinger equation are thus sufficient for describing a great many phenomena. Indeed, much of the fields of "Quantum Chemistry" and "Condensed Matter Physics" are devoted to solving this problem. However, in this experiment you will measure splittings of atomic energy levels at the nano-eV scale, or 9 orders of magnitude smaller than

the Columb interaction! We will thus need to refine our description of matter to include several small effects that produce splittings of the energy levels of our Rb atoms. The good news is that quantum mechanics allows us to do this very nicely via perturbation theory.

The $5\ ^2P_{1/2}$ and $5\ ^2P_{3/2}$ levels, which would be degenerate in the Coulomb-only description, are split by a perturbation called spin-orbit coupling, as shown in figure 1. The splitting is approximately 0.03 eV, much smaller than the ~ 1.6 eV separating the $5S$ and $5P$ levels. Spin-orbit coupling is one component of several relativistic corrections to the Schrödinger equation which are lumped together in the term "fine structure". You can tell that the Schrödinger equation is intrinsically non-relativistic because it treats space and time differently, with two spatial derivatives and only one time derivative (c.f. the wave equation). Relativistic quantum mechanics can be handled by the Dirac equation, from which all the terms contributing to fine structure can be derived very neatly [3, 4]. However, our principle concern here is spin-orbit coupling because this is what splits the $5P$ energy level into two.

You can qualitatively understand spin-orbit coupling as an effect due to the magnetic fields produced by the orbiting particles. For example, in the rest frame of the electron, the nucleus is orbiting the electron and produces a magnetic field[2]. The energy of the electron's magnetic moment $\boldsymbol{\mu}$ in the magnetic field $\mathbf{B}$ is $-\boldsymbol{\mu} \cdot \mathbf{B}$. The magnetic field will be proportional to the orbital angular momentum $\mathbf{L}$ and the electron's magnetic moment is proportional to its spin angular momentum $\mathbf{S}$, so the spin-orbit term is proportional to $\hat{\mathbf{L}} \cdot \hat{\mathbf{S}}$. The important thing to note is that with the addition of spin-orbit coupling the Hamiltonian, L_z no longer commutes with the Hamiltonian, since $[\hat{\mathbf{L}} \cdot \hat{\mathbf{S}}, \hat{L}_z] \neq 0$. Thus M_L (previously called m when talking about the hydrogen atom), is no longer a good quantum number. However, since $\hat{\mathbf{J}} = \hat{\mathbf{L}} + \hat{\mathbf{S}}$, we can write

$$\hat{\mathbf{L}} \cdot \hat{\mathbf{S}} = \frac{1}{2} \left(\hat{\mathbf{J}}^2 - \hat{\mathbf{L}}^2 - \hat{\mathbf{S}}^2 \right) \qquad (10)$$

so the total angular momentum $\hat{\mathbf{J}}^2$ does commute with the Hamiltonian and J is a good quantum number. We now label the state by the quantum numbers J, L, and S, corresponding to the operators $\hat{\mathbf{J}}^2$, $\hat{\mathbf{L}}^2$, and $\hat{\mathbf{S}}^2$. The quantum numbers give the eigenvalues through the usual relationship for angular momentum, such as

$$\hat{\mathbf{J}}^2 \psi = \hbar^2 J(J+1)\psi \qquad (11)$$

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[2] Recall that magnetism is actually a relativistic phenomenon [5], which explains why spin-orbit coupling has the same order of magnitude as the other relativistic effects that determine the fine structure.
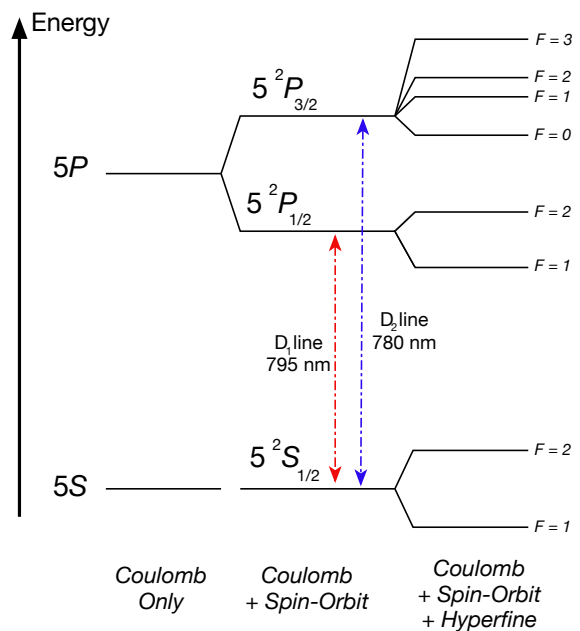

FIG. 1. Schematic diagram of the energy level splittings in ^{87}Rb. Note that this is not to scale, and not even close. Spin-orbit splitting of the 5P level is about 0.03 eV, or 7 THz in frequency, whereas the hyperfine structure splittings are on the order order of GHz or less. The blue line illustrates the D_2 transition used in the saturation spectroscopy experiment and the red line illustrates the D_1 line used in the optical pumping experiment. See Steck [6, 7] for a more detailed diagram. It is a good exercise to draw the same diagram for ^{85}Rb, with nuclear spin 5/2.

and likewise for the spin and orbital angular momenta.

At course resolution, such as one might obtain with a grating spectrograph, two strong absorption lines are observed in the near infrared spectrum of Rb, the spitting is due to spin-orbit coupling:

$$\text{D}_1 \text{ line @795 nm} : 5\ ^2P_{1/2} \leftarrow 5\ ^2S_{1/2} \qquad (12)$$

$$\text{D}_2 \text{ line @780 nm} : 5\ ^2P_{3/2} \leftarrow 5\ ^2S_{1/2} \qquad (13)$$

In the Optical Pumping and Magnetic Resonance experiment, you will make use of radiation at the D_1 line. In the saturation spectroscopy experiment across the room, they use the D_2 line.

Hyperfine Splitting

The energy levels determined by fine structure are further split by the so-called hyperfine interaction, due to the spin of the nucleus. The nuclear spin angular momentum $\hat{\mathbf{I}}$ couples to the the magnetic field produced by the electrons, $\mathbf{B}_e$, in similar fashion to spin orbit coupling. The difference here is that the magnetic moment

of the nucleus, $\mu_I = g_I \mu_N I$, is more than a thousand times smaller than that of the electron, so the energy splitting is much smaller [8]. The hyperfine Hamiltonian is thus

$$\hat{H}_{\text{HF}} = -\boldsymbol{\mu_I} \cdot \mathbf{B}_e \tag{14}$$

The magnetic field produced by the electrons is proportional to their angular momentum $\mathbf{J}$ [8], so the hyperfine Hamiltonian is proportional to $\hat{\mathbf{I}} \cdot \hat{\mathbf{J}}$. Now we again have to revise our quantum numbers. Introducing the total angular momentum (electron + nuclear) $\hat{\mathbf{F}} = \hat{\mathbf{J}} + \hat{\mathbf{I}}$, the good quantum numbers become I, J, F, and M_F. M_F gives the z-component of the total angular momentum. Figure 1 illustrates the progression from the Coulomb-only result to the field-free atomic eigenstates of ^{87}Rb, which has nuclear spin $I = 3/2$, as progressively smaller corrections to the Hamiltonian are turned on. Notice how the angular momenta adds up for the various states. In the ground state ($5\,^2S_{1/2}$), we have $J = 1/2$ and $I = 3/2$, so the smallest total angular momentum $F = 3/2 - 1/2 = 1$ and the largest is $F = 3/2 + 1/2 = 2$ and there are no steps in between. The same is true for the $5\,^2P_{1/2}$ state. However, for the $5\,^2P_{3/2}$ state we have $J = 3/2$ and $I = 3/2$ so the smallest total angular momentum is $F = 3/2 - 3/2 = 0$ and the largest is $F = 3/2 + 3/2 = 3$ and there are two steps in between.

Now we have refined the atomic structure of Rb down to the $\sim$10 nano-eV energy scale. However, in the OPMR experiment, we will measure splittings even smaller than this, so we must look at still one more effect on the atomic energy levels!

Zeeman Effect

Each of the hyperfine energy levels contains $2F + 1$ magnetic sublevels, denoted with the z-component of angular momentum M_F. However, an isolated atom is spherically symmetric - there is no preferred direction in space. Thus, the energy levels do *not* depend on M_F. The energy is the same regardless of which way the angular momentum is oriented and each hyperfine energy level is $(2F + 1)$-fold degenerate. However, when we add an external electric or magnetic field, this situation changes. In this section we will discuss the splitting of the energy levels in a static (DC) external magnetic field, $\mathbf{B}_{\text{ext}}$. The Hamiltonian for interaction with the external field is determined by the *total* magnetic moment of the atom $\boldsymbol{\mu}_{\text{atom}}$ via

$$\hat{H}_{\text{Zeeman}} = -\boldsymbol{\mu}_{\text{atom}} \cdot \mathbf{B}_{\text{ext}} \tag{15}$$

The magnetic moment of the atom consists of the sum of of the components due to electron spin angular momentum, electron obital angular momentum, and nuclear spin angular momentum, and is written in the following way:

$$\boldsymbol{\mu}_{\text{atom}} = -\frac{\mu_B}{\hbar} \left(g_S \mathbf{S} + g_L \mathbf{L} + g_I \mathbf{I} \right) \tag{16}$$

The leading minus sign is due to the negative charge of the electron. $\mu_B = e\hbar/(2m_e)$ is the Bohr magneton. The g-factors, or "gyromagnetic ratios", relate the angular momentum to the magnetic moment (more on this later). For orbital angular momentum, g_L is approximately 1 [7]. g_S of the electron would be exactly 2 in Dirac theory, but is slightly shifted from two by quantum electrodynamics effects. This has been measured (and calculated) very precisely [9]. g_I is determined by the complicated internal structure of the nucleus and must be determined experimentally. You can refer to the tabulated values of these g-factors in the documents by Steck [6, 7]. Taking the external magnetic field to be in the z-direction, our Hamiltonian becomes:

$$\hat{H}_{\text{Zeeman}} = \frac{\mu_B B_{\text{ext}}}{\hbar} \left(g_S \hat{S}_z + g_L \hat{L}_z + g_I \hat{I}_z \right) \tag{17}$$

So now if we were working in a basis of eigenstates of the operators $\hat{S}_z$, $\hat{L}_z$, and $\hat{I}_z$, with quantum numbers M_S, M_L, and M_I, we could very easily evaluate the expectation value of this Hamiltonian to determine the energy level splittings. However, we are not! Recall that the spin-orbit coupling and hyperfine interaction excluded the z-components of the individual angular momenta ($\mathbf{L}$, $\mathbf{S}$, and $\mathbf{I}$) from being good quantum numbers, because these operators no longer commute with the atomic Hamiltonian. This seems to put us in a bind. The Zeeman Hamiltonian would have us use (M_S, M_L, and M_I) as the quantum numbers to define the angular momentum, but the spin-orbit coupling and the hyperfine interaction have driven us to use J, I, F, and M_F as the good quantum numbers.

Fortunately, we are rescued from this predicament by the fact that it turns out that actually it is only the component of the angular momentum parallel to the total angular momentum that matters. This can be justified rigorously using the Wigner-Eckart theorem [8], and qualitatively using the so-called "vector model" [1, 8]. In the vector model, one can think of the components $\mathbf{J}$, $\mathbf{S}$, and $\mathbf{I}$ all precessing about the total angular momentum vector $\mathbf{F}$. Averaged over time, only the component along $\vec{F}$ remains. This simplification lets us write things like

$$\hat{\mathbf{S}} \rightarrow \frac{(\hat{\mathbf{S}} \cdot \hat{\mathbf{F}})}{\hat{F}^2} \hat{\mathbf{F}} \tag{18}$$

and similar expressions for $\hat{\mathbf{L}}$ and $\hat{\mathbf{I}}$. With this simplification, we can rewrite equation (17) in terms of only the z-component of the total angular momentum, with the appropriate prefactor:

$$\hat{H}_{\text{Zeeman}} = g_F \frac{\mu_B B_{\text{ext}}}{\hbar} \hat{F}_z \quad \text{(Weak B-field)} \tag{19}$$
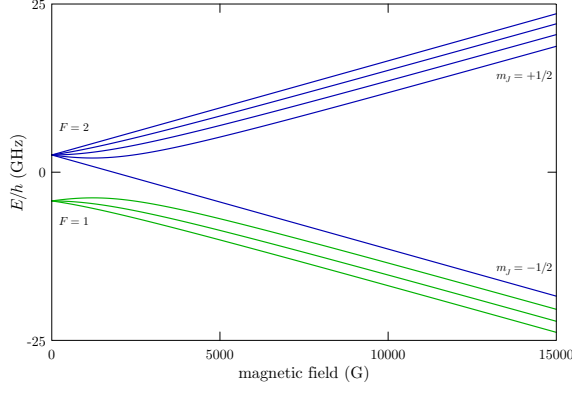
FIG. 2. ^{87}Rb $5^2S_{1/2}$(ground) level hyperfine structure in an external magnetic field. The levels are grouped according to the value of F in the low-field (Zeeman) regime and m_J in the high field (Paschen-Back) regime. Taken from [7].

with the hyperfine Landé g-factor given by

$$g_F = g_J \frac{F(F+1) - I(I+1) + J(J+1)}{2F(F+1)} + g_I \frac{F(F+1) + I(I+1) - J(J+1)}{2F(F+1)} \quad (20)$$

and the fine structure Landé g-factor, g_J by

$$g_J = g_L \frac{J(J+1) - S(S+1) + L(L+1)}{2J+1} + g_S \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \quad (21)$$

A detailed compilation of all the accepted values of the g-factors can be found in the references by Steck [6, 7]. You can evaluate this with first order perturbation theory via:

$$\Delta E = \langle F, M_F | \hat{H}_{\text{Zeeman}} | F, M_F \rangle \quad \text{(Weak B-field)} \quad (22)$$

However, one needs to be a little bit careful here, because perturbation theory only makes sense if the perturbation is small compared to the Hamiltonian that determines the field-free eigenstates. As the magnetic field strength is increased, it is actually possible that the external magnetic field becomes larger than the internal field responsible for the hyperfine splitting. In this case, the $|F, M_F\rangle$ states are no longer the good basis, since they are formed from the coupling of the nuclear spin $\mathbf{I}$ with the electron total angular momentum $\vec{J}$. If the interaction with the magnetic field is stronger than this hyperfine coupling, $\mathbf{I}$ and $\mathbf{J}$ effectively decouple and the good basis reverts back to the $|J M_J I M_I\rangle$ basis:

$$\hat{H}_{\text{Zeeman}} = \frac{\mu_B B_{\text{ext}}}{\hbar} \left(g_J \hat{J}_z + g_I \hat{I}_z \right) \quad \text{(Strong B-field)} \quad (23)$$

$$\Delta E = \langle J, M_J, I, M_I | \hat{H}_{\text{Zeeman}} | J, M_J, I, M_I \rangle \quad \text{(Strong B-field)} \quad (24)$$

Figure 2 illustrates the splitting of the ground state of ^{87}Rb in both the weak field regime and the strong-field regime. For weak magnetic fields, regime this is referred to as the Zeeman effect and for strong magnetic fields this is referred to as the Paschen-Back effect. We haven't yet stated what exactly is meant by "weak" and "strong". To do this, we introduce the dimensionless parameter

$$x \equiv \frac{(g_J - g_I)\mu_B B_{\text{ext}}}{\Delta E_{\text{HF}}} \quad (25)$$

with ΔE_{HF} the field-free hyperfine splitting. $x << 1$ corresponds to the Zeeman regime, and $x >> 1$ corresponds to the Paschen-Back regime. In the intermediate regime, in general one must resort to numerically diagonalizing $\hat{H}_{\text{HF}} + \hat{H}_{\text{Zeeman}}$, but in the case of the ground state of Rb with $J = 1/2$, there is an analytical solution know as the Breit-Rabi formula.

$$E_{I, m_I, m_J} = -\frac{\Delta E_{HF}}{2(2I+1)} + g_I \mu_B m B_{\text{ext}} \pm \frac{\Delta E_{HF}}{2} \left(1 + \frac{4mx}{2I+1} + x^2 \right)^{1/2} \quad (26)$$

with $m = m_I \pm m_J$. The plus sign corresponds to the upper manifold of hyperfine states ($F = I+1/2$) and the minus sign corresponds to the lower manifold ($F = I-1/2$). It is a good exercise to confirm that the Breit-Rabi formula converges to what you would expect from equation (19) in the low-field limit. In your experiment, you will measure the splittings of the Rb atomic energy levels due to both the ambient magnetic field and a magnetic field you supply by running a current through the electromagnets wrapping around the Rb cell, comparing your results

to those predicted by the Breit-Rabi equation and equation (22). However, the Zeeman splitting can be fantastically small! For example in the earth's magnetic field, the splitting is only a few hundred kHz, or 9 orders of magnitude smaller than energy separation between the $5S$ and $5P$ levels. We will need some clever tricks to measure such a small effect, which we will discuss in the next section.

THE EXPERIMENT: OPTICAL PUMPING AND MAGNETIC RESONANCE

Electromagnetic radiation (a.k.a "light") can promote transitions between the atomic energy levels. Indeed, most of what we know about quantum mechanics comes from measuring the absorption and emission of light as atoms and molecules make transitions between their quantum states. A necessary condition for an atom to make a transition is the conservation of energy, so the energy of the absorbed or emitted photon, $h\nu$, must be the same as the energy difference between the two quantum states. Another way to say this is that the light frequency must be *resonant* with the atomic transition. However, this is not the only condition that must be satisfied for an atom to absorb or emit light. We must also satisfy the so-called *selection rules*, which can be derived from conservation of angular momentum. It is the selection rules which give us optical pumping and allow us to measure the Zeeman splitting of Rb to fantastic accuracy with very simple and inexpensive equipment.

In the experiment you will send circularly polarized light, resonant at the D_1 transition, with its propagation vector parallel to the magnetic field through a sample of Rb atoms. This is why the apparatus is tilted at a funny angle, to be roughly parallel to the magnetic field of the earth. The helicity of the circularly polarized light is something you can figure out in the experiment, but for the sake of exposition, here lets assume it is σ_+ polarized so that we have the selection rule for absorption: $\Delta M_F = +1$. For example, an atom in the $5^2S_{1/2}F = 1, M_F = 0$ state of ^{87}Rb can only make a transition to the $5^2P_{1/2}$ $F = 1, M_F = 1$ state or the $5^2P_{1/2}$ $F = 2, M_F = 1$ state. These excited P states live for about 30 ns, due to very rapid spontaneous emission back down to the $5^2S_{1/2}$ state. However, since the spontaneous emission is unpolarized, it can cause transitions with $\Delta M_F = 0,1$, or -1. So when we excite the atom with D_1 light, we always take one step up the M_F ladder, but have a somewhat random process coming back down, as illustrated in figure 3.

However, something special happens for atoms that end up in the $5^2S_{1/2}$ $F = 2, M_F = 2$ level: there is no $5^2P_{1/2}$ $M_F = 3$ level for them to be excited to! They cannot absorb the D_1 σ^+ light and will remain "pumped up" to this state! Although an excited state, this state is "metastable", meaning its spontaneous emission rate is extremely slow, so in the absence of collisions, it effectively does not decay. You can see what will happen now, since atoms that end up in $5^2S_{1/2}$ $F = 2, M_F = 2$ stay there, eventually all the atoms will end up in this state and atomic medium is optically pumped[3]. Furthermore, since now all the atoms are excited, the medium
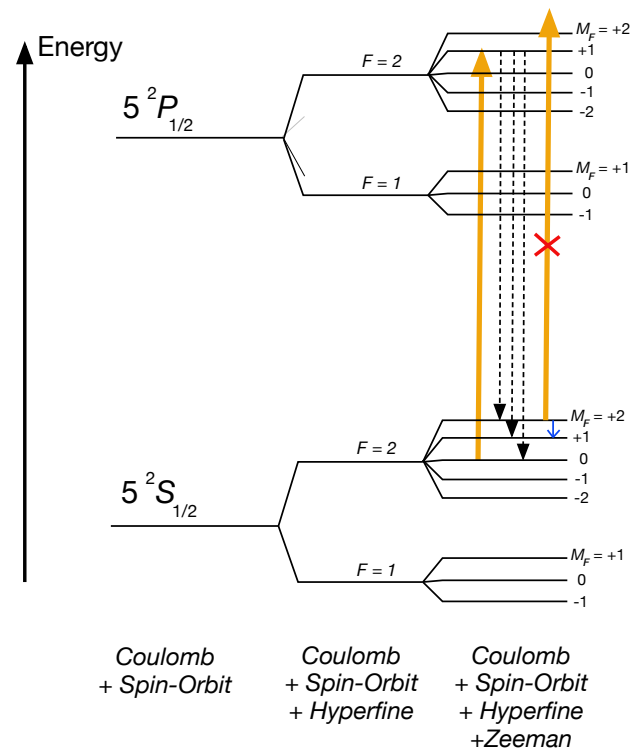

FIG. 3. Illustration of optical pumping in ^{87}Rb with σ^+ light. The upward orange arrows correspond to transitions induced by the circularly polarized pumping light from the lamp. The downward black dashed lines correspond to spontaneous emission. When atoms reach the M_F sublevel of the ground state, further excitation with the pump light is not allowed, unless the atoms are "dumped" down to lower M_F levels through stimulated emission with an RF field.

becomes transparent, and our resonant D_1 σ^+ light which was getting strongly absorbed by the Rb atoms will now pass through them.

Now although the spontaneous relaxation rate of the excited magnetic sublevel is very slow, it can be made to undergo stimulated emission at a reasonable rate by applying a resonant radio-frequency (RF) field. This is a magnetic dipole transition and is called "magnetic resonance". Atoms that get "dumped" down to lower magnetic sublevels by the magnetic field can now absorb the circularly polarized D_1 light again. This double resonance spectroscopy is the primary measurement you perform in the experiment: you measure the transmission of the D_1 light vs. the frequency of the RF field. Figure 4 shows some data from the experiment. When the RF field is resonant, a dip is seen in the D_1 light transmitted by the sample. By determining the center of this

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[3] Of course, you can never get *all* the atoms pumped into the excited state, due to collisional decay processes, but a large fraction can be excited. You can learn about these decay processes by analyzing the line shapes and widths you observe
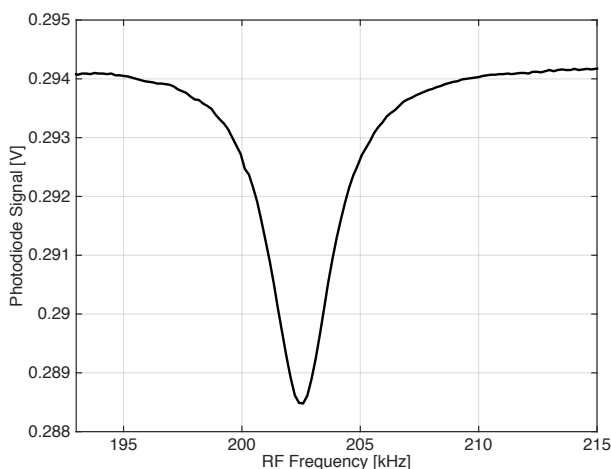
FIG. 4. Some example data taken with the apparatus. As the RF field frequency is tuned into resonance with the Zeeman splitting of the ground state, a decrease in the transmitted D_1 light is observed.

dip, you can determine the splitting between the Zeeman sub-levels.

Maybe you are thinking now: "This seems complicated. Why do we do it this way? Can't I just measure the absorption or emission of the RF field?". The reasoning for performing the experiment this way is as follows: The D_1 line photon energy is about 1.6 eV, and this radiation is very easy to detect using a silicon photodiode. It is even straightforward to detect single 1.6 eV photons using a photomultiplier. It is much easer to detect the D_1 light than the radio frequencies that correspond to magnetic resonance, but it is much easier to to finely tune the radio frequencies because they can be easily generated precisely using a synthesizer. So the OPMR experiment utilizes both these conveniences. Furthermore, optical pumping prepares the atomic ensemble to be predominantly in one magnetic sublevel, whereas in thermal equilibrium the entire ground state manifold would be populated, complicating the spectrum.

THE APPARATUS

The apparatus is shown in figure 5. Radiation at the Rb D_1 and D_2 lines emerges from the Rb discharge lamp and is collimated with a lens. A spectral filter selects the D_1 light and a polarizer + quarter wave-plate make the light traversing the Rb cell circularly polarized (helicity to be determined by you!). The Rb cell contains both ^{87}Rb and ^{85}Rb isotopes and also about 20 Torr of Argon. The Argon acts as a buffer gas which prevents the Rb atoms from hitting the wall too frequently, which would rapidly depolarize them. Light that makes it through the Rb cell is refocused by another lens onto a Si photodiode, which

is reverse biased with a 9V battery and wired in series with a 300 kΩ resistor. The resistor converts the photocurrent of the diode into a voltage, which you measure using the 34401A multimeter and the computer.

The apparatus is tilted to be roughly parallel to the magnetic field of the earth. Surrounding the Rb cell is a set of "Maxwell Coils", which you will use to apply your own magnetic field. The Maxwell coils produce an extremely uniform magnetic field in the region of the Rb cell (Can you figure out why this is important?). You control the current going through the Maxwell coils in the experiment to control the magnetic field, but of course you need some details about the coils to determine the relation between magnetic field and current. These details can be found in the appendix.

Radio frequency fields are applied using the Helmholtz coils, which are orthogonal to the Maxwell coils. You can tune the RF field frequency using the synthesizer. Most measurements in the experiment are made using a DC magnetic field, sweeping the synthesizer frequency across resonance, and recording a dip in the transmitted light.

Rb shows up as a solid in the periodic table. However, it has a reasonably high vapor pressure, which can increased dramatically with a modest increase in temperature. You can find formulas and plots for the vapor pressure of Rb as a function of temperature in the summaries written by Steck [6, 7]. To get more Rb in the gas phase, you will heat the cell using the heat gun which is controlled by a variable AC transformer. You can measure the temperature with the thermometer sticking out of the opposite side of the Rb cell. **DO NOT TOUCH THIS THERMOMETER. JAMMING IT COULD BREAK THE RB CELL**.

Strange effects on the line shapes have been observed at temperature above 45° C or so, which are not completely understood by the faculty. So I recommend staying at temperatures below 40° C. Of course if you can figure out the double peak phenomena observed at higher temperatures, you will almost certainly earn an A$^+$ grade!

GETTING STARTED

The first thing you need to do is turn on the lamp. The lamp is turned on by switching on the power supply labelled "LAMP" on the floor next to the apparatus. The lamp should turn on with 18V or less on this power supply. **DO NOT EXCEED 20 V**, as this can damage the lamp and then you will not be able to do your experiment. The lamp may not come on immediately. Be patient, it takes a while for the Rb lamp to warm up. You an observe if the lamp is on by seeing a dim pink glow on a piece of paper held near the lamp output port. Do you know why it appears so dim?
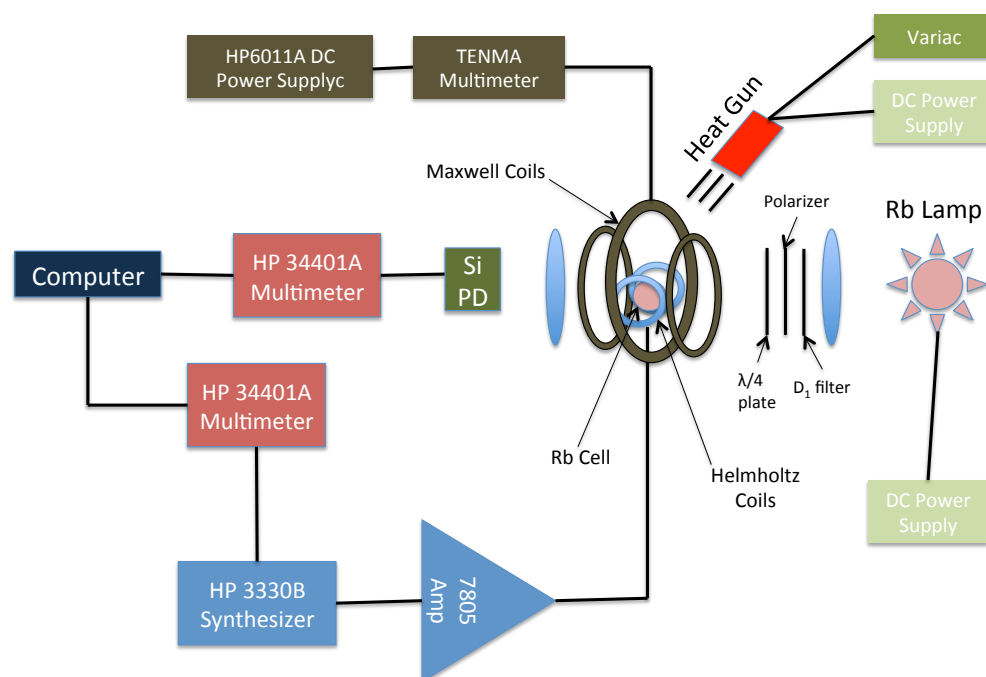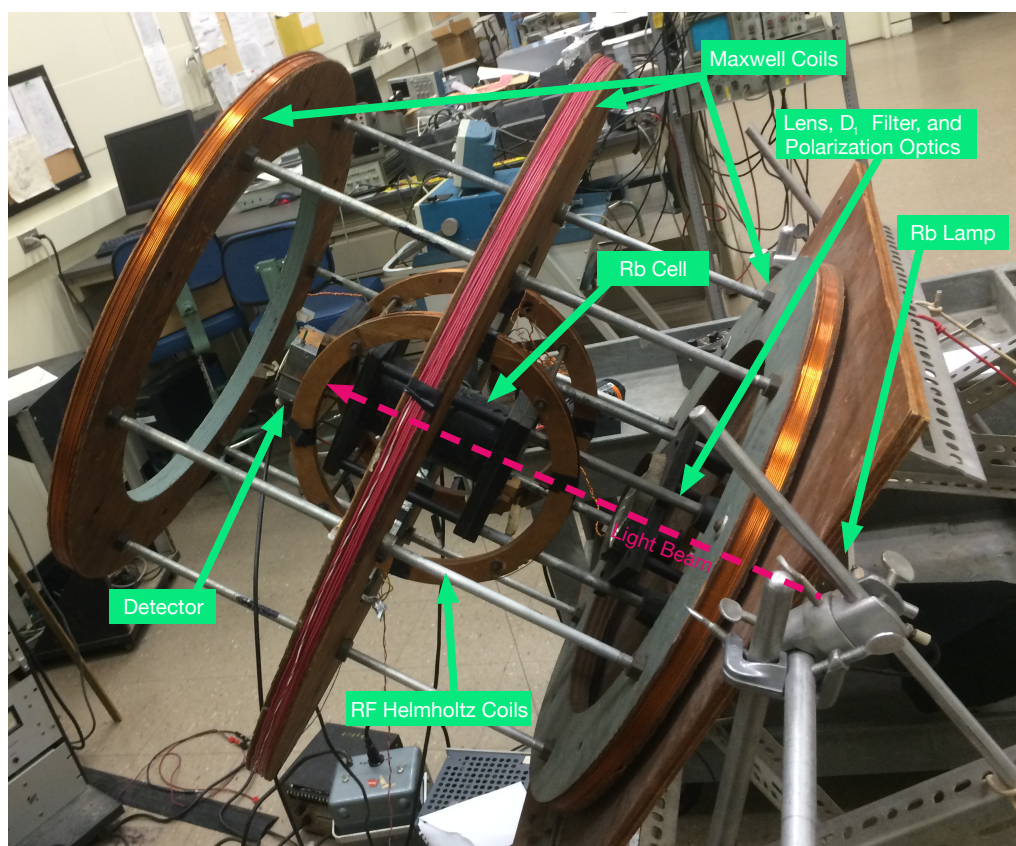
FIG. 5. The Optical Pumping apparatus.

You can monitor the output of the lamp by turning on the detector and its associated electronics. Do this by switching on the reverse bias voltage for the photodetector. The photodiode voltage is read out by an Agilent 34401A digital multimeter which is connected to the computer via GPIB. To record the photodiode voltage with the computer, start up LabVIEW and open the virtual instrument (VI) "OpticalPumping 10-25-10.vi". This VI has two tabs. One is called "Lamp, Cell Warm Up", and the other is called "Frequency vs. Transmission". Start by using the Lamp, Cell Warm Up tab to record photodiode signal vs. time as the lamp warms up.

Once the lamp output has stabilized, you will need to warm up the Rb cell. To do this, first switch on the power supply on the floor labeled "FAN". This turns on the fan to the heat gun. Next dial the variable AC transformer on the floor labeled "HEAT" to 50 V or so and switch it on. This controls the voltage to the heater coils in the heat gun and thus allows you to control the temperature of the cell. You can measure the cell temperature using the thermometer protruding from the cell on the oposite side of the lamp. Be careful! There should be no need to touch the thermometer, and doing so might break the Rb cell, and then you will not be able to do your experiment. As the cell warms up, you will see that the photodiode signal goes down as the Rb atoms absorb the D_1 light. You should record the temperature and photodiode voltage as the cell warms up. you will use this to estimate the absorption cross section of the Rb atoms.

Once the cell temperature has stabilized, you can now search for magnetic resonance. Do this first in the ambient magnetic field. In the Prelab questions, you determined where to look for magnetic resonance in both ^{87}Rb and ^{85}Rb in the earth's magnetic field. You will now use this information to program the HP3330B synthesizer to sweep the RF frequency around where you expect to observe magnetic resonance. Switch to the "Frequency vs. Transmission" program of the LabVIEW program. Turn on the synthesizer and set the amplitude output to -40 dBm. Also set the frequency to your expected magnetic resonance frequency for either ^{87}Rb or ^{85}Rb. Also turn on the 7805 amplifier next to the synthesizer. Program the synthesizer to sweep the frequency about +/- 20% of your calculated value, and use the LabVIEW program to record a frequency sweep. Once you determine the frequencies of the magnetic resonance peaks, you can of course "zoom-in" with your scan and record better data.

To apply an external magnetic field, you will use the HP6011A power supply in series with the Tenma multimeter. We have found the current to be more stable running the power supply in constant voltage mode and just using the multimeter to record the current. You can change the direction of the current (and thus the magnetic field), by swapping the two alligator clips on the back of the power supply. Of course only do this when the power supply is off.

WHAT YOU SHOULD MEASURE

If you are particularly keen, this experiment allows you to explore atomic physics with an incredible level of depth. At a bare minimum, your report should contain the following measurements and analyses:

- **Absorption Cross Section:** Record the lamp warm up and also the Rb cell warmup curves. Use your data to estimate the absorption cross section of your optically pumped Rb atoms.

- **Rb magnetic moment and g-factors:** Use the Optical Pumping/Magnetic resonance scheme to measure the Zeeman splitting of both ^{87}Rb and ^{85}Rb in both the earth's magnetic field and a range of magnetic fields you apply using the Maxwell coils. Use your data to determine the appropriate g-factors and compare to quantum theory for both ^{87}Rb and ^{85}Rb.

- **Ambient Field:** Use your experimentally determined g-factors or cancellation of the ambient field with your Maxwell coils to measure the ambient magnetic field in the advanced laboratory. You can compare your result to the magnetic field of the earth at Stony Brook predicted by the World Magnetic Model [10].

There is so much Physics to do with the OPMR apparatus, that really you could spend the whole semester on this experiment. There are many more advanced measurements you can make with the apparatus, which you are encouraged to undertake, both for your edification, and for your grade!

- **High B-field regime:** Turn up the current in the Maxwell coils to the point where the degeneracy between the different ΔM_F transitions is broken. Observed multiple transitions in one frequency sweep and compare your results to that predicted by the Breidt-Rabi formula. Use your results to determine the helicity of the D_1 pumping light.

- **Multi-Photon Transitions:** It is possible to observe multi-photon transitions with $\Delta M_F = 2$ using strong RF fields. You will need to work in the high B-field regime to observe this (Do you know why?).

- **Line Shapes and Power Broadening:** A great deal of information about the relaxation processes in the atomic gas can be learned from analyzing the line shapes. Is the magnetic resonance line shape better fit by a Lorentzian or a Gaussian curve? At high RF field strengths, it is possible to observe "power broadening". Can you observe this and compare to theory [8].

Appendix: Useful Apparatus Details

The Maxwell coils were last rewound in 1994 with 16 gauge copper wire of 0.132(5) cm diameter. The central large coil consists of 14 layers of wire, with 11 turns in odd-numbered layers and 10 turns in even-numbered layers, except for layer 14 which has 5 turns, for a total of 142 turns. The inner diameter of the large coil is 78.4(5) cm. The spacing along the beam direction between the large coil and the two smaller Maxwell coils is 26.5(2) cm. Each small coil consists of a 110 total turns of wire, arranged in 11 layers. The inner diameter of the small coils is 59.1(5) cm. The even numbered layers have 10 turns, and the odd numbered layers have 11 turns. The total DC resistance of all three coils in series is about 10 Ω.

The Rb vapor cell is 5 cm in diameter and the beam traversing it is about 1 cm, defined by an aperture, so the effective path length of the light through the Rb medium is about 5 cm.

Many details regarding the operation of the synthesizer and the multimeters can be found in their manuals. The operation of the LabVIEW codes is fairly straight-forward, but there are also instructions for this on the VI's front panel.

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